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Feasibility Analysis Regarding the Manner of Development of the Former Edmund Szyc Stadium Area in Poznań

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Abstract: The paper presents a feasibility analysis of changes in the manner of development a former sports facility, Edmund Szyc Stadium in Poznań. The terrain and adjacent areas were inventoried, including the assessment of inter-area relationships. Based on the inventory and authors' surveys, three developmental variants were selected for further analysis. Particular attention was paid to the purpose of the area in the local zoning plan (local spatial development plan) and the preferences of its local community. A multi-criteria analysis carried out with three different methods – AHP, MAUT and PROMETHEE II indicated the second variant as optimal. Additionally, the authors performed a sensitivity analysis of the AHP method to determine the weight of adopted criteria. This allowed for observing what impact these changes had on the final result. The sensitivity analysis was performed only for 3main groups of criteria. The implementation of activities planned in the concept will allow for optimal land development, improvement in functionality as well as improvement in visual and landscape characteristics of the city.

Keywords: multi-criteria analysis, AHP, MAUT, PROMETHEE II, sports facility, spatial development, sensitivity analysis, revitalization

1. Introduction

Revitalization of Polish cities is currently one of the most urgent issues related to the continuous degradation of urban substance (Parysek 2015, 2017, Tofiluk et al. 2019). The matter was pointed out by legislators when they introduced the Act on Revitalization of October 9, 2015 (Journal of Laws of 2015, item 1777). Revitalization is a process that aims to stop the degradation of urban areas, counteract violent crisis incidents by making local residents involved in, strengthen pro-environmental activities, and protect the current national heritage by taking into account all principles of sustainable development (Boryczka 2016). Therefore, it is a direct response to the progressive social, spatial and economic degradation of urban space (Domański & Gwosdz 2010). A properly carried out revitalization process should take into account not only social, economic and technical aspects (Urbańska-Galewska et al. 2013) but also formal and legal (Ostręga & Uberman 2005) as well as environmental perspectives (Przewoźniak 2005). Sometimes, it is quite problematic, particularly in the context of reconciling conflicting requirements or expectations regarding revitalization. In such a situation, a decision problem may arise, which can be tried to be solved by using one of numerous methods of multi-criteria decision support.

Post-industrial facilities are often revitalized, and with great success. The following implementations can serve as an example here: Manufaktura in Łódź, Stary Browar in Poznań, Graffica in Rzeszów – all have been recently revitalized and serve as shopping centres (Budner & Pawlicka 2013, Dąbrowski 2012, Frey & Kozicki 2009, Świerczewska-Pietras 2009, Tölle 2007, Twardzik 2015). Revitalization of post-industrial facilities may be intended for use as modern apartaments i.e. "Tkalnia 14" in Zielona Góra – the object built in 1864 and originally used as a weaving mill (Turek 2013) or as cultural/ touristic facilities (museums), i.e. the Museum of Artistic Foundry (Muzeum Odlewnictwa Artystycznego) on the premises of Steelworks and Foundry in Gliwice (Nitkiewicz-Jankowska 2006).

Sports facilities are built or revitalized often when major sporting events are to be organised in a not so distant future e.g. National Stadium in Warsaw or the Stadion Energa Gdańsk (Kamrowska-Załuska & Kostrzewska 2014, Sobiera 2012). New facilities are often located in former brownfields or heavily degraded urban areas. Such investments are undoubtedly a major stimulus towards a socio-economic recovery, an improvement in spatial order, and also have a positive impact on improving the image of a given city and the local identity of its residents (Taraszkiewicz 2018, Taraszkiewicz & Nyka 2017, Tomanek 2015, Wojtowicz-Jankowska 2010). The higher rank of an organised event, the more the revitalization activities contribute to better spatial order (Kostrzewska 2016). Undoubtedly, it is problematic how to use these facilities after the event itself (Berbeka 2013, Kamrowska-Załuska & Kostrzewska 2014). Large sports facilities, constructed or modernised on the occasion of major sporting events, do not play a leading role when the events end. Indeed, an isolated facility will not be an attraction in itself. It must have an appropriate subsidiary premises thanks to which it could be recognized, in addition to its original purpose, as a tourist attraction. However, it requires additional investments, e.g. construction of a sports museum, etc. Therefore, such decisions should be preceded by a comprehensive analysis.

A separate issue is the modernisation and revitalisation of sports facilities that have ceased to perform their original functions, with insufficient functionalities, when there is a lack of adequate complementary infrastructure or they have simply fallen into ruin. Former sports facilities, erected during the communist era and enjoying great interest at that time, often require or have required major modernisation and revitalisation. If it has been carried out, sports facilities can be further used successfully (Masierek & Torzewski 2018, Pędraszewska-Sołtys & Dzioban 2018). Sometimes, however, they are abandoned, forgotten, neglected and fall into ruin. An example here would be Edmund Szyc Stadium (Polish: Stadion im. Edmunda Szyca) in Poznań, a multipurpose stadium opened in 1929, which until 1995 served as the stadium of Warta Poznań Sports Club. The article is an attempt to assess the revitalisation potential of the former sports complex and possible indication of directions of changes in the development of the facility and its adjacent areas.

2. Facility

The history of former Lech stadium's grounds named after Edmund Szyc dates back to as early as the first half of the 20th century and is associated with the "Comprehensive National Exhibition" (Powszechna Wystawa Krajowa) in Poznań in 1929. The facility found its location in the close proximity to the city centre, unfortunately in wetlands, where the Warta riverbed once existed, and then there was a backwater area (Fig. 1).

During World War II, the premises of the stadium became a Jewish labour camp and a place of execution. Considering this tragedy, near the stadium there was erected a monument dedicated to the memory of the victims of this crime.

The stadium was successfully rebuilt after 10 years of functioning in the urban space, in 1957. It brought the times of prosperity for the facility and turned it into one of the most important sports centres in Poland. The stadium's first degrading factor was the change of Lech's club location to the facility at Bułgarska Street in 1980. However, the main factor that led to the stadium's total collapse was the withdrawal of the main sponsor in 1989. The difficult financial situation forced the management to sell the plot, and the terrain of the stadium was intended for housing development.

The city authorities, after many years of discussions and efforts, managed to achieve success in this matter. They bought the facility with adjacent areas of approx. 6,5 ha. Ipso facto, the area was given a chance to renew its character and commence works related to its revitalisation.

Currently, the stadium is devastated. A detailed inventory showed large amount of glass and litter on its premises (Fig. 2).

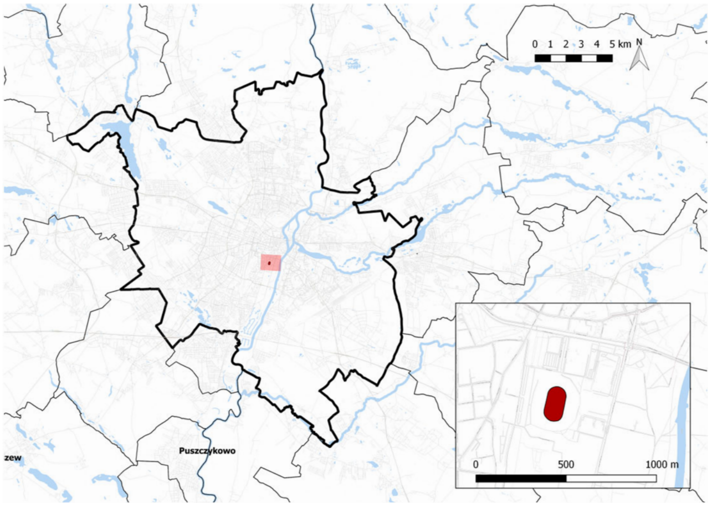

Fig. 1. Location of the stadium Edmund Szyc against the background of the city of Poznań

Fig. 2. Current stadium status

3. Analysis

The authors made a feasibility analysis of the manner the object could be developed using multi-criteria analysis tools (MCDM) i.e. Analytic Hierarchy Process – AHP (Saaty 2008), Multi-Attribute Utility Theory – MAUT (Wallenius et al. 2008) and Preference Ranking Organization METHod for Enrichment of Evaluations – PROMETHEE II (Vincke & Brans 1985).

Five main criteria were identified: social – G1, environmental – G2, functional – G3, spatial – G4 and economic – G5. Sub-criteria were assigned to each of the designated groups, which allowed for a more detailed analysis of the significance of individual criteria with reference to selected variants. In total, 19 sub-criteria were defined (Table 1). In order to additionally verify the created ranking of variants, the results obtained with the AHP method were compared with the results from the MAUT and PROMETHEE II methods. Table 1 also compares the adopted values of individual expert assessments based on own experience, the area inventory, the analyses of MPZP and SUiKZP and the expectations of the local community (surveys). The weights of individual criteria (Table 1) were determined by the AHP method using a pair-wise comparison matrix.

The decision problem can be illustrated with a simple graph showing the adopted hierarchical structure (Fig. 3).

Three land development variants were proposed for consideration:

V1 – sports, cultural and artistic facility / sports and entertainment hall,

V2 – recreation area / park with small architecture elements,

V3 – recreation and service facility / restaurants.

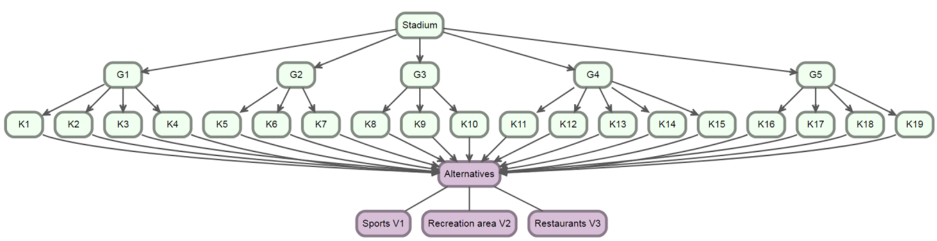

Fig. 3. Hierarchical structure of the problem of optimising development concerning Edmund Szyc stadium

Table 1. Assessments of analysed variants for changes in the manner of area development developed

Criterium		Scale of assessment	Weight	Variant		
				V1	V2	V3
Social G1						
K1	Target reach	1-3	0.079	3	2	2
K2	Local community preferences	%	0.152	33.3	58.8	7.8
K3	Number of job openings	1-3	0.04	3	1	2
K4	Aesthetics and spatial order	1-3	0.023	2	3	2
Environmental G2						
K5	Improvement in urban greenery	0-2	0.068	0	2	1
K6	Improvement in biodiversity	0-2	0.061	0	2	1
K7	Environmental nuisance (noise, heavy traffic)	1-3	0.011	3	1	2
Functional G3						
K8	Increased attractiveness with regard to tourists and new investors	0-2	0.083	2	2	1
K9	Transport accessibility	0-2	0.011	2	1	1
K10	Number of social or media events organised annually	0-2	0.047	2	1	0
Spatial G4						
K11	Development with regard to specific functions – paved areas [ha]	ha	0.034	4	0.8	3
K12	Distance from the nearest facility with similar functionality	km	0.03	3.2	0.65	1.5
K13	Integration with existing infrastructure	1-3	0.068	3	3	1
K14	Fitting in existing landform	1-3	0.072	3	1	0.5
K15	Adaptation of land development to applicable spatial development documentation	0-3	0.145	3	3	1
Economic G5						
K16	Estimated investment cost	1-3	0.013	3	2	1
K17	Estimated investment gains	0-2	0.032	1	0	2
K18	Securing of financing sources	1-3	0.009	2	2	1
K19	Operating costs	1-3	0.017	3	2	1

Variant 1 (V1 – Hall) is based on the existing land use with current landform. The key assumption is the introduction of current land development plans in the concept of constructing a sports and entertainment hall. The variant assumes that building development will constitute 26% of the area, 57% of the area will be left biologically active, whereas 17% of the area will be designated for pedestrian access/ entry, internal roads and access roads.

Variant 2 (V2 – Park) is based on the existing land use with necessary surface levelling and demolition of stadium remains. Part of the high and low vegetation found in the area will be used to develop green space in the park. The variant assumes no building development, 90% of the area will be left biologically active, whereas pedestrian access/ entry, internal roads and access roads will constitute 10% of the area.

Variant 3 (V3 – Service) is based on the assumption that the former stadium premises will feature a recreation and service facility, including restaurants and residential buildings with service outlets. The variant assumes that building development will constitute 26% of the area, 54% of the area will be left biologically active, while pedestrian access/ entry, internal roads and access roads will constitute 20% of the area.

The results of analyses obtained with AHP, MAUT and PROMETHEE II are summarised in Table 2.

Table 2. Summary of results obtained with 3 considered methods

Variant	AHP		MAUT		Promethee II	
	index	rank	index	rank	index	rank
W1	0.347	II	0.665	II	0.148	II
W2	0.419	I	0.713	I	0.278	I
W3	0.233	III	0.180	III	-0.427	III

Additionally, the authors carried out a basic analysis of model sensitivity to parameter changes. The sensitivity analysis consisted in changing the weights of selected main criteria. There were chosen the following options:

- the first analysis for the economic criterion G5 – 44% (7,1%),
- the second analysis for the environmental criterion G2 – 50%, (14%),
- the third analysis for the functional criterion G3 – 49%, (14,1%).

The weights of individual criteria before modification are shown in parentheses. The analysis consisted in appropriate modification of a pair-wise comparison matrix of main criteria, as a result of which the weight values are not in full tens. The sensitivity analysis was performed only for the AHP method. Changes in the weights of criteria resulted in a change in the ranking obtained. Emphasis on economic issues (G5) provided a new solution with Variant

3 (V3 – residential/ service) indicated as optimal. Respectively, due to increase in the weight of G2 (environmental criterion), Variant 2 (V2, Fig. 4) took first place in the ranking, similarly to the baseline study. In the case of emphasis on functional solutions (G3), Variant 1 (V1) proved to be the most advantageous.

The sensitivity analysis indicated that the final ranking depends on stakeholder's preferences and the appropriate objective development of a pair-wise comparison matrix implemented by experts. A sensitivity analysis should be carried out for each multi-criteria simulation/ analysis. It enables, among others, a more complete understanding of a given problem, and thus reduce the risk of ill-chosen subjective preferences.

4. Summary

The presented analyses indicated the second variant (Park) as an optimal solution. The project particularly responds to the needs and expectations of residents, supported by authors' surveys and other inquiries (already in 2012 in a deliberative survey, residents postulated to create a park in this area). 76% of participants in public consultations also opted for this solution)[1]. The project includes bicycle routes (existing and planned in the vicinity) and suggests new ones. Another important aspect included in the project is the idea of the "Southern Green Wedge in Poznań" (Południowy klin zieleni) located in the designed area. The city park in place of the former stadium will ensure a continuation of urban green zones and will be a link between Izabela and Jarogniew Drwęski Park and John Paul II park.

The concept will open prospects for recreation in this area, improve urban aesthetics, affect residents' well-being and the overall microclimate of the city. It will have a positive impact on biodiversity and provide a continuity in two important respects: recreation and ecology.

On the site of the former stadium, the city authorities alternatively have proposed to build a Music Centre, which will include the new headquarters of the Poznań Philharmonic. However, this concept has been objected to by local socially engaged activists. The Committee of Civic Dialogue at the Faculty of Environmental Development and Protection presented its stand on the matter. "Referring to the statements of local politicians, the president of Poznań and the marshal of the voivodship regarding the plans for cubature development of Edmund Szyc stadium with philharmonic facilities that completely ignore the will of residents, NGOs of naturalists and social activists [...] stand that if the philharmonic building is recognized as necessary, its construction should not take place at the expense of an extraordinary enclave of greenery in the very centre of the city."

[1] https://tenpoznan.pl/poznan-filharmonia-zamiast-stadionu-szyca-co-z-parkiem/ (date of access 11.03.2021)

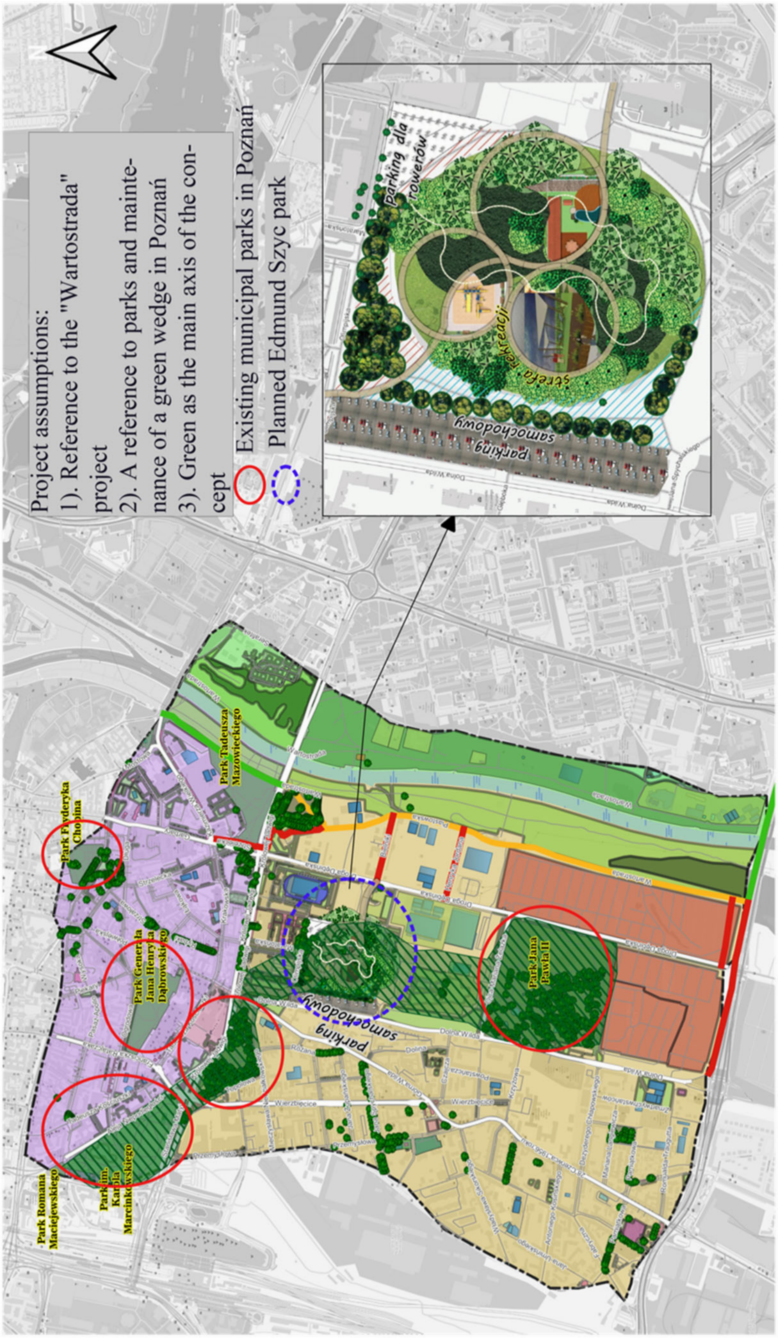

Fig. 4. Visualization of the concept

The initiative to create an enclave of greenery in this area has been also supported, among others, by the Association of "Prawo do Miasta", the Coalition of "Za Zieleń Poznań", the Club of Naturalists.

It has not been decided whether the Poznań Philharmonic will be erected on the grounds of the former stadium. The city authorities carried out preliminary analyses, which showed that the area of today's marketplace in the district of Dolna Wilda could be a better location for this purpose[2].

Therefore, there is still a chance to use the stadium's greenery to create a park expected by residents.

References

Berbeka, J. (2013). The Evolution of Forms and the Role of Sports City Tourism. *Studia Ekonomiczne, 147*, 9-20 (in Polish).

Boryczka, E. (2016). Revitalization of cities, W; Z. Przygodzki (red.), *ECOMIASTO # MANAGEMENT Sustainable, intelligent and participatory development of the city*, Łódź: Wydawnictwo Uniwersytetu Łódzkiego. DOI: 10.18778/7969-721-2.08 (in Polish).

Budner, W., Pawlicka, K. (2013). The assessment of the innovative architecture of Poznañ and the growth of attractiveness of the city. *Acta Scientiarum Polonorum, Administrati Locorum* (12)2, 5-20 (in Polish).

Dąbrowski, A. (2012). Revitalization of post-industrial facilities on the example of "Manufaktura" – former Izrael Poznański's Works in Łódź, W: B. Filipiak, (red.) *Space in new economic reality*, WSB Poznań, 25-35 (in Polish).

Domański, B., Gwosdz, K. (2010). A look at the problems of urban regeneration in Poland, W: Z. Ziobrowski, W. Jarczewski (red.), *Revitalization of Polish cities – diagnosis*, Kraków: Instytut Rozwoju Miast (in Polish).

Frey, J., Kozicki, J. (2009). Manufaktura in Łódź, factory that has been given a second chance. *Zeszyty Naukowe. Budownictwo / Politechnika Łódzka* (59), 73-85 (in Polish).

Kamrowska-Załuska, D., Kostrzewska, M. (2014). Mega-events as catalysts for urban regeneration. *Problemy Rozwoju Miast, 2*, 57-70 (in Polish).

Kostrzewska, M. (2016). Urban regeneration through the sporting events and initiatives. *Przestrzeń Ekonomia Społeczeństwo, 9*, 51-65 (in Polish).

Masierek, E., Torzewski, R. (2018). Development of the sport and recreation complex in Poddębice – customers perspective. *Space-Society-Economy, 25*, 37-59. DOI: 10.18778/1733-3180.25.03 (in Polish).

Nitkiewicz-Jankowska, A. (2006). Industrial tourism as a visiting-card of Uppersilesian Industry District (Górnoslaski Okreg Przemysłowy). *Prace Naukowe Instytutu Górnictwa Politechniki Wrocławskiej* (117), 251-256 (in Polish).

[2] Source: UMP Poznań: https://www.propertydesign.pl/architektura/104/gdzie_powstanie_poznanska_filharmonia_na_terenie_bylego_stadionu_czy_targowiska,28518.html (date of access 11.03.2021)

Ostręga, A., Uberman, R. (2005). Legal aspects of post-mining sites revitalisation. *Górnictwo i geoinżynieria, 29*, 115-127 (in Polish).

Parysek, J. J. (2015). Urban renewal in Poland: yesterday, today, and perhaps tomorrow. *Studia Miejskie, 17*, 9-25 (in Polish).

Parysek, Jerzy J. (2017). Urban revitalization in Poland: problems, dilemmas, challenges and hopes. *Studia Regionalia, 50*, 103-121. DOI: 10.12657/studreg-50-0

Pędraszewska-Sołtys, B., Dzioban, K. (2018). Sports facilities in Warsaw in the 1950s and today. *Rozprawy Naukowe Akademii Wychowania Fizycznego we Wrocławiu, 60*, 90-102 (in Polish).

Przewoźniak, M. (2005). Theoretical aspects of ecological revitalization of cities: towards the methodology of integrated urban-ecological revitalization. *Urbanistyki i Studiów Krajobrazowych, 1*, 25-34 (in Polish).

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International journal of services sciences, 1*(1), 83-98. DOI: 10.1504/IJSSci.2008.01759

Sobiera, A. (2012). Sports and communication infrastructure for Euro 2012. *Nowoczesne Budownictwo Inżynieryjne, 3*, 82-89 (in Polish).

Świerczewska-Pietras, K. (2009). Closed revitalization as an example of post-industrial area management in Łódź. *Studies of the Industrial Geography Commission of the Polish Geographical Society, 12*, 173-182.

Taraszkiewicz, K. (2018). The Impact of Large Sport Facilities on Revitalization of Urban Space on the Example of Energa Arena Stadium in Gdańsk. *Studia Komitetu Przestrzennego Zagospodarowania Kraju PAN, 192*, 339-349 (in Polish).

Taraszkiewicz, K., Nyka, L. (2017). Role of Sports Facilities in the Process of Revitalization of Brownfields. *IOP Conference Series: Materials Science and Engineering, 245*, DOI: 10.1088/1757-899X/245/4/042063.

Tofiluk, A. M., Knyziak, P., Krentowski J. (2019). Revitalization of twentieth-century prefabricated housing estates as interdisciplinary issue. *IOP Conf. Series: Materials Science and Engineering, 471*. DOI: 10.1088/1757-899X/471/11/112096

Tölle, A. (2007). The revitalisation process of the city – by the example of Poznań. *Studia regionalne i lokalne, 2*(28), 46-58 (in Polish).

Tomanek, M. (2015). Restoration of sports facilities and its influence on the regeneration of a city on the example of the National Stadium in Warsaw. *Zarządzanie Publiczne, 29*(1), 75-82. DOI: 10.4467/20843968ZP.15.007.3437 (in Polish).

Turek, A. (2013). Revitalisation of postindustrial areas for residential purposes. *Problemy Rozwoju Miast, 1*, 71-86 (in Polish).

Twardzik, M. (2015). *A shopping center as a local city revitalization project (on the example of Galeria Katowicka)*. Prace Naukowe/Uniwersytet Ekonomiczny w Katowicach, 87-101 (in Polish).

Urbańska-Galewska, E., Wiśniewski, R., Apollo, M. (2013). Social, economic and technical aspects of revitalization, on the example of the Letnica borough of Gdansk. *Problemy Rozwoju Miast, 2*, 29-39 (in Polish).

Vincke, J. P., Brans, Ph (1985). A preference ranking organization method. The PROMETHEE method for MCDM. *Management Science, 31*(6), 647-656. DOI: 10.1287/mnsc.31.6.647

Wallenius, J., Dyer, J. S., Fishburn, P. C., Steuer, R. E., Zionts, S., Deb, K. (2008). Multiple criteria decision making, multiattribute utility theory. Recent accomplishments and what lies ahead. *Management Science, 54*(7), 1336-1349. DOI: 10.1287/mnsc.1070.0838

Wojtowicz-Jankowska, D. (2010). *What can happen when a stadium opens in the city? – an example of changes in Gdańsk-Letnica*. Materiały Międzynarodowej Konferencji Naukowej Wydziału Architektury Politechniki Śląskiej: Między Miastem a Nie-Miastem, Odnowa Krajobrazu Miejskiego, Gliwice 09-10 Grudnia 2010, 461-470 (in Polish).

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GIS as a Support Tool for Sensitivity and Decision-Making Analysis for Transport Infrastructure Development

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Abstract: The sustainable implementation of highway projects requires a sensitivity analysis of the terrain and all of its components that have a direct influence on road design, construction and operation. The result of this inquiry involving GIS techniques and methods regarding environmental and economic factors helps in choosing the optimal road route, in order to meet the real-world connectivity requirements. The sensitivity analysis can be applied to road and rail infrastructure projects, aiming to develop a decision-making tool that can be employed by their potential beneficiaries, according to their purposes and interests. This paper aims to create an objective decision-making tool for transport infrastructure development in correlation with the current needs of society regarding the development of transport infrastructure in an economic sustainable manner with low environmental impact. Furthermore, the study tries to identify the best highway corridor in an area with environmental constraints (especially geomorphological), that is in balance with both environment and financial resources.

Keywords: GIS, transport infrastructure development, sensitivity analysis, decision-making analysis

1. Introduction

Sustainable transport has become an important goal in transportation planning and research in recent decades (Jacyna et al. 2018, Chamier-Gliszczynski & Bohdal 2016), especially with the development of Geographic Information System (GIS) techniques and methods (Rybarczyk & Wu 2010).

The sensitivity analysis is a mathematical method that examines the effect of changes in the values of input elements in the output values. In addition to the dependence between input / output data, the sensitivity analysis is a technique by which this dependence can be assessed and the importance of each input element in the generation of output data can be investigated. The sensitivity analysis is a key element in any decision-making analysis, especially in the field of transport (Ježek et al. 2018, Borgonovo 2017, Iooss & Saltelli 2015, Koltai & Terlaky 2000, Pandian & Kavitha 2012, Bonsall et al. 1977, Dodgson et al. 2009, Kabir et al. 2014, Saltelli et al. 2008).

The pioneers of these types of analyzes are Datzing (1950), who laid the foundations of the simplex algorithm for parametric programming, along with Orchard-Hays in 1952, Hoffman and Jacobs in 1952. Heller was the first author to mention the term sensitivity analysis in 1954. The sensitivity analysis as an essential part of the decision-making process was first highlighted by Samson (1988) and French (1986, 1989) (Gal 1997, Triantaphyllou 1997).

To date, the sensitivity analysis has become widely used within studies regarding the development of transport infrastructure, especially in alternative alignment studies as part of a multi-criteria analysis. As the weighting of the criteria is the least objective part of an analysis, mainly due to the fact that two individuals will not give the same weights due to individual assessments, the sensitivity analysis by developing different scenarios brings the results expected by the decision makers (Antov 2018). Taking all of this into consideration, we were not able to identify comprehensive studies regarding an integrated approach (from a strategic connectivity point of view), sustainable development of transport infrastructure by analyzing all the geographical environmental data and also alternative alignments objectively ranked to estimate as real as possible the environmental and cost impact for a future infrastructure project.

In order to develop a transport infrastructure unity across all member states of the European Union, as well as of the neighboring countries, the TEN-T Trans-European Transport Network was established, with two levels: TEN-T Core and TEN-T Comprehensive. The ultimate goal is to connect all regions of the European Union in a unitary, balanced, economically and environmentally sustainable manner.

In order to align to the European criteria, the Romanian Government has adopted the General Transport Master Plan of Romania, a strategic document which establishes and prioritizes transport infrastructure projects in Romania in the period from 2014 to 2030 and correlates them with the available funding sources (Bolos et al. 2016).

The adaptation of transport infrastructure to the needs and requirements of connectivity represents a priority at national, regional and European level and is based on several defining steps in regard to sustainable socio-economic development and environmental impact (Dobre & Păunescu 2020).

The process of identification, selection and implementation of infrastructure projects that are economically sustainable, with social benefit and in harmony with the environment prove to be defining stages and priority decision-making criteria (Dobre 2016).

This paper aims to create an objective decision-making tool based on scientific criteria utilizing GIS, in correlation with the current needs of society regarding the development of transport infrastructure in an economic sustainable manner with low environmental impact. Furthermore, the study tries to create a new methodology in objectively establishing and evaluating the analysis criteria, which would provide substantiated physical-geographical and socio-economic solutions. This can be applied to all geomorphotechnical assessments regarding transport infrastructure (road or rail) in order to refine the results by identifying optimal transport corridors in accordance with other environmental elements (Dobre et al. 2011, Păunescu et al. 2019, Schweikert et al. 2014, Jiang et al. 2015).

In order to highlight the usefulness and complexity of this scientific decision-making tool, it is necessary to apply the method in a heterogeneous area in terms of components and analyzed criteria, with geological and geomorphological variety, protected areas and high anthropic pressure (materialized by large built-up areas, either with logistical, agricultural or industrial areas or with new residential areas). In this context, the eastern metropolitan area of Brașov was chosen as a study area, an important pole of Romania's economic growth, located in the center of the country, at the intersection of several European and national transport corridors (Fig. 1).

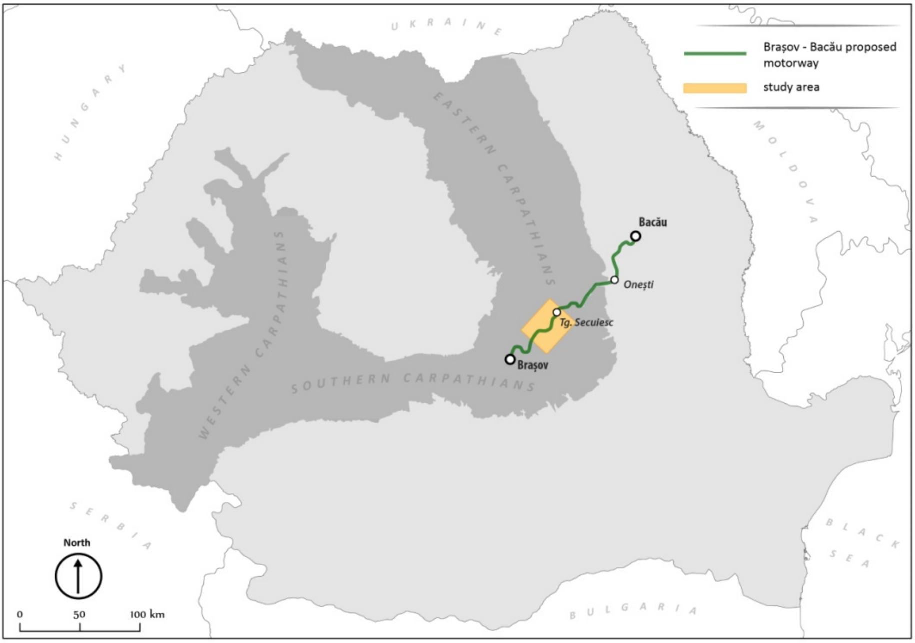

Fig. 1. Study area

2. Methodology

Scientific studies aimed at multi-criteria analyses are numerous and have emerged to solve the need for rationally and objectively choosing between the resulting solutions, in areas with obvious uncertainties. Despite the fact that the choice of criteria, attributes and their valorization were arguably difficult steps, multi-criteria analyses have proved their usefulness highlighting the obtained results level of performance and in general were a decisive indicator in making the most appropriate choice, depending on the interest of the beneficiary (Fig. 2).

The proposed methodology aims at an objective evaluation of the relevant environmental components (with emphasis on geological and geomorphological factors), in relation to the cost elements, which will ultimately lead to the identification of optimal decisions in relation to the needs of society regarding the implementation of a highway project.

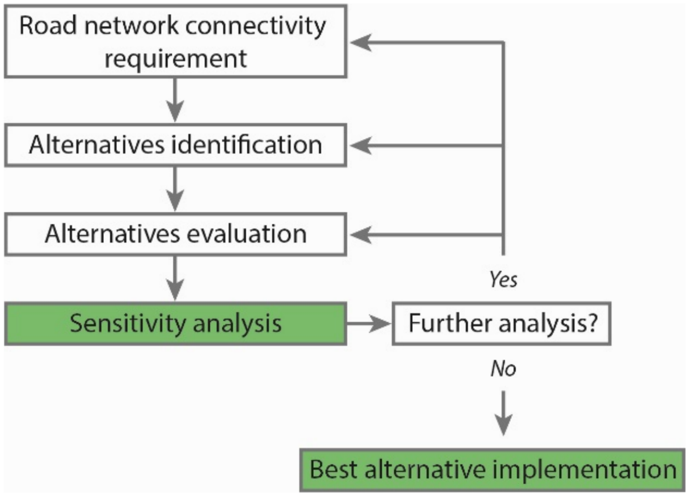

Fig. 2. Steps in decision-making process (modified after Borgonovo, 2017)

The present analysis consists of a geographical analysis performed with GIS modeling and a series of quantitative analyses, as part of an integrated study of applied geomorphology. The data sets used in this scientific approach are varied and have different scales and resolutions. For this reason, after data collection and introduction into the GIS environment, the first stage in this analysis consisted in standardizing and rescaling them, without losing the accuracy (Dobre 2016). The data sets relevant for the multi-criteria analysis are: map of protected areas, orthophotomosaic, topographic map, areas of geomorphological favorability, transport corridors, map of the hydrographic network and populated areas (Table 1).

In the proposed analysis, two criteria were taken into account:

a) environmental impact,

b) the influence of the geomorphological factor on a transport corridor.

Table 1. Digital data used

Data	Source	Topology	Characteristics (resolution, year etc.)
Natura 2000 protected areas	The Ministry of Environment	Vector	2015
Orthophotomosaic	The Ministry of National Defence (MaPN) and own data (UAV)	Raster	2017 (50 cm – MaPN, 10 cm – own data)
Topographic map of Romania (contour lines and elevation data), scale 1:25000	Military Topographic Directorate (DTM) and own data (RTK GPS)	Vector	1974 (DTM), 2020 (own data)
Areas of geomorphological favorability and restrictivity	Own data	Raster	2020 (5 m)
Transport corridors	General Transport Master Plan of Romania (GTMP) and own data	Vector	2016 (MPGT), 2020 (own data)
Hydrographic network	National Agency for Cadastre and Real Estate Advertising (ANCPI), own data	Vector	2012 (ANCPI), 2020 (own data)
Inhabited areas	Corine Land Cover 2018, own data	Vector	2018 (CLC), 2020 (own data)

Within the extended project, the research team is currently developing the integration of several factors in the sensitivity analysis (the relationship of the corridor with the anthropized areas, the pedological and geological factor, the hydrological factor, the impact on public utility networks, etc.)

Regarding environmental impact, the European Commission's Natura 2000 databases have been used. Natura 2000 is the cornerstone of nature conservation in the European Union. The environmental impact for each transport corridor was spatially calculated, depending on the percentage by which the corridor affects the crossed protected areas.

By crossing a transport corridor (a buffer zone at a distance of 70 m from the motorway alignment on each side) with a protected area, three components have been determined: the affected area (in hectares), the linear distance of the corridor within the protected area (in km) and the percentage of the affected area in relation to the total area of the protected area (in %). This enabled us to establish a hierarchical scale of transport corridors in terms of environmental impact in the final score (the relationship corridor/impact on protected areas was assessed in the range between 0 to 100, in progression from no impact to strong impact).

The protected areas in the analyzed area occupy approximately 14977 ha and they are classified into three categories: protected areas (NPA), sites of Community importance (SCI), special avifauna protection areas (SPA) (Table 2).

The influence of the geomorphological factor was determined following numerous field campaigns and by acquired geospatial data. The primary data source to represent the geomorphological factor is represented by the contour lines with equidistance of 5 m that were extracted from the Topographic Map of Romania (scale 1: 25.000, Military Topographic Directorate). These were used to create the digital elevation model (DEM), which was further enhanced by the addition of point field data (accuracy below 1 m) in the interpolation process, acquired with a RTK GPS device with ROMPOSS (**Rom**anian **Pos**itioning **S**ystem).

In the post-processing stage of the digital elevation model, the areas that were identified as being subject to current erosion processes were improved by adding three-dimensional (3D) and digital surface (DSM) models that were developed using drone acquired data. The final digital elevation model was thus filtered and improved in order to represent as accurately as possible the topographic surface.

Table 2. Nature 2000 areas

Protected area type	Name and indicative	Goal of protection	Surface (ha)
Protected area of national interest	Mestecănișul Reci and Bălțile de la Ozun Sântionlunca – RONPA0389	Flora and fauna – rare species and glacial relics	2124.7
Site of Community Importance	Ciomad Balvanyos – ROSCI0037	Five types of natural habitats	585.5
Site of Community Importance	Mestecănișul de la Reci – ROSCI0111	Seven types of natural habitats of community interest	2124.7
Site of Community Importance	Oltul Superior – ROSCI0329	Protected species (mammals, fish and invertebrates)	89.3
Site of Community Importance	Râul Negru – ROSCI0374	Protected species (mammals, amphibians and reptiles)	1892.8
Special protection area (avifauna)	Munții Bodoc Baraolt – ROSPA0082	Protected species (birds and birds with regular migration)	6267.2
Special protection area (avifauna)	Valea Râului Negru – ROSPA0147	Protected species (birds)	1892.8
Total			14977

In order to establish another defining criterion for the sensitivity analysis, the cost factor in correlation with the landforms crossed was developed, based on the types of technical solutions necessary for the implementation of the projects. Thus, each of the road alternatives were evaluated based on a cost standard used on a national scale within the General Transport Master Plan of Romania, and updated within the Investment Plan for the Development of Transport Infrastructure in 2020-2030. In terms of geomorphological factor, this approach allowed us to create a proportional hierarchical scale for transport corridors (0 to 100) (Table 3 and Table 5).

Table 3. Highway costs per km used

The dominant landform within the corridor	Estimated cost (mil. EUR. per km)
mountainous	20
mountainous – hilly	12
hilly	8
lowlands – hilly	5.5
lowlands	4.5

Thus, each transport corridor was included in one of these categories that were defined by the percentage of the dominant landform crossed by the highway alignment.

GIS software solutions were used to define the corridors, highlighting the geomorphological constraints (Dobre 2016), the impact on Natura 2000 sites (Morelli et al. 2014; van Bohemen & van de Laak 2003), determining the lengths of the strategic level corridors and the estimated costs.

The spatial analysis was conducted in the ArcGIS suite, with additional use of Agisoft Metashape for modeling drone three dimensional and imagery data. For statistical analyses, weighted calculations and modeling the sensitivity matrix, Microsoft Excel was employed, using GIS extracted data.

2.1. Area of application

The Brașov - Bacău highway project (which includes the analyzed sector Târgu Secuiesc - Onești) is part of the TEN-T Comprehensive (Fig. 3) network and is included in both the General Transport Master Plan of Romania as well as in the Investment Plan for the Development of Transport Infrastructure in 2020-2030, the most important strategic programmatic documents in Romania. TEN-T Comprehensive networks provide connections to the Core network, namely TEN-T Core which connects all regions of the European Union. This highway sector is one of the six Transcarpathian highway sectors most important for Romania's development, namely Târgu Mureș - Iași, Brașov - Bacău, Ploiești - Brașov, Pitești - Sibiu. According to the Investment Plan for the Development of Transport Infrastructure in 2020-2030, the Brașov - Bacău highway will be operational by the end of 2030.

Fig. 3. TEN-T Network in Romania and neighboring countries

In this case, the Sibiu - Brașov - Bacău highway connects two of the most important TEN-T Core corridors within Romania:
1. The Transcarpathian Corridor: Constanța (the largest port on the Black Sea) - Bucharest - Pitești - Sibiu - Arad - Nădlac (border with Hungary) with,
2. Siretului Road Corridor: Giurgiu (border with Bulgaria) - Bucharest - Ploiești - Bacău - Suceava - Siret (border with Ukraine).

The current road connection between Brașov and Bacău is outdated in terms of traffic volumes, has geometries in longitudinal and transverse profile imposed by relief, which restrict traffic speeds and have a negative impact on traffic safety. It also generates significant amounts of CO_2 emissions.

While the Brașov - Bacău highway is expected to take over the traffic from the national road 11 (DN11), it will also generate new trips due to shorter travel times and less traffic delays.

2.2. The highway project at regional level

The Brașov - Bacău highway project connects with the A3 motorway sector (Sibiu - Brașov) within the vicinity of the town of Hărman, with further crossing territorial administrative units of Sfântu Gheorghe, Târgu Secuiesc, Onești and Bacău. In the area of the city of Bacău, it connects with the A7 Bucharest-Buzău - Bacău - Suceava - Siret highway.

Regarding the relief configuration, we can distinguish three distinct units, well individualized by their geological and geomorphological characteristics and particularities, as follows:

- The depression sector – Brașov tectonic depression (with flat or slightly inclined plain characteristics);
- The mountain sector – Eastern Carpathians, sector formed by Nemira Peak (with high slopes and intense riverbed and slope geomorphological processes);
- The Subcarpathian sector – with valley compartments and depression but also with slopes intensely affected by gravitational processes.

As shown above, the transport corridors are presented on a systemic scale of connectivity in strategic documents, but for the sustainable establishment of a corridor, detailed multidisciplinary analyses are needed in order to highlight as accurately as possible the areas of favorability and restrictiveness for project implementation.

Thus, in order to establish a working methodology adapted to the current requirements of the General Transport Master Plan of Romania, four corridors were established, as alternatives, component parts of the future Brașov - Bacău highway for Tg. Secuiesc - Onești sector (Fig. 4).

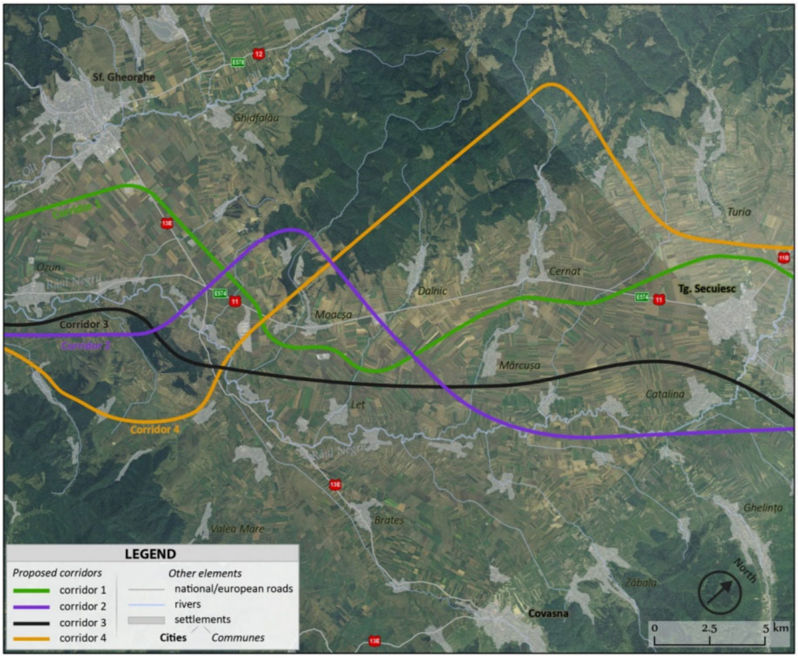

Fig. 4. Proposed highway corridors

The four routes meet the criteria for the construction of highways in Romania (Ind. PD 192-2002), among them listing: the lack of level intersections with other roads, slopes of maximum 5° and radius of curvature that allow traffic speeds of 130 km/h or at least 80 km/h in special conditions.

The four corridors were drawn up in such a way as to highlight the benefits of the sensitivity analysis in choosing an optimal road transport corridor in accordance with the beneficiary's policies and interests. For example, corridor 1 has no impact on Natura 2000 sites, no geomorphological constraints, but due to the sinuous nature imposed by avoiding these unfavorable areas, the length of the corridor is much longer with direct implications on the final cost of implementation and subsequent operating costs. In contrast, corridor 3, with an impact on Natura 2000 sites, but a shorter length by about 4 km, has financial benefits related to the construction and management of the motorway sector.

The four route alternatives were made following the digital modeling of the natural and anthropogenic factors that ensure the support of the proposed road infrastructure. In order to better present the analysis performed, each of the four alternatives has various characteristics related to the impact on Natura 2000 sites, cost standards and geomorphological features (Fig. 5, Table 4 and Table 5):

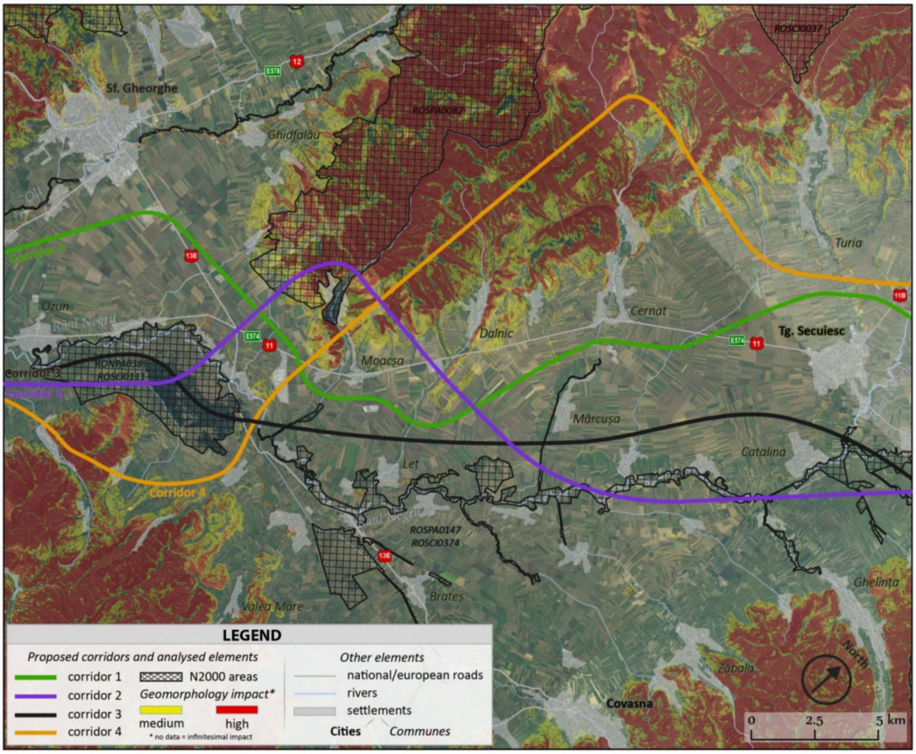

Fig. 5. Proposed highway corridors and analyzed elements

- Corridor 1 (C1) – length of 41.2 km, has no impact on Natura 2000 sites, from a geomorphological point of view crosses stable areas with slopes below 5% and altitudes of approximately 500 m a.s.l.;
- Corridor 2 (C2) – length of 41.1 km, has an impact on Natura 2000 sites, from a geomorphological point of view, it crosses mostly stable areas with slopes below 5% and altitudes of approximately 500 m, but also crosses certain areas with slopes over 10% and altitudes over 600 m. In terms of impact on Natura 2000 sites, out of the total area of protected areas in the working area of 14309.4 ha, corridor 2 affects approximately 10.6% of them, ie 1516.3 ha or 13.4 linear km;
- Corridor 3 (C3) – length of 37.6 km, has an impact on Natura 2000 sites, from a geomorphological point of view, crosses stable areas with slopes of less than 5% and altitudes of approximately 500 m. Regarding the Natura 2000 sites, from the total area of protected areas in the working area of 14309.4 ha, corridor 3 affects approximately 9.9% of them, ie 1416.3 ha or 11 linear km;

- Corridor 4 (C4) – length of 46.2 km, has no impact on Natura 2000 sites, from a geomorphological point of view it crosses mostly unstable areas with slopes of over 15% and altitudes of over 800 m.

Table 4. Proposed highway corridors (summary)

	Impact N2000	Geomorphological factor	Length/cost/cost per km
C1	No	Without constrains	41.2 km/226.7 m. EUR/5.5 m. EUR
C2	Yes	Crosses restrictive areas	41.1 km/329.1 m. EUR/8 m. EUR
C3	Yes	Without constrains	37.6 km/169.1 m. EUR/4.5 m. EUR
C4	No	Crosses restrictive areas	46.2 km/554.3 m. EUR/12 m. EUR

Table 5. Proposed highway corridors (score)

	Environmental criterion score (EC)	Geomorphological criterion and cost score (GCC)
C1	100	80
C2	60	50
C3	80	100
C4	100	30

For calculation of the weighted score of the analyzed corridors for the three selected scenarios, the weighted average was employed.

Scenario 1 (S1 – equal weight) – in this scenario, each element of the analysis contributes equally to the final average.

$$S1 = (EC \times 1) + (GCC\times1) / (1+1)$$

Scenario 2 (S2 – great importance of the environmental criterion) – in this scenario, the environmental criterion (EC) data set contributes five times more to the final average than the geomorphological criterion and cost data (GCC).

$$S2 = (EC \times 5) + (GCC\times1) / (5+1)$$

Scenario 3 (S3 – great importance for the geomorphological criterion and cost) – in this scenario, the data series on the geomorphological criterion and cost (CGC) contributes five times more to the final average than the data series on the environmental criterion (CM).

$$S3 = (EC \times 1) + (GCC\times5) / (5+1)$$

Table 6. Proposed highway corridors (score based on scenario)

	Equal weight (S1)	Environmental criterion weight (S2)	Geomorphological criterion and cost weight (S3)
C1	90.0	96.7	83.3
C2	55.0	58.3	51.7
C3	90.0	83.3	96.7
C4	65.0	88.3	41.7

3. Results

This tool has proven to be a powerful element in the decision-making process, especially in this context where environmental impact and investment costs in relation to the benefits of implementing a major transport infrastructure project are greatly emphasized.

The results of the sensitivity analysis are illustrated in Figure 6 and Table 7.

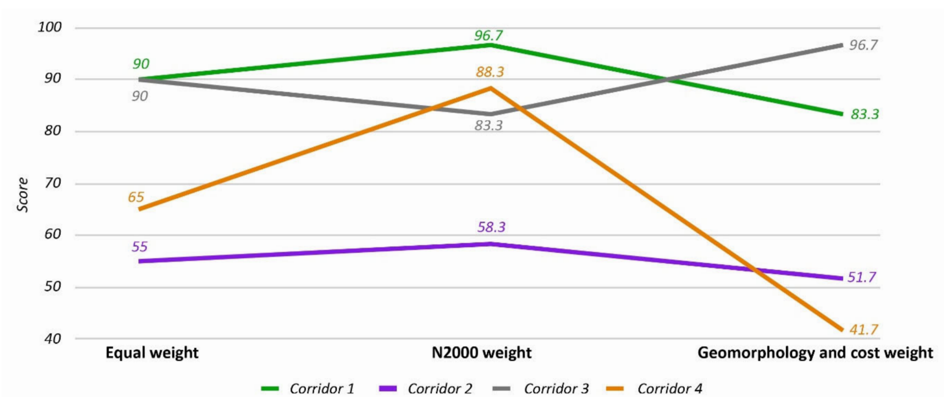

Fig. 6. Sensitivity analysis results (graph)

Table 7. Sensitivity analysis results

Ranking	Equal weight (S1)	Environmental criterion weight (S2)	Geomorphological criterion and cost weight (S3)
1	**Corridor 1** **Corridor 3**	**Corridor 1**	**Corridor 3**
2	**Corridor 4**	**Corridor 4**	**Corridor 1**
3	**Corridor 2**	**Corridor 3**	**Corridor 2**
4	**n/a**	**Corridor 2**	**Corridor 4**

3.1. Scenario analysis

Scenario 1 (S1) – Equal weight. In this scenario, the analysis criteria for the four transport corridors were treated as a unit. Thus, following the ranking according to the score obtained after quantifying the impact on Natura 2000 sites and the geomorphological and cost factor, corridor 1 and 3 are equal to 90 points. Corridor 4 scored 65 points and corridor 2 scored 55 points. The low score of corridor 4 (65 points) results from the high estimated cost of its implementation, crossing complex and geomorphologically unstable areas that generate an estimated cost of 554.3 million euros (12 million euros/km). The score of corridor 2 of only 55 points is caused by the fact that it has the greatest impact on Natura 2000 sites and by the fact that it crosses complex and geomorphologically unstable areas, resulting in an estimated cost of 329.1 mil. euro (8 mil. euro / km).

Scenario 2 (S2) – High weight for environmental criteria. In this scenario, the environmental data series contributes five times more in the final score than the geomorphological and cost data series. Thus, following the ranking according to the score obtained after quantifying the impact on Natura 2000 sites and the geomorphological and cost factor, corridor 1 got the best score, with 96.7 points. This score is due to the fact that this corridor has no impact on Natura 2000 sites, but in order to avoid the intersection with protected natural areas, the corridor is longer (41.2 km) and crosses lowland and hill areas at an estimated cost of 5.5 million euros. / km (lower score for the geomorphological and cost criterion). Corridor 4 is in 2nd place with a final score of 88.3 points, due to the fact that it does not cross protected natural areas. However, it was de-scored within the geomorphological and cost criteria because it crosses the most difficult sector from a geomorphological point of view and has the longest length (46.2 km) and implicitly the highest cost, of 554.3 million euros (12 million. euro / km). Corridor 3 ranks 3rd with a score of 83.3 points, a consequence of the intersection with protected natural areas (ROSPA 0389, ROSCI 0111, ROSCI 0374, ROSPA 0147), even if it is the shortest (37.6 km) and represents the corridor with the lowest cost among those analyzed (estimated cost of 169.1 million euros - 4.5 million euros / km). Corridor 2 is also in this scenario in the last place, as it crosses protected natural areas (ROSPA 0389, ROSCI 0111, ROSPA 0082, ROSCI 0374, ROSPA 0147) and difficult geomorphological areas (hilly areas affected by current geomorphological processes).

Scenario 3 (S3) – High weight for geomorphological criterion and cost. In this scenario, the geomorphological and cost data series contributes five times more to the final average than the environmental data set. Thus, following the ranking, depending on the score obtained after quantifying the impact of the geomorphological / cost factor and Natura 2000 sites, corridor 3 got the highest score of 96.7 points. This score is due to the fact that this corridor does not cross restrictive areas from a geomorphological point of view, being proposed only in lowland areas. This corridor is also the shortest, with a length of 37.6 km, at an estimated cost of 169.1 million euros (4.5 million euros/km). However, the corridor has a larger impact on Natura 2000 sites. In 2nd place there is corridor 1 with a score of 83.3 points. This score is due to the fact that in order to avoid protected natural areas, the corridor is longer (41.2 km) and crosses the plain and hill areas at an estimated cost of 5.5 million euro / km, which ultimately resulted in a lower score for the geomorphological criterion and cost. Corridor 2 is in the 3rd place with a score of 51.7 points, due to the fact that it crosses protected natural areas and difficult geomorphological areas (hilly areas) which imposed an estimated cost of 329.1 million euros and 8 million euros/km. Corridor 4 shows the largest oscillation among the three analyzed scenarios, now being positioned in the last place with a score of 41.7 points. Although it does not cross Natura 2000 sites, it crosses the most difficult sector in terms of relief and has the longest length (46.2 km), implicitly the highest cost, of 554.3 million euros and 12 million euros / km.

4. Disscusion

According to the results, it is clear that in the context of the current environmental policy promoted and supported by the European Commission, through the new Green Deal concept, Scenario 2 (S2) is the best option for the implementation of infrastructure projects. This scenario envisages giving a significant weight to the environmental component and less to the geological or geomorphological ones, resulting in higher costs.

Thus, the ranking of projects resulting from the use of Scenario 2 best corresponds to the current context in which the design, construction and operation of infrastructure projects should be done in an ecologically sustainable manner, in conformity with the environmental regulations and protected areas, even though it results in higher construction and operational costs. Scenarios 1 and 3 are therefore favorable for minor infrastructure projects, in which the environmental component has a lower weight. It has been proven that a GIS based sensitivity analysis is a necessity in choosing the route variant that corresponds to the real connectivity needs. This method, as part of a decision-making process, can be applied by the beneficiary of large transport infrastructure projects for the sustainable implementation of highway projects, representing a rigorous assessment of land and all components that have a direct influence on the design, construction and operation of such project. As part of the multi-criteria analysis, the proposed and tested methodology can thus be applied to both road and rail infrastructure projects.

One of the important goals achieved through this approach was obtaining objective, undisputed results, which through an efficient communication, could be generally accepted by the local communities involved, media and non-governmental organizations.

This methodology proves that it can be an asset in strategic planning which can be applied in other European member states as well, an aspect emphasized by JASPERS Romania office during technical meetings.

5. Conclusions

This paper represents an analysis model which provides geographically substantiated quantitative solutions. This new approach can be introduced as a mandatory study in the legislation for the analysis of route / corridor alternatives that are to be implemented. The analysis aims to establish a route of a sector of Brașov - Bacău highway, which should meet the technical, environmental and cost criteria. In this context, four highway corridors with different, well-individualized physical-geographical features were established and analyzed, which were differentiated based on a score function. The three evaluated criteria took into account the spatial relationship between corridors and protected areas, geomorphological forms and processes and estimated costs. The differentiation of the four alternative routes was made based on the resulting score which had three types of weights (equal weights, high weight for the environmental criterion, high weight for the geomorphological and cost criterion). The three scenarios highlight the hierarchical variations of the corridors according to the assigned criteria and weights. The study can be used at governmental or regional decision-making level because it provides objective information on which scientifically substantiated choices can be made. For an even greater refinement of the results, other data sets can be introduced in the working methodology, such as the disposition of utilities, flood risk, commercial, residential or industrial areas.

References

Addiscott, T. M. & Tuck, G. (1996). *Sensitivity Analysis for Regional-Scale Solute Transport Modeling*. Soil Science Society of America (SSSA)

Assen, A. (2018). *Multi-criteria analysis for Transport Infrastructure Projects*. Retrieved from: shorturl.at/hvMRS

Bolos, M., Dobre, R., Ilie, L., Costache, C. (2016). *Master Planul General de Transport al României*. Ministerul Transporturilor, România

Bonsall, P. W. et al. (1977). Transport Modelling: Sensitivity Analysis and Policy Testing. *Progress in Planning, 7*, Pergamon Press.

Borgonovo, E. (2017). *Sensitivity Analysis. An introduction for the Management Scientist*. Springer

Brunsden, D., Doornkamp, J. C., Fookes, P. G., Jones, D. K. C., Kelly, J. M. H. (1975). Geomorphological mapping techniques in highway engineering. *Journal of the Institution of Highway Engineer, 22*(12), 35-41

Chamier-Gliszczynski, N. & Bohdal, T. (2016). Mobility in Urban Areas in Environmental Protection, *Rocznik Ochrona Srodowiska, 18*(1), 387-399

Dobre, R. (2016). *Relația dinamica reliefului – infrastructura de transport*. Editura Etnologică.

Dobre, R., Păunescu, C. et al. (2020). *Planul Investițional pentru Dezvoltarea Infrastructurii de Transport pentru perioada 2020-2030*. Ministerul Transporturilor.

Dobre, R., Mihai, B. & Savulescu, I. (2011). The Geomorphotechnical Map: a highly detailed geomorphic map for railroad infrastructure improvement. A case study for the Prahova River Defile (Curvature Carpathians, Romania). *Journal of Maps, 7*(1), 126-137. DOI: 10.4113/jom.2011.1155

Dodgson, J.S. et al. (2009). *Multi-criteria analysis: a manual.* Department for Communities and Local Government: London

Gal, T. & Greenberg, H. J. (1997). *Advances in sensitivity analysis and parametric programming*. Springer Science+Business Media

Rybarczyk, G. & Wu, C. (2010). Bicycle facility planning using GIS and multi-criteria decision analysis, *Applied Geography, 30*(2), 282-293, DOI: 10.1016/j.apgeog. 2009.08.005

Intrator, J. & Paroush, J. (1977). Sensitivity analysis of the classical transportation problem. A combinatorial approach. *Computers & Operations Research, 4*(3), 213-226.

Iooss, B., Saltelli, A. (2015). *Introduction to Sensitivity Analysis.* Handbook of Uncertainty Quantification, Springer.

Jacyna, M., Wasaik, M., Lewczuk, K., Chamier-Gliszczynski, N., Dabrowski, T. (2018). Decision Problems in Developing Proecological Transport System. *Rocznik Ochrona Srodowiska, 20*(2), 1007-1025.

Jezek, J., Nozicka, J., Torok, A. (2018). Using sensitivity analysis in Road Transport Pricing. *Scientific Journal on Transport and Logistics, 9*(1), 32-39.

Jiang, L., Kang, J. & Schroth, O. (2015). Prediction of the visual impact of motorways using GIS. *Environmental Impact Assessment Review, 55*, 59-73.

Kabir, G., Sadiq, R. & Tesfamariam, S. (2014). A review of multi-criteria decision-making methods for infrastructure management. *Structure and Infrastructure Engineering, 10*(9), 1176-1210. DOI 10.1080/15732479.2013.795978

Koltai, T. & Terlaky, T. (2000). The difference between the managerial and mathematical interpretation of sensitivity analysis results in linear programming. International *Journal of Production Economics, 65*, 257-274.

Lenferink, S., Tillema, T., Arts, J. (2008). *The potential of life-cycle approach for improving road infrastructure planning in the Netherlands*. Faculty of Spatial Sciences, University of Groningen.

Leng, J-Q., Yang, L-H, Wei-Yi, L., Lin, Z. (2017). *Measuring Road Network Vulnerability with Sensitivity Analysis*. PLoS ONE 12 (1). DOI: 10.1371/journal. pone.0170292

Luathep, P. et al. (2011). *Large-scale road network vulnerability analysis: a sensitivity analysis based approach*. Springer Science+Business Media

Morelli, F., Beim, M., Jerzak, L., Jones, D. & Tryjanowski, P. (2014). Can roads, railways and related structures have positive effects on birds? – A review. Transportation Research Part D: *Transport and Environment, 30*, 21-31.

Pandian, P. & Kavitha, K. (2012). Sensitivity Analysis in Solid Transportation Problems. *Applied Mathematical Sciences, 6*(136), 6787-6796.

Păunescu, C., Dobre, R., Drăghici, T. (2019). Multi-criteria analysis for major road infrastructure projects. Case study: Brașov-Bacău Highway. *GeoPatterns, 4*, 40-44. DOI: 10.5719/GeoP.4/5

Saltelli, A., Tarantola, S., Campolongo, F., Ratto, M. (2004). *Sensitivity analysis in practice: a guide to assessing scientific models*. John Wiley and Sons Ltd

Schweikert, A., Chinowsky, P., Kwiatkowski, K., Espinet, X. (2014). The infrastructure planning support system: Analyzing the impact of climate change on road infrastructure and development. *Transport Policy, 35*, 146-153.

Triantaphyllou, E. & Sanchez, A. (1997). A sensitivity analysis approach for some deterministic multi-criteria decision-making methods. *Decision Sciences, 28*(1), 151-194.

van Bohemen, H.D. & van de Laak, W.J. (2003). The influence of road infrastructure and traffic on soil, water, and air quality. *Environmental management, 31*(1), 50-68.

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Numerical Modeling and Experimental Studies of the Operational Parameters of the Earth-To-Air Heat Exchanger of the Geothermal Ventilation System

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Abstract: This article is devoted to the analysis of the heat engineering characteristics of the operation of an Earth-to-Air Heat Exchanger, EAHE, with a circular cross-sectional shape, which is a component of the geothermal ventilation system. The authors analyzed literature sources devoted to the research of heat exchangers of the soil-air type of various designs and for working conditions in various soils. Much attention is paid to the issues of modeling the operation of such heat exchangers and the distinctive features of each of these models. Also important are the results of experimental studies carried out on our own experimental bench and with the help of which the numerical model was validated. The results of these studies are the basis for the development of a method for determining the optimal diameter of an EAHE under operating conditions for soil in Kyiv, Ukraine.

Keywords: geothermal ventilation, earth to air heat exchanger, experimental studies, numerical modeling, renewable energy sources

1. Introduction

For a comfortable stay of people in buildings, an important condition is the availability of fresh air that complies with sanitary and hygienic standards, the supply of which is ensured by a forced ventilation system. Ventilation system performs the function of exchanging air in the room to remove excess heat, moisture, carbon dioxide, harmful and polluting substances in order to ensure an acceptable microclimate and air quality in the zone of human presence. Compliance with the normative air exchange in residential and administrative buildings, determined by the state building standards of Ukraine, is mandatory for new construction or reconstruction of existing buildings.

Increasing the energy efficiency of buildings standards complicates the design of ventilation systems due to with significant year-round costs of energy for heating and cooling the supply air. Air heating process requires a significant amount of energy (Cepiński et al. 2020). One of the solutions to the problem of reducing energy intensity is the use of a geothermal ventilation system, due to which it is possible to reduce the difference in the supply air temperature with the standard value and reduce the energy costs for heating (or cooling) before supplying air to the room.

The aim of this work is to develop a numerical model of the year-round operation of an Earth-to-Air Heat Exchanger, EAHE, with a circular cross-sectional shape with further its validation based on the obtained experimental data. We consider that these studies can form the basis for the development of methods for calculating and designing geothermal ventilation systems for climate conditions of Ukraine.

2. Background

To minimize the energy consumption of buildings, various systems have recently been used to extract low-grade soil heat. For example, vertical ground source heat pump heat exchangers (Dolan & Mikielewicz 2017a, 2017b), horizontal ground source heat pump heat exchangers (Díaz-Hernández et al. 2020), earth-to-air heat exchangers (Agrawal et al. 2019).

The main element of the geothermal ventilation system is an EAHE that is located in the soil mass at a certain depth – from 1.0 to 3.0 m, depending on the climatic conditions of a particular area. The EAHE usually has channels with a round cross-sectional shape and various lengths (see Table 1).

Article (Sakhri et al. 2020) shows main designs of typical EAHE. Operational parameters of these type heat exchangers have been widely studied throughout the world over the past decade. For example, studies conducted in Europe (Tzaferis et al. 1992, Badescu et al. 2007, Benkert et al. 1997, Congedo et al. 2019, Greco & Masselli 2019), CIS countries (Filatov & Volodin 2013), Africa (Sehli et al. 2012, Amara et al. 2011, Hamdi et al. 2018, Serageldin et al. 2016), Asia (Sanusi 2012, Ariffin et al. 2014, Misra et al. 2018, Agrawal et al. 2019, Verma et al.) and America (Díaz-Hernández et al. 2020, Krarti & Kreider 1996).

Ukraine also begins to carry studies in this direction (Basok & Novitska 2017, Nakorchevsky & Belyaeva 2005, Tkachenko et al. 2020, Basok et al. 2020), but their results are not enough to develop methods for calculating and designing geothermal ventilation systems for the corresponding climate conditions and local soils.

The active development of geothermal ventilation systems necessitates theoretical studies to understand the processes occurring in EAHE and to determine the quantitative effect of various parameters on the energy and economic efficiency of such a system. In general, the energy efficiency of a heat exchanger may depend on the following parameters (Ariffin et al. 2014):

• configuration and geometric dimensions of the heat exchanger,
• climatic conditions,
• thermophysical properties of the soil.

The consideration of these factors together or singly is a difficult task that modern researchers face. Recently were published in information sources several studies of the operation of EAHE using numerical simulation (Díaz-Hernández et al. 2020, Tzaferis et al. 1992, Badescu 2007, Greco et al. 2020, Serageldin et al. 2016, Rouag et al. 2018). An analysis of such heat exchangers usually involves either calculating the thermal conductivity of the soil mass to the wall of the heat exchanger or calculating the parameters of convective heat transfer between the air in the heat exchanger and the soil mass. Articles usually considered one, two- and three-dimensional numerical models of EAHE with various restrictions.

For example, article (Badescu 2007) describes a two-dimensional numerical model for calculating the parameters of an EAHE containing a single circular cross-section pipe with length of 36.0 m. The model is based on the determination of temperature values on the soil surface and in the vertical section of the soil mass. Calculations considered only the horizontal part of the heat exchanger, the influence of the vertical sections of the air inlet and outlet was considered insignificant. On the soil surface, the model takes into account convective heat flux, long-wave radiation from the soil surface, absorption of insolation energy by the surface of the soil, as well as latent heat of evaporation.

In (Tzaferis et. al. 1992), a comparison is made of eight existing at the time of publication of numerical models describing the heat exchange of air in the channel with the ground. The work describes an assessment of the sensitivity of methods to such parameters as inlet air temperature, air velocity, pipe length, radius and depth of the heat exchanger. In addition, the calculation results were compared with experimental data.

Table 1. Geometric characteristics of Earth to Air Heat Exchangers

Author	Cross-section shape	The size of the cross-section, m	Length of the EAHE, m	Depth of the EAHE, m	Links, notes
H.P. Díaz-Hernández et al.	circular	0.1016 (D)	12	2.5	Hernández et al. 2020
Tzaferis et al.	circular	0.125 (R)	30	1.5	Tzaferis et al. 1992
V. Badescu	circular	0.05-0.25 (D)	36	3.0	Badescu 2007
Benkert S et al.	circular	0.125 (D)	42	0.7-1.8	*Benkert et al.* 1997
P. Congendo et al.	circular	0.2 (D) 0.25 (D)	20 20	2.5; 3.0; 4.0; 3.0	*Congendo et al.* 2019
S. Filatov, V. Volodin	annular channel	0.54×0.05	4-17	vertical orientation	Filatov & Volodin 2013
A. Sehli, et al.	circular	0.110 (D)	53.16	3	Sehli et al. 2012
S. Amara, et al.	circular	0.21 (D)	60	1-5	Amara et al. 2011
Sanusi et al.	circular	0.076 (D)	25	0.5-1.5	Sanusi et al. 2012
NoorAziahMohd Ariffin	circular, pipe in pipe	0.05 (D)	25	1	Ariffin et al. 2014
M. Krarti, J. Kreider	circular	0.2 (D)	80	1.5	Krarti & Kreider 1996
Rouag, Amar et al.	circular	0.3 (D)	10	-	Rouag et al. 2018
B. Basok et al.	circular	0.16(D)	43	2.2	Basok et al. 2020

A semi-analytical model for determining the temperature of the soil near an EAHE with circular cross-section in long-term operation is shown in (Rouag et al. 2018). The aim of the work was to determine the optimal distance between the pipes of such a device, as well as between the devices themselves in the case of several heat exchangers located at a distance.

An original scheme for the removal of soil heat or cold by energy piles with air filling as a coolant was calculated based on numerical simulation in paper (Filatov & Volodin 2013). It was found, that when using energy piles as part of the supply ventilation system, in the warm season, the air temperature decreased by 3-6°C, and in the cold – it was heated by 6-9°C. At the same time, no more than 0.3% of energy was spent on air transportation from the energy of the heat flux of the energy pile.

In addition to works that are devoted to CFD modeling, articles describing experimental studies are also widely presented in the scientific literature (Cepiński et al. 2020, Díaz-Hernández et al. 2020, Hamdi et al. 2018, Serageldin et al. 2016, Misra et al. 2018). In these works, thermal performance of EAHE of different heating and cooling systems were analyzed. For example, article (Bonuso et al. 2020) shows ways for practical usage of EAHE in greenhouse and providing both the results of computational modelling and some experimental data of thermal performance of these EAHE.

Airflow in systems of this type is usually constant and selects at the discretion of the authors. Data on the flow rate or speed of air passing through the EAHE are shown in Table 2.

An important characteristic that used in the calculations is the climatic data on the temperature of the soil depending on the depth and its thermophysical properties (Table 3). In the literature, it is possible to find data on soil temperatures for a number of countries (Díaz-Hernández 2020, Benkert et al. 1997, Sanusi 2012), including and Ukraine (Nakorchevsky & Belyaeva 2005), as well as its thermophysical properties (Benkert et al. 1997, Congedo et al. 2019, Amara et al. 2011, Rouag et al. 2018, Basok et al. 2009). In the works it is usually accepted the assumption that soil is a homogeneous and isotropic medium. Several works also shows that the properties of the soil, namely its thermal conductivity, slightly affect the air temperature at the outlet of the EAHE. So, for example, in (Congedo et al. 2019), calculations of the parameters of an EAHE located at a depth of 3.0 m in soil with thermal conductivity in the range 1.49-2.1 W/(m·K) are presented, and it is concluded that such a range values does not significantly affect the air temperature at the outlet of the heat exchanger. The authors attribute this result to the low heat capacity of the air, which leads to a rapid decrease in air temperature to a value that is close to the soil temperature.

Table 2. Air velocity or flow rate in EAHE

Author	Cross-section shape	Air velocity or flow rate	Links, notes
Tzaferis et al.	circular	5 m/s	Tzaferis et al. 1992
Benkert S et al.	circular	140 m^3/h	*Benkert et al.* 1997
P. Congendo et al.	circular	450 m^3/h; 1200 m^3/h	Congendo et al. 2019
S. Filatov, V. Volodin	annular channel	0.073 kg/s	*Filatov & Volodin* 2013
A. Sehli et al.	circular	1-5 m/s	Sehli et al. 2012
S. Amara et al.	circular	3.79 m/s	Amara et al. 2011
Sanusi et al.	circular	5.6 m/s	Sanusi et al. 2012
NoorAziahMohd Ariffin et al.	circular, pipe in pipe	0.5 m/s	Ariffin et al. 2014
M. Krarti, J. Kreider	circular	3.5 m/s	*Krarti & Kreider* 1996
B. Basok, Novitska, M.	rectangular	natural convection	Basok & Novitska 2017

Table 3. Thermophysical properties of the soil

Author	Soil thermal conductivity, λ, W/(m·K)	Heat capacity of soil, C_p, kJ/(kg·K)	Soil density, ρ, kg/m^3	Links
V. Badescu	1.20	2.20	1800	Badescu 2007
S. Benkert et al.	1.50	1.30	1600	Benkert et al. 1997
P. Congendo et al.	1.49 2.30 1.24	1.34 2.85 1.65	1800 1650 1520	Congendo et al. 2019
S. Filatov, V. Volodin	2.00	1.10	1850	Filatov & Volodin 2013
A. Sehli et al.	2.01	1.38	2300	Sehli et al. 2012
S. Amara et al.	2.01	1.38	2300	Amara et al. 2011
Amar Rouag et al.	1.74 0.52	1.99 1.84	1868 2050	Rouag et al. 2018
B. Basok et al.	1.42	1.15	1840	Basok et al. 2009
B. Basok et al.	0.99	1.59	1920	Basok et al. 2020

Thus, the analysis of literature sources showed that now there are quite a lot of studies devoted to the issues of geothermal ventilation. The results of EAHE's modeling with various geometric data and which operate in their authentic soils under various hydraulic regimes and that are located at different depths are widely presented. However, these studies do not allow obtaining generalized patterns of heat transfer during the operation of soil-air heat exchangers and the influence of the geometric parameters of the heat exchanger on the operation of the geothermal ventilation system as a whole.

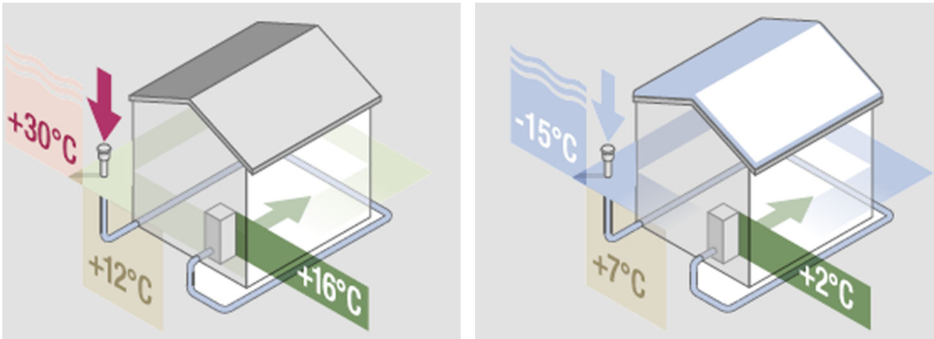
3. Description of the proposed numerical model

To solve the problems of heat accumulation by soil, it is necessary to know the depth of annual temperature changes in the soil H, which determines the soil layer that responds to changes in the temperature of the Earth's atmosphere. Below depth *H*, the temperature regime of the soil mass is stable and determined solely by the geological state. As shown in (Nakorchevsky & Belyaeva 2005), the values of *H* can vary from 3.9 m to 5.0 m, and the temperature of the soil mass below this depth can be from 5°C to 9°C, for different regions of Ukraine. Therefore, when fresh air passes through the EAHE, it heats in winter or cools in summer, as shown in Figure 1.

In this paper, to study the air flow in a pipe located in an array of soil, we used a numerical model based on the following assumptions:

- all materials used in the calculations were considered isotropic and homogeneous,
- in accordance with the data given in (Nakorchevsky & Belyaeva 2005), it is accepted that the temperature of the soil depends on the depth.

The calculations performed based on the system of equations for conservation of momentum, energy, kinetic energy of turbulence, and dissipation rate of kinetic energy of turbulence (1-8), which characterizes the processes of aerodynamics and heat transfer in an air-soil heat exchanger.



a) b)

Fig. 1. Schematic diagram of the operation of geothermal ventilation system: a) in summer; b) in winter

The continuity equation:

$$\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}+\frac{\partial w}{\partial z}=0\,. \tag{1}$$

The equations of conservation of momentum:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right), \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right), \tag{3}$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\mu}{\rho}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right). \tag{4}$$

Energy conservation equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=a\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right). \tag{5}$$

Equation of thermal conductivity of soil:

$$a\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=0 \tag{6}$$

To close the system of equations of turbulent transfer, we use the k - ε model of turbulence. This model described by using equations for the kinetic energy and dissipation rate.

The equation of conservation of kinetic energy:

$$\frac{\partial uk}{\partial x}+\frac{\partial vk}{\partial y}+\frac{\partial wk}{\partial z}=\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right]+\frac{\partial}{\partial z}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right]+G_k-\rho\varepsilon\,, \quad (7)$$

and the dissipation rate conservation equation:

$$\begin{aligned}&\frac{\partial u\varepsilon}{\partial x}+\frac{\partial v\varepsilon}{\partial y}+\frac{\partial w\varepsilon}{\partial z}=\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right]+\\&+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right]+\frac{\partial}{\partial z}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z}\right]+G_{1\varepsilon}G_k\frac{\varepsilon}{k}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}\end{aligned}, \quad (8)$$

The basic equations were solved using the finite volume method. In most areas, the computational grid consisted of elements in the form of prisms. The Navier-Stokes equations were calculated with the first order of accuracy.

The thermophysical properties of the materials, which we used in the calculations, are in Table 4.

Table 4. Thermophysical properties of soil and air that accepted in the numerical model

	Thermal conductivity, W/(m·K)	Heat capacity, kJ/(kg·K)	Density, kg/m^3
air	0.02420	1006.43	1.225
soil	0.99262	1059.87	1920

When performing calculations in the model, the following boundary conditions were used:

1) On the surface of the soil mass that is in contact with the environment, the heat transfer coefficient of 23.0 W/(m^2·K) and temperature equal to the value of the air temperature at the inlet to the EAHE were set.
2) On the sides of the soil massif, which is limited by the calculation area, the temperature of the soil (in Kelvin degrees) was set, which depended on the depth and time of the year:

mid-April: $T(z)=0.16z^3+0.6899z^2+0.343z+277.24$

mid-July: $T(z)=0.431z^2+2.685z+287.3$

mid-October: $T(z)=-0.245z^3-0.702z^2-0.494z+285.1$

mid-January: $T(z)=-0.54392z^2-2.4523z+277.54$

At the lower boundary of the region, the soil temperature T_S was constant and was according to (Sanusi 2012): April – 4°C; July – 13.0°C; October – 10.5°C; January – 4.75°C.

3) At the entrance to the EAHE air velocity v, m/s and air inlet temperature T_{in}, K were set. As turbulence parameters, we chose turbulence intensity of 10% and a hydraulic diameter corresponding to the diameter of the pipe.

4. Experimental studies of operation of EAHE for the geothermal ventilation system

To conduct experimental research on the operation of the geothermal ventilation system at the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine an experimental stand was created. This stand is designed to study thermophysical processes during the operation of a geothermal ventilation system elements.

The main element of the experimental stand is EAHE with a circular cross section and a total length of 43.0 m. The heat exchanger is made of PVC-U pipes Ø110 mm and located in the soil mass at a depth of 2.2 m (significantly lower than the seasonal depth of freezing in Kyiv). This heat exchanger is operated in two modes: in the warm season – air cooling mode, in the cold period – supply air heating mode for the supply and exhaust ventilation system.

The study of the geothermal ventilation system was carried out in two hydrodynamic modes: the supply air was pumped through the heat exchanger at a speed of 4.4 m/s and 5.5 m/s in the flow core. These speed values correspond to a volumetric air flow rate of 29.0 dm^3/s and 37.0 dm^3/s. The experimental stand is equipped with a measuring system – a Testo 405-V1 hot-wire anemometer, BME280 semiconductor temperature sensors (33 sensors in total, located in the soil mass near the heat exchanger), humidity and pressure sensors (at the inlet and outlet) and secondary computational device based on microprocessors.

The main parameters that were measured at the inlet and outlet of the heat exchanger and recorded by a special automated measuring system and testified to the efficiency of the heat exchanger – temperature, relative humidity and flow pressure. All measurements were carried out during the year (with short breaks for maintenance work) with a duty cycle of one survey of all sensors after a time period of 10 minutes. Also, the equipment used makes it possible to achieve a duty cycle of measurements up to measuring once every 1 second. Further, the data was archived and preprocessed on a computer. Uncertainties (random errors) of the experimental values were:

- for temperature – ±0.2°C,
- for absolute humidity – ±0.5-1%,
- for pressure – ±20 Pa,
- for air velocity – ±0.05 m/s.

Typical measurement results are shown in Figures 2-4. In particular, Figure 2 shows a complete generalized array of temperature measurement data for the total duration of the experiments from October 2018 to the end of September 2019. The abscissa axis shows the time of measurement of the experimental point parameter values, first obtained once every 1 minute, and starting from 10 800 minutes (75 days of operation of the heat exchanger) once every 10 minutes. The total measurement time – 516 240 minutes, that is, 358.5 days – almost the calendar year.

As we can see, the outdoor temperature fluctuated during the study period from +36°C to -14°C (weather data for Kyiv in 2018-2019). At the same time, the temperature of the air pumped through a horizontal heat exchanger was quasistationary (almost independent of the time of the current day) and varied from +18°C in summer to +2.5°C in winter.

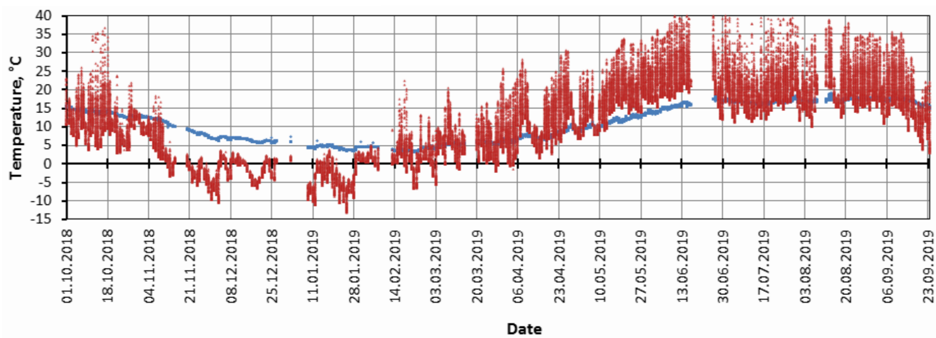


Fig. 2. Experimental data for ventilation air temperature (red drops – air inlet in EAHE; blue drops – air outlet from EAHE)

Ventilation air was almost not sensitive to local changes (daily, ten-day) in the ambient air temperature, and its temperature level was determined solely by the thermal regime of the soil mass surrounding the EAHE. That is, in the summer the air was cooled to a maximum of 18°C, and in the winter, it was heated to a maximum of 16°C to positive temperatures (which is important because there was no freezing of the soil at this depth). Air temperature was in the range of changes between the two red horizontal lines. In particular, in late spring, summer and early autumn, the temperature of ventilation air did not change much and amounted to 18°C. Due to this effect, the energy efficiency of the geothermal ventilation and air conditioning system of the house increased.

Fig. 3 shows detailed experimental studies of local changes in temperature, humidity and pressure for the day on August 18, 2018. The temperature difference reached almost 12°C (see Fig. 3a). At a midday temperature peak of the outdoor air at 29.5°C, the temperature of the soil mass near the heat exchanger barely changed after 3 hours – was observed temperature increase of 0.5°C.

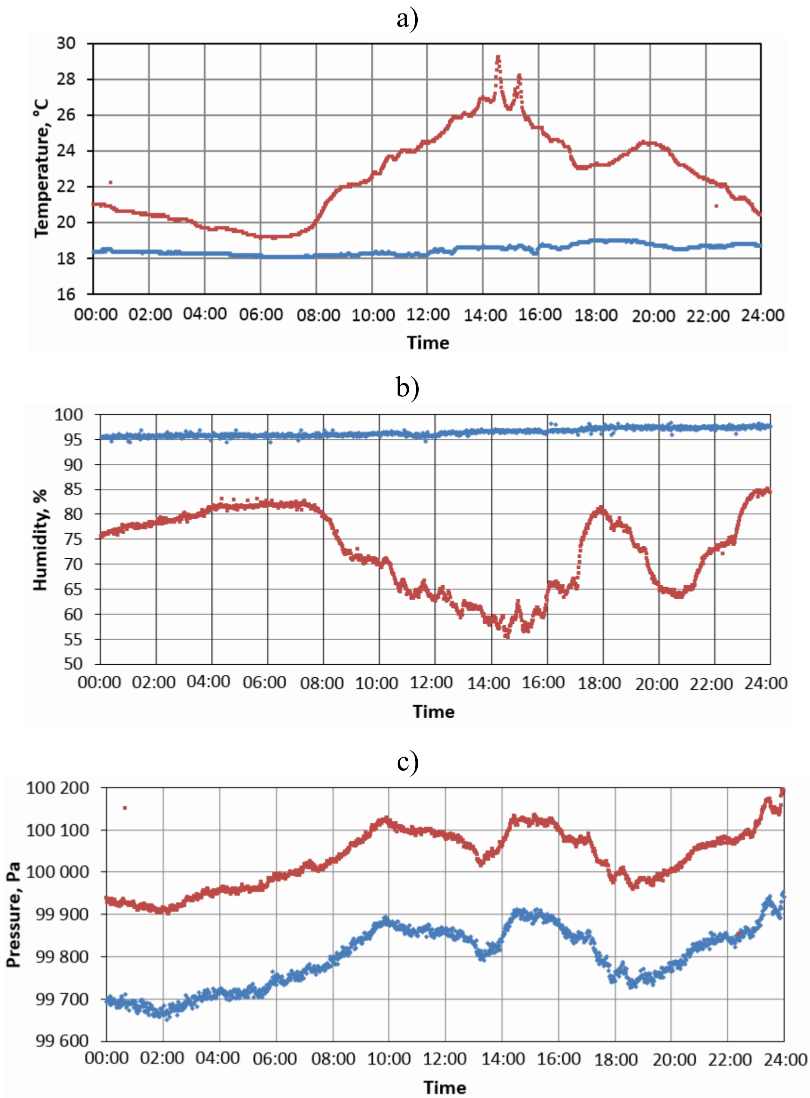
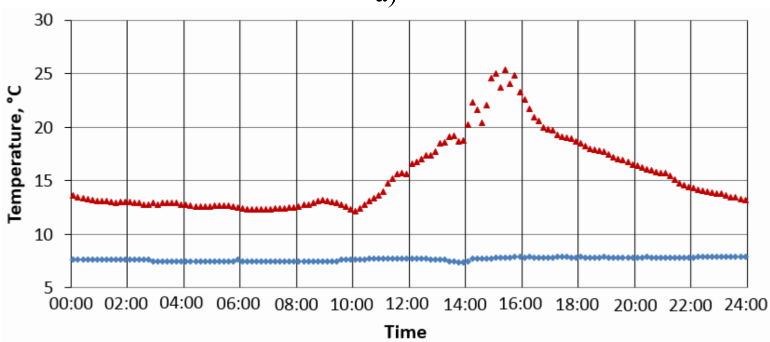


Fig. 3. Experimental data, obtained 18.08.2018: a) air temperature; b) air humidity; c) air pressure (red drops – air inlet in EAHE; blue drops – air outlet from EAHE)

Humidity of ventilation air (Fig. 3b) was quite high at the level of 95%. The ambient air humidity varied significantly from 55% at the peak of the noon temperature to 85% during the night cool. The time of minimum of the relative humidity of the outdoor air clearly coincided with the maximum of the dynamics of changes in its temperature.

The dynamics of pressure change of the airflow at the inlet and outlet of the EAHE correlated with the dynamics of changes in the external temperature. Both curves in Fig. 3c are clearly equidistant, the pressure drop over the entire measured period was 225 ... 235 Pa, which fully corresponds to the aerodynamic loss for the geometry of the heat exchanger channels.

a)



b)

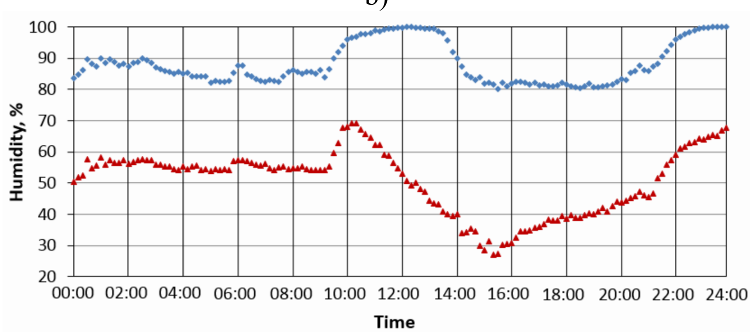


Fig. 4. Experimental data, obtained 09.04.2019: a) air temperature; b) air humidity (red drops – air inlet in EAHE; blue drops – air outlet from EAHE)

Fig. 4 shows effects of partial condensation of water vapor from outside air at the inlet to EAHE. Condensation of vapors occurred during the spring period of operation of the geothermal ventilation system, when the heating season was almost over.

The average daily ambient temperature almost coincided with the temperature of the soil mass near the heat exchanger (Fig. 4a). During this period, the humidity of the ventilation air was mainly dominated by the humidity of the outside air (Fig. 4b), and water vapor condensation occurred in some intervals.

5. Grid analysis and validation of a numerical model using experimental data

The calculation area was a parallelepiped with dimensions of 22.0 m *x* 4.0 m *x* 4.2 m (length *x* width *x* height), in which the EAHE pipe with a diameter of ∅ 110 mm was located. The domain was divided into cells by means of a pyramidal network with different thickening closer to the EAHE. Three mesh variants with different size of calculation cells were selected. The results of the comparison are presented in Fig. 5.

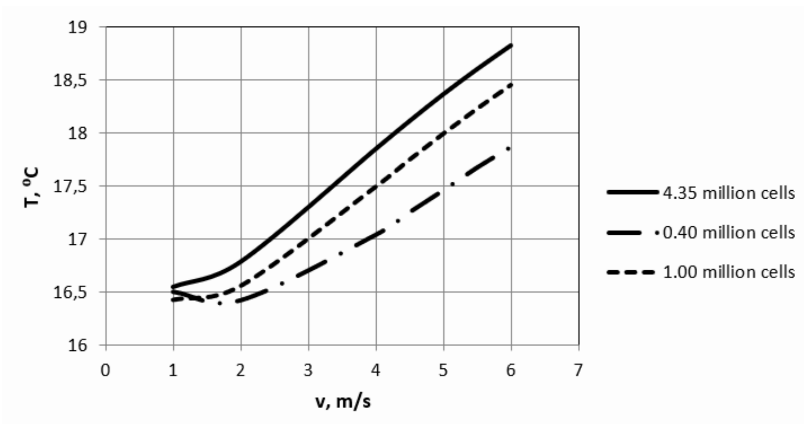


Fig. 5. Grid analysis

According to the results of comparison, for further calculations, a mesh with 1 million cells was selected. Since the difference between the calculation results between this and the grid with 4.35 million cells is less than 0.5°C (in contrast to the difference in the calculation of temperature between grids of 400 thousand and 1 million cells), this is only slightly more than the temperature measurement uncertainty at experimental research. The computational domain diagram is shown in Fig. 6.

We present the validation of the calculation results, which was carried out on the basis of the data obtained at the experimental stand. The data of a full-scale experiment are compared with the data of numerical simulation, provided that the stationary problem of air movement in an EAHE is solved at various average daily inlet air temperatures.

When the model was validated, the boundary temperature values in October and April, which were calculated according to (9), were set as boundary conditions on the lateral surface of the soil massif. On the upper surface the temperature equal to the temperature of the air entering the heat exchanger was set as a boundary condition.

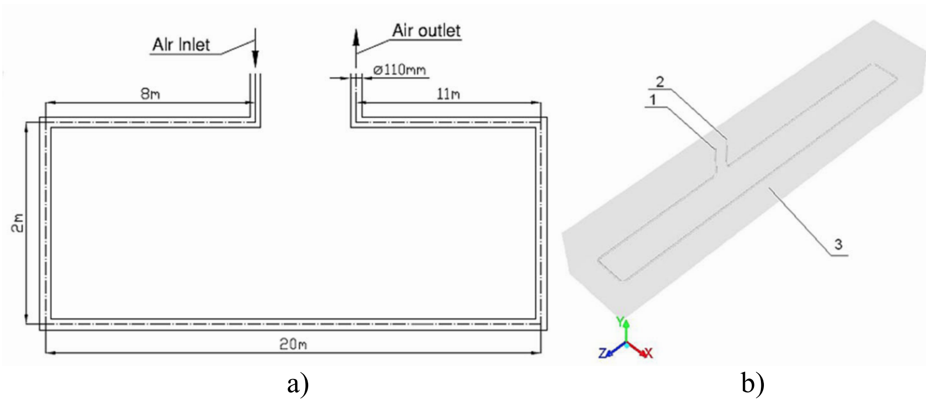


Fig. 6. Geometric dimensions of the heat exchanger (b) and scheme of the calculation area (b): 1 – air inlet to the EAHE; 2 – air outlet from the heat exchanger; 3 – soil mass

Figure 7 shows a comparison of the experimental temperature data at the outlet of the EAHE and the results of numerical simulation.

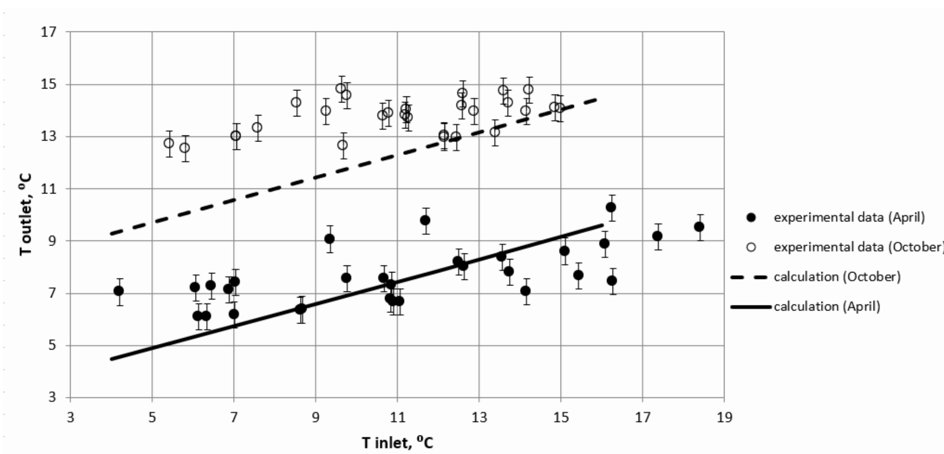


Fig. 7. Validation of numerical simulation using experimental data

As can be seen from Fig. 7, part of the experimental data coincides with the calculation within the experimental error. Some points lie above the calculated curve, this is because the calculation was carried out in a stationary setting, and cannot take into account the accumulation of heat in the soil with a sharp change in the temperature regime of inlet air. That is, if the average daily temperature during the previous days before the measurement time differed by several degrees compared with the day of measurement, then, thermal energy accumulated in the soil mass around the pipe of the EAHE and caused a higher air temperature at the outlet of the heat exchanger. These non-stationary process parameters were not taken into account in the model that was used in this case. But in general, in the absence of a sharp change in weather conditions, the model predicts the temperature at the outlet of the EAHE with the accuracy of experimental measurements.

For the obtained data, the calculation of the average relative error was performed by the formula:

$$\sigma = \frac{T_{outlet(\exp erimental)} - T_{outlet(numerical)}}{T_{outlet(\exp rimental)}} \cdot 100\% \tag{10}$$

Figure 8 shows the range of distribution of the relative error.

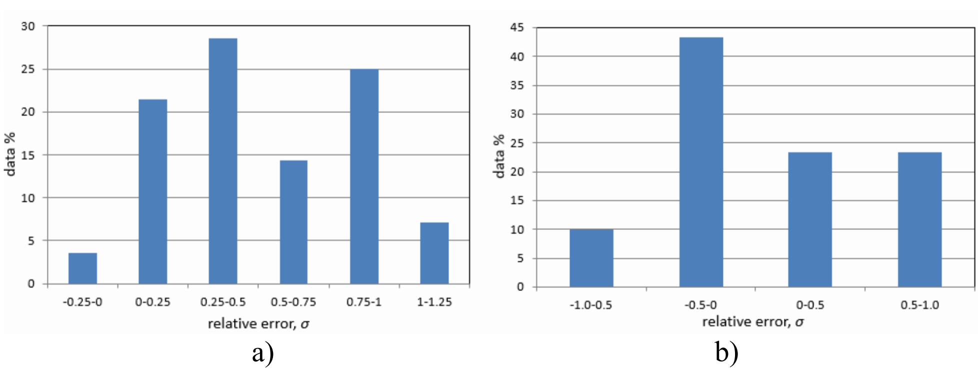


Fig. 8. Range of distribution of relative error for: a) October; b) April

The results of calculating the distribution of the relative error showed that it varies in the range from -0.25 to 1.25% (Fig. 9b). Most of the data for October 2018 (28%) has a relative error in the range of 0.25-0.5%. For April 2018, the range of relative error ranged from -1 to 1%. Most of the data for April (Fig. 9a) (40%) have a relative error from 0 to 0.5%.

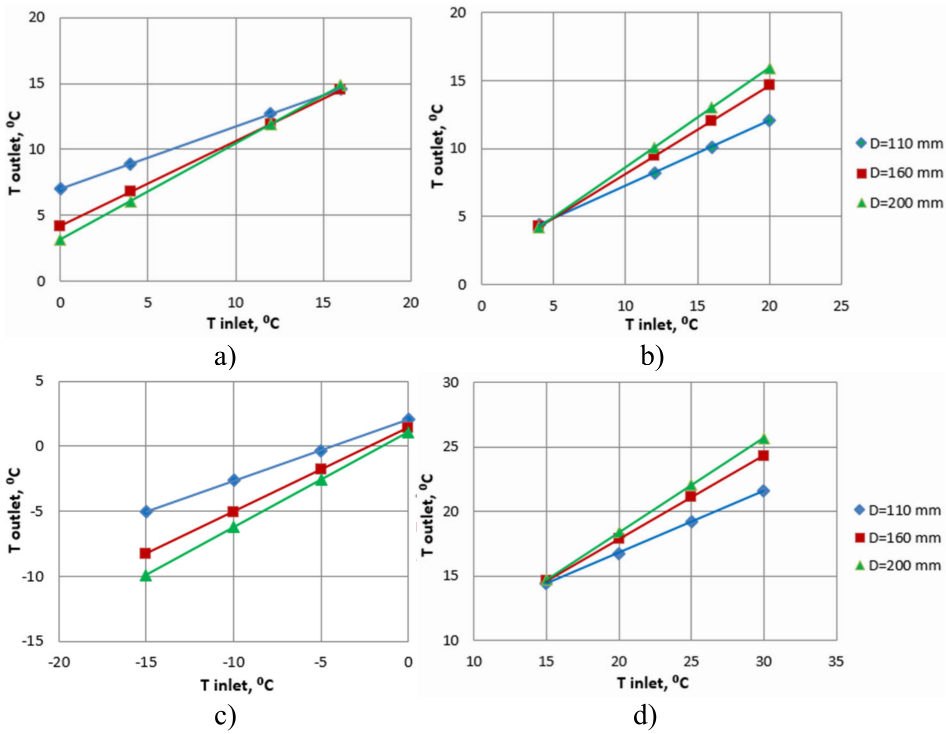


Fig. 9. Dependence of the air temperature at the outlet of the EAHE at various pipe diameters for: a) October; b) April; c) January; d) July

6. Results and discussion

Some researchers have investigated the diameter influences of EAHE on the performance of the whole system (Greco & Masselli 2020, Serageldin et al. 2016, Krarti & Kreider 1996). Krarti, M. and Kreider, J.F. (Krarti & Kreider 1996) developed a simplified analytical model of an underground air tunnel. The model was applied to a circular pipe buried at 1.5 m deep in ground. The ambient inlet temperature was assumed to vary sinusoidally within a 24 hour period, with an average value at 19°C and an amplitude of 9°C. The authors founded that outlet temperature depends significantly upon the pipe diameter. Increasing the pipe diameter results in a higher outlet air temperature.

(Serageldin et al. 2016) performed serpentine horizontal EAHE investigation in the weather conditions of Egypt. The results showed that with an increasing of the pipe diameter during EAHE operation in heating mode, the outlet air temperature decreases.

The authors of (Greco & Masselli 2020) optimized the parameters of the thermal performance of a horizontal single-duct heat exchanger on basis of the 2D numerical model. They founded that if the pipe is designed with smaller diameters and slower air flows, with other conditions that remain, the outlet temperatures come closer to the ground temperature. They proposed the combination that optimizes the performance of the EAHE system, with design condition for cooling and heating, is D = 0.1 m, v = 1.5 m/s; L = 50 m.

In our work, using the numerical model of the EAHE, that was described above, the operation parameters of the heat exchanger were calculated using pipelines with various typical outside diameters – 110, 160 and 200 mm. The initial temperature was the air temperature at the inlet to the heat exchanger and the air velocity, which was taken from the experimental data and amounted to 5.5 m/s.

Using the numerical model, the air temperature at the outlet of the EAHE and the linear density of the heat flux from the soil mass to the air flow that was pumped through the heat exchanger were calculated. Figures 7 and 8 show the corresponding data for the middle of four months – October, January, April and July. These months can be considered as those that generally characterizes climatic data that are relevant for the corresponding period of the year.

As can be seen from Fig. 9, the value of the outer diameter of the pipeline has a sufficiently significant effect on the difference in air temperature at the inlet and outlet of the EAHE. So, at the beginning (from October 15) and in the middle of the heating period (Fig. 9a and Fig. 9c), when the recuperative ventilation system has a significant contribution to the operation of the heating system, a pipeline with an outer diameter of 110 mm is optimal relative to the temperature head.

However, in the summer (Fig. 9d), to ensure air conditioning, without violating sanitary and hygienic and construction standards (State Building Regulations of Ukraine 2013), the outer diameter of the pipeline is 200 mm, at which the temperature difference between the outgoing and incoming air is kept at 5°C. With such a difference in air temperature, it is possible to abandon the use of additional devices for cooling the supply air and minimize energy costs for air conditioning.

Figure 10 shows the dependences of the influence of the outer diameter of the EAHE pipeline on the linear density of the heat flow.

We founded that the linear density of the heat flux during operation of the EAHE weakly depends on the outer diameter of the heat exchanger pipeline at the beginning and at the end of the heating period (April 15) (Fig. 10a and Fig. 10b).

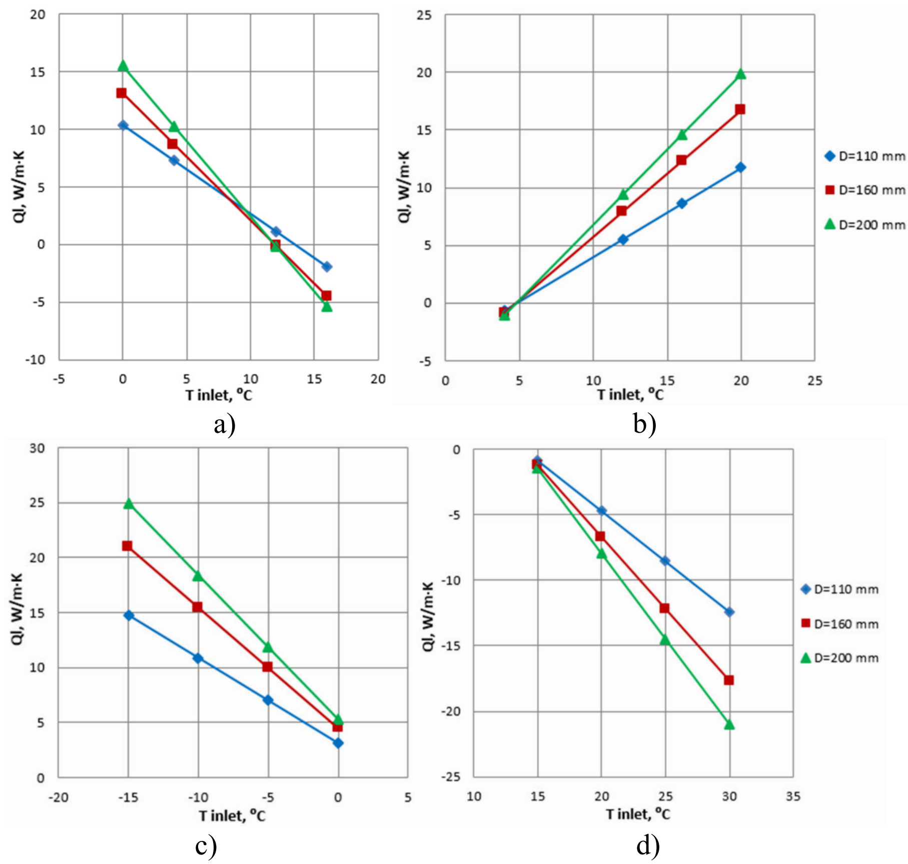


Fig. 10. Dependence of the linear heat flux density of the EAHE at different pipe diameters: a) October; b) April; c) January; d) July

In the middle of the heating period (Fig. 10c), the influence of the outer diameter of the pipeline on the linear heat flow is more significant. Thus, when switching from a diameter of 110 mm to 160 mm, the linear heat flux increases, on average, by 30%. In the transition from a diameter of 160 mm to 200 mm, the growth of the linear heat flux decreases and amounts to 16%.

In the summer (Fig. 10 d), a similar situation is observed. When there is the transition from a diameter of 110 mm to 160 mm, the linear heat flux increases, on average, by 32%, in the transition from a diameter of 160 mm to 200 mm, by 19%.

Thus, the optimal from the point of view of linear heat flow in a geothermal ventilation system is the use of an EAHE with an outer diameter of pipe of 160 mm.

7. Conclusions

Improving the energy efficiency of buildings using geothermal ventilation systems is currently an actual area of research.

The efficiency of heat transfer in the EAHE may be influenced by such parameters as the depth of placement, geometric size, shape of cross section, soil temperature, properties of heat exchanger materials, soil thermal and physical properties, mass flow through the system or its speed, climatic conditions, terrain features, etc.

A comparison of calculation results with experimental data showed that the proposed numerical model adequately describes the processes of aerodynamics and heat transfer in the EAHE.

Comprehensive experimental studies and comparisons of their data with the results of calculations using the developed numerical model of complex heat transfer processes made it possible to conduct a comparative analysis of the heat engineering parameters of air-ground heat exchangers with different pipe diameters.

Thus, for the operation of regenerative geothermal ventilation in winter and air conditioning in summer, for a given length of EAHE, corresponding to the thermal properties of the soil and airflow, it is optimal to use plastic pipes with an outer diameter of 160 mm.

References

Agrawal, K., Misra, R., Bhardwaj, M., Das Agrawal, G., & Mathur, A. (2019). Computational Fluid Dynamics Simulation Based Comparison of Different Pipe Layouts in an EATHE System for Cooling Operation. ASME. J. Thermal Sci. Eng. Appl. DOI: https://doi.org/10.1115/1.4042856

Amara, S., Nordell, B. & Benyoucef, B. (2011). Using Fouggara for heating and cooling buildings in Sahara. *Energy Procedia*, *6*, 55-64.

Ariffin, N., Sanusi, A. & Noor, A. (2014). Materials for the Earth Air Pipe Heat Exchanger (EAPHE) System as a Passive Cooling Technology for Hot-Humid Climate. *Abstract of Emerging Trends in Scientific Research*, *2*, 1-19.

Badescu, V. (2007). Simple and accurate model for the ground heat exchanger of a passive house. *Renewable energy*, *32*(5), 845-855.

Basok, B. & Novitska, M. (2017). Thermophysical modeling of an air-ground heat exchanger for a thermal curtain of front walls of an experimental energy-efficient building. *Thermophysics and Thermal Power Engineering*, *39*(1), 49-52. DOI: 10.31472/ihe.1.2017.07

Basok, B., Avramenko, A., Ryzhkov, S. & Lunina, A. (2009). The dynamics of heat transfer of liquid in a single rectilinear soil pipe element (heat exchanger). *Industrial heating technology, 31*(1)*,* 62-67.

Basok, B., Novitska, M., Bozhko, I., Priemchenko, V. & Tkachenko, M. (2020). *Smart geothermal ventilation system.* IEEE 7th International Conference on Energy Smart Systems (ESS), Kyiv, Ukraine, 226-229, DOI: 10.1109/ESS50319.2020. 9160244.

Benkert, S., Heidt, F. & Scholer, D. (1997). September. Calculation tool for earth heat exchangers GAEA. In *Proceeding of Building Simulation, Fifth International IBPSA Conference, Prague, 2*, 9-16.

Bonuso, S.; Panico, S.; Baglivo, C.; Mazzeo, D.; Matera, N.; Congedo, P.M.; Oliveti, G. (2020). Dynamic Analysis of the Natural and Mechanical Ventilation of a Solar Greenhouse by Coupling Controlled Mechanical Ventilation (CMV) with an Earth-to-Air Heat Exchanger (EAHX). *Energies*. DOI: https://doi.org/10.3390/en13143676

Cepiński, W., Kowalski, P., & Szałański, P. (2020). Waste Heat Recovery by Electric Heat Pump from Exhausted Ventilating Air for Domestic Hot Water in Multi-Family Residential Buildings. *Rocznik Ochrona Środowiska*, *22*(2), 940-958.

Congedo, P., Lorusso, C., Baglivo, C., Milanese, M. & Raimondo, L., (2019). Experimental validation of horizontal air-ground heat exchangers (HAGHE) for ventilation systems. *Geothermics*, *80*, 78-85. DOI: 10.1016/j.geothermics.2019.02.010

Díaz-Hernández, H., Macias-Melo, E., Aguilar-Castro, K., Hernández-Pérez, I., Xamán, J., Serrano-Arellano, J., López-Manrique, L. (2020). Experimental study of an earth to air heat exchanger (EAHE) for warm humid climatic conditions, *Geothermics*, 84, DOI: 10.1016/j.geothermics.2019.101741

Dolna, O. & Mikielewicz, J. (2017). Studies on the Field Type Ground Heat Exchanger Coupled with the Compressor Heat Pump (Part 1). *Rocznik Ochrona Środowiska, 19*, 240-252.

Dolna, O. & Mikielewicz, J. (2017). Studies on the Field Type Ground Heat Exchanger Coupled with the Compressor Heat Pump (Part 2). *Rocznik Ochrona Środowiska*, *19,* 253-269.

Filatov, S. & Volodin, V. (2013). Efficiency of using energy piles with air coolant in ventilation and heat supply systems. *Industrial heating technology, 35*(3), 44-50.

Greco, A., Masselli, C. (2020). The Optimization of the Thermal Performances of an Earth to Air Heat Exchanger for an Air Conditioning System: A Numerical Study. Energies, 13. https://doi.org/10.3390/en13236414

Hamdi, O., Brima, A., Moummi, N. & Nebbar, H. (2018). Experimental study of the performance of an earth to air heat exchanger located in arid zone during the summer period. *Journal homepage: http://iieta. org/Journals/IJHT*, *36*(4), pp.1323-1329. DOI: 10.18280/ijht.360422

Kamal Kumar Agrawal, Rohit Misra, Ghanshyam Das Agrawal, Mayank Bhardwaj & Doraj Kamal Jamuwa (2019). Effect of different design aspects of pipe for earth air tunnel heat exchanger system. *International Journal of Green Energy*, *16*(8), 598-614, DOI: 10.1080/15435075.2019.1601096

Krarti, M. & Kreider, J. (1996). Analytical model for heat transfer in an underground air tunnel. *Energy conversion and management*, *37*(10), 1561-1574.

Kumar Verma, M., Bansal, V., Bihari Rana. Development of passive energy source as earth air pipe heat exchangers (eaphe) system – a review. *Journal of Thermal Engineering*.

Misra, R., Jakhar, S., Agrawal, K., Sharma, S., Jamuwa, D., Soni, M. & Agrawal, G. (2018). Field investigations to determine the thermal performance of earth air tunnel heat exchanger with dry and wet soil: Energy and exergetic analysis. *Energy and Buildings*, *171*, 107-115. DOI:10.1016/j.enbuild.2018.04.026

Nakorchevsky, A. & Belyaeva, T. (2005). Regression analysis of the depths of annual temperature fluctuations in the upper soil layers. *Industrial heat engineering, 27*(6)*,* 86-90.

Rouag, A., Benchabane, A. & Mehdid, C. (2018). Thermal design of Earth-to-Air Heat Exchanger. Part I a new transient semi-analytical model for determining soil temperature. *Journal of Cleaner Production*, *182*, 538-544. DOI: 10.1016/ j.jclepro.2018.02.089.

Sakhri, N., Menni, Y., Chamkha, A.J., Salmi, M., Ameur, H. (2020). Earth to air heat exchanger and its applications in arid regions – an updated review. *TECNICA ITALIANA-Italian Journal of Engineering Science*, *64*(1), 83-90. DOI:10.18280/tiijes.640113

Sanusi, A. (2012). Low energy ground cooling system for buildings in hot and humid Malaysia. *A thesis submitted for the degree of Doctor of Philosophy, De Montfort University, 271.*

Sehli, A., Hasni, A. and Tamali, M. (2012). The potential of earth-air heat exchangers for low energy cooling of buildings in South Algeria. *Energy Procedia*, *18*, 496-506.

Serageldin, AA, Abdelrahman, AK, Ookawara, S. (2016). Earth-air heat exchanger thermal performance in egyptian conditions: experimental results, mathematical model, and computational fluid dynamics simulation. *Energy Convers Manag,* 122, 25-38.

State Building Regulations of Ukraine B.2.5-67: 2013 "Heating, ventilation and air conditioning".

Tkachenko, M., Goncharuk, S., Lysenko, O., Novitska, M., Nedbailo, O. (2020). *Experimental validation of numerical simulation of air-earth heat exchanger with round cross section*. In IV International Scientific-Technical Conference “Actual problems of renewable power engineering, construction and environmental engineering”. 108-109.

Tzaferis, A., Liparakis, D., Santamouris, M., Argiriou, A. (1992). Analysis of the accuracy and sensitivity of eight models to predict the performance of earth-to-air heat exchangers. *Energy and buildings*, *18*(1), 35-43.

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Numerical Simulation of Emergency Release of Liquid Petroleum Gas on a Car Gas Station

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Abstract: LPG storage tanks may be seriously threatened by a fire coming from nearby fuels or by leakage appearance. The aim of the study was to prepare a three-dimensional model of LPG release on a car gas station under different environmental conditions. CFD simulations of liquid and gas phase release from a tank localized on a car gas station was performed. First, ALOHA software was applied to determine mass flow rate, while Ansys software was used to determine the shape and size of hazardous zone. To reflect real condition atmospheric stability classes were applied. It was observed that for classes A-D the hazardous zone was decreasing. While, for E and F class the range was increased. It was noticed that the location of the leakage affects the extent of the danger zone. For the leaking below the liquid surface analyzed LPG has liquid form. While, for the leaking above the liquid surface analyzed LPG has gas form. Furthermore, for liquid leakage the largest hazard zone of release was observed.

Keywords: gas emergency release, liquid petroleum gas, CFD simulation, atmospheric stability class

1. Introduction

The large population density increases probability of any hazardous material release (Pontiggia et al. 2011, Piecuch et al. 2015, Polanczyk et al. 2019, Majder-Lopatka et al. 2020). Dispersion of storage gases due to the natural or the industrial accidents may lead to tragic consequences (Polanczyk et al. 2018, Polanczyk et al. 2020). Moreover, transportation of liquefied flammable products is affected by severe accidents (D'Aulisa et al. 2014, Polanczyk et al. 2018). To prevent the effects of these disasters different approaches have been introduced in the literature (Lovreglio et al. 2016, Polanczyk et al. 2018). Past accident data analysis shows that about 33% of accidents occurred during road or rail LPG transportation resulted in boiling liquid expanding vapor explosions (D'Aulisa et al. 2014, Polanczyk et al. 2020). When exposed to severe distant source radiation induced by fire, LPG tanks may be subjected to severe heat-up and consequent pressurization, which may lead to the catastrophic rupture of the tank (Scarponi et al. 2017). LPG storage tanks may be seriously threatened by a fire, particularly in those cases where negligence or regulatory gaps allow a very close exposure of these tanks to flames coming from nearby fuels or by leakage appearance (EmrysScarponi et al. 2020). Furthermore, fragments resulting from the destruction of the tank shell can be projected to the surrounding, potentially worsening the consequences of the explosion (Tugnoli et al. 2013). The lack of an effective safety distance between the LPG tank and the surrounding fuels caused the opening of the safety relief valves and intense jet fires (EmrysScarponi et al. 2020).

To assist decisions and planning in case of hazardous gases numerical techniques are applied (Hannaa et al. 2009, Polanczyk & Salamonowicz 2018). Moreover, in industrial processes numerical tools are present (Wawrzyniak et al. 2012, Wawrzyniak et al. 2012, Czapczuk et al. 2017). In recent years, more detailed models for the simulation of LPG vessels exposed to fire were developed, based on computational fluid dynamics (CFD) Various computational tools are applied for description of dispersion process i.e. Phast software (Wang et al. 2017), Aloha software (Thoman et al. 2006), Ansys software (Polanczyk et al. 2013, Salamonowicz et al. 2015) and FDS (Salamonowicz et al. 2021). However, the simulation set up considered only full engulfment conditions, and the possible transient evolution of fire scenario was not systematically considered. Therefore, the aim of the study was to prepare a three-dimensional model of LPG release on a car gas station under different environmental conditions.

2. Materials and methods

2.1. Case study

Analyzed case was composed of the area included one gas tank, three gas distributors, one building and one carport. During a regular day the side surface of Liquid Petroleum Gas (LPG) tank on a car gas station was unsealed. The emergency release was provoked by the lack of proper maintenance, inspection and damage on detachable flange connections. Two different approaches of unsealed tank were considered: 1) in the lower part of the tank (0.3 m measuring from the ground), where liquid phase is localized, liquid phase of LPG leak appeared; 2) in the upper part of the tank (0.7 m measuring from the ground), where gas phase is localized, gas phase of LPG leak appeared.

According to the first approach the phenomenon was directed into the leak appearance above the liquid level and release of gas vapors. The LPG released in this way is further dispersed. While, propane-butane is heavier then air, the released gas slowly settle on the ground and flood the depressions, e.g. sewage wells. The dispersed gas creates an explosive atmosphere which together with ignition source may explode. Moreover, gas remaining in depressions of the land may remain there for a long time.

According to the second approach the phenomenon was directed into the leak appearance in the part of the tank with liquid LPG. As a result a boiling pool of propane-butane is formed on the ground (boilling temperature -41.2°C). Combustible vapors arising from boiling pool are mixing with air and creating an explosive atmosphere.

2.2. Model description

The fluid dynamic response of the LPG tank exposed on different environmental conditions was modeled by two- and three-dimensional simulations. The following boundary conditions for numerical simulation of LPG release on a car gas station were assumed: free ejection of LPG into open space (T = 25°C and P = 101325 Pa, air ($\rho = 1.23$ kg/m^3, $\eta = 1.79\ 10^{-5}$ kg/(m s)). The properties of analyzed LPG were approximated as for the following composition: propane - mass fraction 0.595, n-butane – mass fraction 0.405, temperature 25°C.

In the first step, with the use of Ansys SpaceClaim software (ANSYS, Canonsburg, PA USA) and technical documentation a three-dimensional model (length = 200 m, width = 100 m, heigh = 20 m) of a gas station was reconstructed (Fig. 1). In the analyzed domain 6 objects were localized (one gas tank, three distributors, one building and one carport) (Table 1).

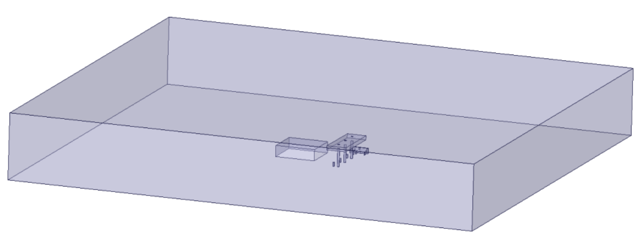


Fig. 1. Three-dimensional model of a gas station

The following boundary conditions were used: mass flow outlet from the unsealed tank, wall (for all obstacles). Moreover, at the inlet to the geometry, velocity inlet boundary representing flowing air was applied.

Table 1. Dimensions of objects on the car gas station

Object	Length [m]	Width [m]	Height [m]
Gas tank	4	1	1
Distributor	0.5	0.5	1.5
Building	20	10	4
Carport	10	5	7

Next, digital grid with the use of Ansys Meshing software (ANSYS, Canonsburg, PA USA) composed of tetrahedrons with boundary layer was created. After mesh independent tests the number of numerical grid elements was established at approximately 5 000 000, with boundary layer for whole analyzed domain composed of 10 layers (Fig. 2).

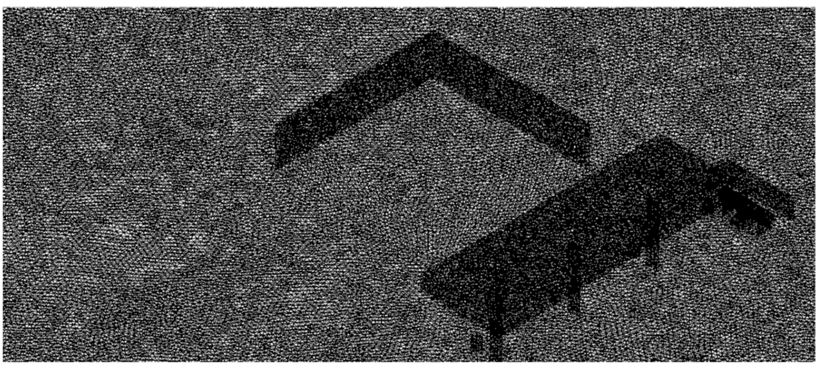


Fig. 2. Three-dimensional mesh model of gas station.

Moreover, for the calculation of mass flow rate (eq. 1) Aloha software was used (Thoman et al. 2005, Tsenga et al. 2012, Sun et al. 2013). Mathematical domain was limited to the cylindrical tank (diameter = 4 m, high = 1 m, length = 1 m). However, there were no obstacles. For the gas phase upwards emission at 1.5 m level was observed. While, for the liquid phase downwards emission was observed at 0.5 m level was observed. Moreover, gas phase leak was analyzed at constant temperature equal to 25°C. While, for the liquid phase, the gas temperature was lowered due to the immediately phase transition from liquid to gas after it escaped into the atmosphere through the leaks. Therefore, gas phase was observed closer to the ground after release from the tank, while it is heavier than air and is colder than air. Convergence level was set at 1 e^{-5}.

Next, three-dimensional LPG release with the use of Ansys Fluent 19 software (ANSYS, Canonsburg, PA USA) was analyzed. Reynolds Averaged Navier-Stokes equations (eq.1-3) were applied (Ganta et al. 2014, Zieminska-Stolarska et al. 2015).

$$\left(\frac{\partial v_x}{\partial t} + v_x\frac{\partial v_x}{\partial x} + v_y\frac{\partial v_x}{\partial y} + v_z\frac{\partial v_x}{\partial z}\right) = \rho g_x - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left((\mu+\mu_t)(2\frac{\partial v_x}{\partial x})\right) + \frac{\partial}{\partial y}\left((\mu+\mu_t)(\frac{\partial v_z}{\partial y}+\frac{\partial v_y}{\partial x})\right) + \frac{\partial}{\partial z}\left((\mu+\mu_t)(\frac{\partial v_x}{\partial z}+\frac{\partial v_z}{\partial x})\right) \tag{1}$$

$$\rho\left(\frac{\partial v_y}{\partial t} + v_x\frac{\partial v_y}{\partial x} + v_y\frac{\partial v_y}{\partial y} + v_z\frac{\partial v_y}{\partial z}\right) = \rho g_y - \frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left((\mu+\mu_t)(\frac{\partial v_y}{\partial x}+\frac{\partial v_x}{\partial y})\right) + \frac{\partial}{\partial y}\left((\mu+\mu_t)(2\frac{\partial v_y}{\partial y})\right) + \frac{\partial}{\partial z}\left((\mu+\mu_t)(\frac{\partial v_y}{\partial z}+\frac{\partial v_z}{\partial y})\right) \tag{2}$$

$$\rho\left(\frac{\partial v_z}{\partial t} + v_x\frac{\partial v_z}{\partial x} + v_y\frac{\partial v_{zy}}{\partial y} + v_z\frac{\partial v_z}{\partial z}\right) = \rho g_z - \frac{\partial p}{\partial z} + \frac{\partial}{\partial x}\left((\mu+\mu_t)(\frac{\partial v_z}{\partial x}+\frac{\partial v_x}{\partial z})\right) + \frac{\partial}{\partial y}\left((\mu+\mu_t)(\frac{\partial v_z}{\partial y}+\frac{\partial v_y}{\partial z})\right) + \frac{\partial}{\partial z}\left((\mu+\mu_t)(\frac{\partial v_z}{\partial z})\right) \tag{3}$$

where:
v_x, v_y, v_z – velocity components for x, y, z directions, [m/s],
t – time [s]; g – acceleration in x, y, z direction, [m^2/s],
μ – fluid viscosity, [Pa s],
ρ – fluid density, [kg/m^3],
μt – turbulent viscosity, [Pa s].

In this work, the k–ε model was used to represent the effects of turbulence (Pontiggiaa et al. 2010). Moreover, as a wind speed is a crucial parameter, reconstruction of dispersion in real conditions required usage of Pasquill stability class. While, it required reflection of the wind profile along the height depending on the atmospheric stability Pasquill stability class (Table 2) (Eduardo Krügera and Emmanuel 2013).

Table 2. Velocity profile in function of atmospheric stability class

Stability class	Coefficient [-]	Wind speed [m/s]	Equation
A	0.109	1	$v = (y/10)^{0.109}$
B	0.112	3	$v = (y/10)^{0.112}$
C	0.12	5	$v = (y/10)^{0.12}$
D	0.142	7	$v = (y/10)^{0.142}$
E	0.203	3	$v = (y/10)^{0.203}$
F	0.253	2	$v = (y/10)^{0.253}$

3. Results

The methodology presented in this work provides a numerical tool to assess whether the exposure of a LPG tank to a given atmospheric scenario can be deemed safe (Scarponi et al. 2020). The influence of environmental parameters as well as released phase on the size of hazardous zone was analyzed. The methodology presented in this study provided a numerical tool to assess whether the exposure of an LPG tank to a given environmental scenario can be deemed safe on a car gas station. To reconstruct a realistic conditions of wind appearance, an atmospheric stability classes were applied. It was in line with Mack et al. who investigated CO_2 dispersion where experimentally measured inlet profile of wind was simulated (Mack & Spruijt 2014). Moreover, in our study we assumed turbulent character of flow, therefore, standard k-ε model was used to describe its properties. It was in line with Xing et al. who observed that the results from the standard k-ε model were in acceptable agreement with the experimental data for the gas dispersion process (Xing et al. 2013). However, contrary to this Sklavounos et al. found that the standard k–ε model overestimate maximal concentration of heavy gas (Sklavounos & Rigas 2004). Nevertheless, our study indicated that this turbulent model may be used in simulation of LPG release.

In the first step, ALOHA software was applied to estimate the range of emergency zone. While, the leak was not limited by any obstacles, equal emergency range was observed for both analyzed phases (Table 3). Increasing of atmospheric stability class from A to F resulted in hazardous zone range equal to 11 m for gas phase and liquid phase.

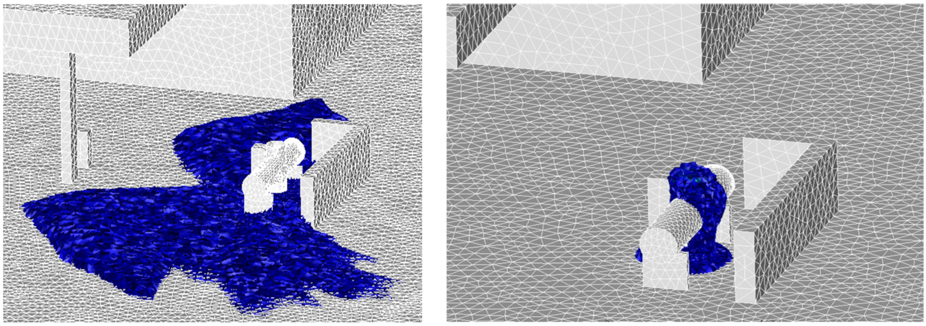
In the next step the three-dimensional car gas station was analyzed. It was observed that wind direction and atmospheric stability class as well as retaining wall and anti-burst wall had impact on the explosive range for both phases (Table 4). For the same atmospheric stability classes higher range of zone for gas phase compare to the liquid phase was observed. Fig. 3 presents a leak of LPG for both phases, the iso-surfaces are presented for a concentration of 2%, which corresponds to the lower explosive limit (LEL). Liquid phase was spread on the ground, while gas phase surrounded LPG tank. When B atmospheric stability class was applied liquid was longitudinally concentrated, while gas phase was mostly concentrated under a tank (Fig. 4). For C atmospheric stability class, the range of liquid phase zone was about 5 times shorter compare to the gas phase (Fig. 5). Moreover, comparison of C and D atmospheric stability class indicated further decrease of hazard zone range (Fig. 6). While, for E and F atmospheric stability class increase of hazardous zone was observed. For E class the range of hazardous zone was equal to 4.5 m and 37.5 m for gas and liquid, respectively. While, for F class the range of hazardous zone was equal to 45 m and 19.6 m for gas and liquid, respectively.

Table 3. The range of explosive zone calculated with ALOHA software

Phase	Atmospheric stability class	Range of zone [m]
Gas	A	11
	B	11
	C	11
	D	11
	E	11
	F	11
Liquid	A	11
	B	11
	C	11
	D	11
	E	11
	F	11

Table 4. The range of explosive zone calculated with Ansys software

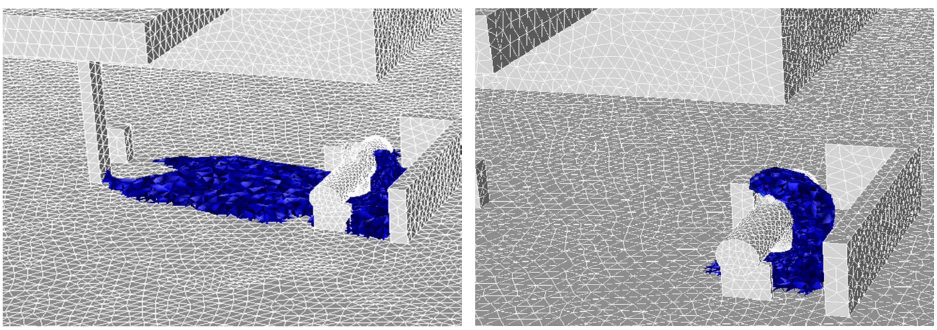
Phase	Atmospheric stability class	Range of zone [m]
Gas	A	3.5
	B	1.9
	C	1,0
	D	0.8
	E	4.5
	F	5,0
Liquid	A	17.5
	B	11,0
	C	5.5
	D	2.3
	E	37.5
	F	19.6



(**a**) (**b**)

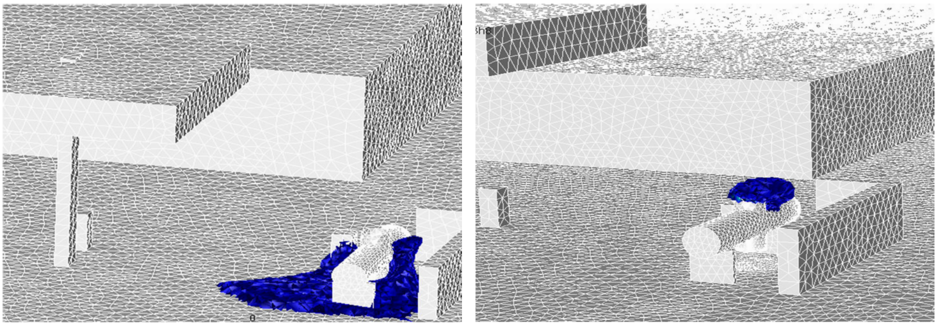
Fig. 3. Graphical representation of LPG leak for the atmospheric stability class A: (**a**) gas phase of propane, (**b**) liquid phase of propane. Color bar presents mole fractions of propane

Each time released LPG was not presented behind anti-burst wall. Which corresponds to the real situation on a car gas station. Moreover, hazardous zone only for F stability class for gas phase was presented in the area of distributors. Furthermore, for A stability class for gas phase hazardous zone was observed close to the building.



(**a**) (**b**)

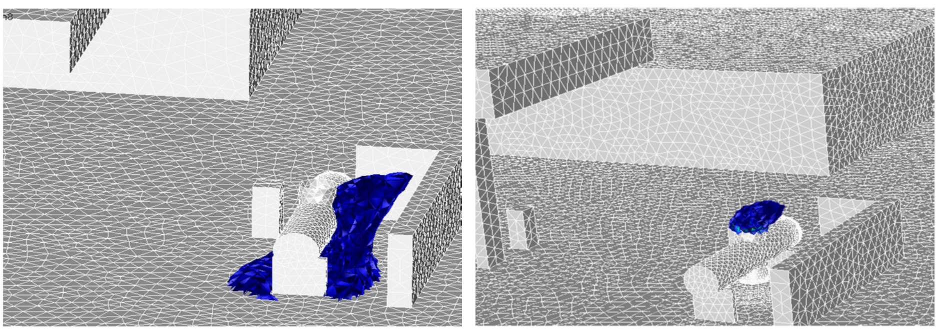
Fig. 4. Graphical representation of LPG leak for the atmospheric stability class B: (**a**) gas phase of propane, (**b**) liquid phase of propane. Color bar presents mole fractions of propane



(**a**) (**b**)

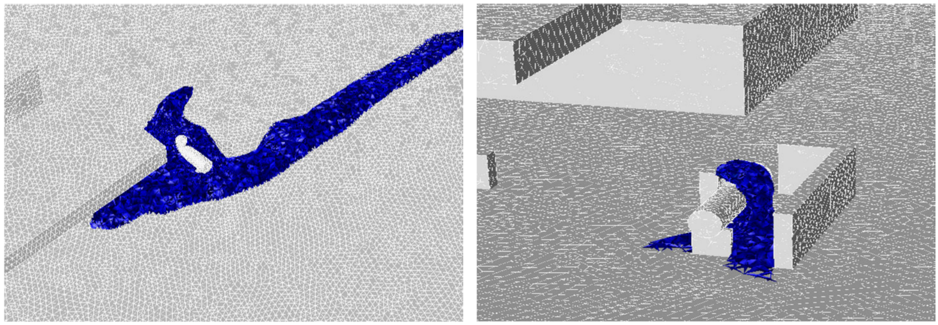
Fig. 5. Graphical representation of LPG leak for the atmospheric stability class C: (**a**) gas phase of propane, (**b**) liquid phase of propane. Color bar presents mole fractions of propane

Moreover, it was noticed that not only a character of wind (different atmospheric stability class) but also the direction of wind had impact on the range and size of hazardous zone (Fig. 9). When wind was directed from the left side of the mathematical domain, longitudinal range of hazardous zone was equal to 11 m (Fig. 9a), while wind directed from the right side affected extend of the hazardous zone to 15 m. Which was caused by appearance of retaining wall as well as anti-burst wall.



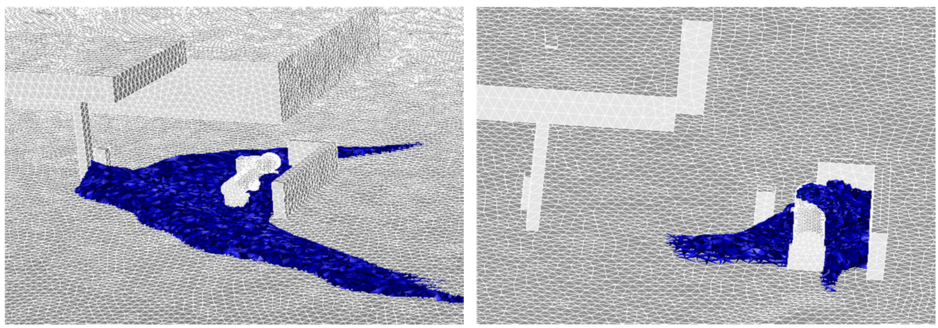
(**a**) (**b**)

Fig. 6. Graphical representation of LPG leak for the atmospheric stability class D: (**a**) gas phase of propane, (**b**) liquid phase of propane. Color bar presents mole fractions of propane



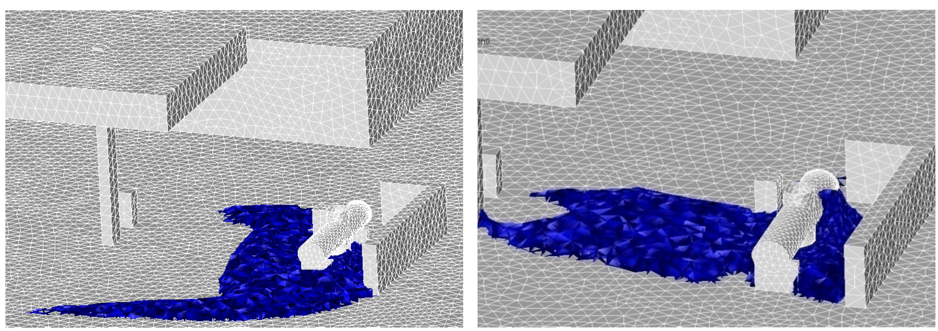
(**a**) (**b**)

Fig. 7. Graphical representation of LPG leak for the atmospheric stability class E: (**a**) gas phase of propane, (**b**) liquid phase of propane. Color bar presents mole fractions of propane



(**a**) (**b**)

Fig. 8. Graphical representation of LPG leak for the atmospheric stability class F: (**a**) gas phase of propane, (**b**) liquid phase of propane. Color bar presents mole fractions of propane



(**a**) (**b**)

Fig. 9. Comparison of liquid phase release for different wind direction for the atmospheric stability class B: (**a**) for the left side of the analyzed domain, (**b**) from the right side of the analyzed domain

3.1. Limitation to the study

Presented model was analyzed within one car gas station. In the future we would like to analyze different spatial configurations of gas car stations. Moreover, we analyzed the process under constant temperature. In the future we would like to include different environmental temperatures which may reflect different seasons.

4. Conclusions

The proposed CFD model enabled analysis of LPG emergency release from a tank at the car gas station. It was observed that urban obstacles have a significant effect on gas propagation. All analyzed cases indicated that the explosive zone was located several dozen centimeters above ground. Moreover, the range of the explosion hazard zone is strongly dependent on the weather conditions. Considering the obtained results, it can be observed that the lower the wind speed, the greater the explosion hazard zone. The leakage of the gas and liquid phase was the largest for the low wind speed (wind speed class: A, E, F). Furthermore, LPG tanks should be located in an open area which enables freely diluting of released gases.

Moreover, it was observed that the location of the leakage affects the extent of the danger zone. For the leaking below the liquid surface analyzed LPG has liquid form. While, for the leaking above the liquid surface analyzed LPG has gas form. Furthermore, for liquid leakage the largest hazard zone of release was observed.

References

Pontiggia, M., Landucci, G., Busini, V., Derudi, M., Alba, M., Scaioni, M., Bonvicini, S., Cozzani V. & Rota, R. (2011). CFD model simulation of LPG dispersion in urban areas. *Atmospheric Environment*, *11*.

Piecuch, T., Andriyevska, L., Dabrowski, J., Dabrowski, T., Juraszka, B. & Kowalczyk, A. (2015). Treatment of Wastewater from Car Service Station. *Rocznik Ochrona Środowiska*, *14*.

Polanczyk, A., Piechota-Polanczyk, A. & Dmochowska, A. (2019). The influence of the soil type on the permeability of petroleum derivatives. *Rocznik Ochrona Środowiska*, *13*.

Majder-Lopatka M., Wesierski, T., Dmochowska, A., Salamonowicz, Z. & Polanczyk, A. (2020). The Influence of Hydrogen on the Indications of the Electrochemical Carbon Monoxide Sensors. *Sustainability.*

Polanczyk, A., Salamonowicz, Z., Majder-Lopatka, M., Dmochowska, A., Jarosz, W., Matuszkiewicz R. & Makowski, R. (2018). 3D Simulation of Chlorine Dispersion in Rrural Area. *Rocznik Ochrona Środowiska*, *14*.

Polanczyk, A., Majder-Lopatka, M., Dmochowska, A. & Salamonowicz, Z. (2020). Analysis of combustion process of protective coating paints. *Sustainability.*

D'Aulisa, A., Tugnoli, A., Cozzani, V., Landucci, G. & Birk, A.M. (2014). CFD Modeling of LPG Vessels Under Fire Exposure Conditions. *AIChE Journal*, *14*.

Polanczyk, A., Ciuka-Witrylak, M., Synelnikov O. & Loik, V. (2018). Analysis of sorption of vehicle liquids with sand that appear after car accidents reproduced in laboratory scale. *MATEC Web of Conferences*, *8*.

Lovreglio, R., Ronchi, E., Maragkos, G., Beji, T. & Merci, B. (2016). A dynamic approach for the impact of a toxic gas dispersion hazard considering human behaviour and dispersion modelling. *J Hazard Mater*, 758-771.

Polanczyk, M. Majder-Lopatka, Z. Salamonowicz, A. Dmochowska, W. Jarosz, R. Matuszkiewicz R. & Makowski R. (2018). Environmental Aspects of Sorption Process. *Rocznika Ochrona Środowiska*, *13*.

Polanczyk, A., Piechota-Polanczyk, A., Dmochowska, A., Majder-Lopatka, M. & Salamonowicz, Z. (2020). Analysis of the Effectiveness of Decontamination Fluids on the Level of Biological Contamination of Firefighter Suits. *International Journal of Environmental Research and Public Health*, *10*.

Scarponi, G.E., Landucci, G., Heymes, F. & Cozzani, V., (2017). Experimental and numerical study of the behavior of LPG tanks exposed to wildland fires. *Process Safety and Environmental Protection*, *20*.

Giordano EmrysScarponi, G.E., Pastor, E., Planas, E. & Cozzani, V. (2020). Analysis of the impact of wildland-urban-interface fires on LPG domestic tanks. 15.

Tugnoli, A., Cozzani, V., Khan, F. & Amyotte, P. (2013). 6 - Missile Projection Effects. *Domino Effects in the Process Industries Modelling, Prevention and Managing*, *48*.

Hannaa, S. R. Olav, R., Hansenb, R., Ichard M. & Strimaitis, D. (2009). CFD model simulation of dispersion from chlorine railcar releases in industrial and urban areas. *Atmospheric Environment*, *9*.

Polanczyk, A. & Salamonowicz, Z. (2018). Computational modeling of gas mixture dispersion in a dynamic setup – 2d and 3d numerical approach. *E3S Web of Conferences*, *8*.

Wawrzyniak, P., Podyma, M., Zbicinski, I., Bartczak Z., Polanczyk, A. & Rabaeva, J. (2012). Model of Heat and Mass Transfer in an Industrial CounterCurrent Spray-Drying Tower. *Drying Technology*, *9*.

Wawrzyniak, P., Polanczyk, A., Zbicinski, I., Jaskulski, M., Podyma, M. & Rabaeva, J. (2012). Modeling of Dust Explosion in the Industrial Spray Dryer. *Drying Technology*, *10*.

Czapczuk, A., Dawidowicz, J. & Piekarski, J. (2017). Application of Multilayer Perceptron for the Calculation of Pressure Losses in Water Supply Lines. *Rocznik Ochrona Środowiska*, *11*.

Wang, K., Liu, Z., Qian, X. & Huang, P. (2017). Long-term consequence and vulnerability assessment of thermal radiation hazard from LNG explosive fireball in open space based on full-scale experiment and PHAST. *Journal of Loss Prevention in the Process Industries*, *10*.

Thoman, D.C., O'Kula, K.R., Laul, J.C., Davis, M.W. & Knecht, K.D. (2006). Comparison of ALOHA and EPIcode for Safety Analysis Applications. *Journal of Chemical Health and Safety*, *14*.

Polanczyk, A., Wawrzyniak, P. & Zbicinski, I. (2013). CFD analysis of dust explosion relief system in the counter-current industrial spray drying tower. *Drying Technology*, *10*.

Salamonowicz, Z., Kotowski, M., Polka, M. & Barnat, W. (2015). Numerical simulation of dust explosion in the spherical 20l vessel. *Bulletin of the Polish Academy of Sciences. Technical Sciences*, *5*.

Salamonowicz, Z., Krauze, A., Majder-Lopatka, M., Dmochowska, A., Piechota-Polanczyk, A. & Polanczyk, A. (2021). Numerical Reconstruction of Hazardous Zones after the Release of Flammable Gases during Industrial Processes. *Processes*, *17*.

Thoman, D.C., Davis, M.W. & O'Kula, K.R. (2005). A Comparison of EPIcode and ALOHA Calculations for Pool Evaporation and Chemical Atmospheric Transport and Dispersion. *Washington Safety Management Solutions LLC*, *15*.

Tsenga, J.M., Sua, T.S. & K. C.Y. (2012). Consequence Evaluation of Toxic Chemical Releases by ALOHA. *Procedia Engineering*, *6*.

Sun, B., Utikara, R. P., Pareeka, V. K. & Guob, K. (2013). Computational fluid dynamics analysis of liquefied natural gas dispersion for risk assessment strategies. *Journal of Loss Prevention in the Process Industries*, *12*.

Ganta, S.E., Narasimhamurthyb, V.D., Skjoldb, T., Jamoisc, D. & P. C. (2014). Evaluation of multi-phase atmospheric dispersion models for application to Carbon Capture and Storage. *Journal of Loss Prevention in the Process Industries*, *23*.

Zieminska-Stolarska, A., Polanczyk, A. & Zbicinski, I. (2015). 3-D CFD simulations of hydrodynamics in the Sulejow dam reservoir. *Journal of Hydrology and Hydromechanics*, *8*.

Pontiggiaa, M.M., Derudi, M., Alba, M., Scaioni, M. & Rota, R. (2010). Hazardous gas releases in urban areas: Assessment of consequences through CFD modelling. *Journal of Hazardous Materials*, *8*.

Krügera, E. & Emmanuel, R. (2013). Accounting for atmospheric stability conditions in urban heat island studies: The case of Glasgow, UK. *Landscape and Urban Planning*, *10*.

Scarponi, G.E., Pastor, E., Planas, E. & Cozzani, V. (2020). Analysis of the impact of wildland-urban-interface fires on LPG domestic tanks. *Safety Science*.

Mack, M. & Spruijt, M.P.N. (2014). CFD dispersion investigation of CO_2 worst case scenarios including terrain and release effects. *Energy Procedia*, *10*.

Xing, J., Liu, Z., Huang, P., Feng, C., Zhou, Y., Zhang, D. & Wang, F. (2013). Experimental and numerical study of the dispersion of carbon dioxide plume. *J. Hazard Mater*, *40*(8).

Sklavounos, S. & Rigas, F. (2004). Validation of turbulence models in heavy gas dispersion over obstacles. *J. Hazard Mater*, *9*(20).

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An Assessment of Progress in the Implementation of the BWM Convention on Ships as an Important Element in Protecting Aquatic Ecosystems

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Abstract: The purpose of this study was to assess progress in the implementation of rules for the control and handling of ballast water and sediments, regulated by the International Convention on the Control and Handling of Ship Ballast Water and Sediments (BWM Convention). The survey was conducted in 2018-2019 among seafarers responsible for handling ballast tanks. Analysis of the survey data revealed that despite the introduction of water treatments, ballast water continues to be a vector for the transfer of non-native organisms. This is due to the low effectiveness of the methods used, and the fact that 8% of the respondents answered that no BWT systems were used on the ships they manage. Despite this, some seafarers (4.7%) indicated that increasing environmental awareness and adherence to BWM principles should result in improved protection of aquatic ecosystems. Therefore, the global problem concerning the transport of non-native organisms via ballast water has still not been solved effectively. In the near future, improved BWT systems should be introduced, which after proper training of the crew will act as a barrier to the transfer of non-native organisms in ballast water.

Keywords: ballast water, foreign species, BWM convention, ballast water treatment, sea transport

1. Introduction

The chemical composition of water is shaped by natural phenomena and, to a large extent, depends on the structure of the catchment area, soil and rock environment, and the level of pollution in the area of the water's origin (Pyłka-Gustowska 2000). The chemical composition has been significantly affected by the development of the economy and maritime transport. Aquatic and terrestrial areas used by port infrastructure to enable maritime transport are subject to a strong anthropogenic influence (Directive 2002/413/EC of 30 May 2002). The continuous flow of ships arriving and departing from many different environments provides a basis for the transmission of marine organisms in ballast tanks (David & Gollasch 2018, Gollasch & David 2019). These organisms have a major impact on the environment surrounding the ports which has led to many studies on the composition of species in the ships' ballast waters (Zvyagintsev & Selifonova 2010, Butron et al. 2011, Carney et al. 2011) and ballast water treatment systems (Albert et al. 2013). Under favourable environmental conditions, e.g. temperature, suitable substrate and salinity, non-native species transported in ballast water may establish and spread in the ecosystems surrounding the port where ballast water was exchanged (Ojaveer et al. 2016, Normant-Saremba et al. 2017, David et al. 2019, Gollasch & David 2019).

The problem of uncontrolled movement of aquatic organisms and pathogens from ballast water as a result of international maritime transport has resulted in the creation of the International Convention for the Control and Management of Ships' Ballast Water and Sediments (Rastegary 2017), or the Ballast Water Management convention. Drafted in 2004 under the supervision of the International Maritime Organisation (IMO), and ratified on the 8th of September 2016, the document became a legal instrument which covers all elements of international shipping (Rastegary 2017, David & Gollasch 2018, Gollasch & David 2019). According to the principles of the Convention, as of the 7th of September 2017, all shipowners who have ships designed or constructed to carry ballast water, are obliged to comply with it. Under the BWM regulations, ships are required to carry out an inspection on the basis of which they can receive an International Ballast Water Management Certificate and to have an approved Ballast Water Management Plan (BWMP) and a Ballast Water Record Book (BWRB) (International Convention for the Control and Management of Ships' Ballast Water and Sediments, Rahman 2017, Gollasch & David 2019, Kuroshi et al. 2019).

The BWM Convention also forced ship masters to remove ballast water at a distance of at least 370 km from the coast, to clean the ballast tanks more frequently and introduce various ballast water treatment systems. The water treatment systems recommended by IMO that meet the Convention's D-2 norm are based, among other things, on the use of UV radiation, filtration, water heating, biodegradation, and chemical disinfection, often working in combination with one another (BWM Convention, Kuroshi et al. 2019).

The aim of this work is to assess the progress in the implementation of the principles of Control and Management of Ships' ballast water and sediment regulated by the BWM Convention and the attitude of seafarers, who are responsible for managing the exchange of ballast water, towards the new regulations.

2. Material and Methods

This study was based on surveys used to collect information from seafarers active in various posts. The surveys were carried out in 2018 and 2019, with 2000 questionnaires in total handed to seafarers in charge of the management of ballast tanks and related work. This group of respondents was chosen due to the nature of their work on the ship which was related to the International Convention for the Control and Management of Ships' Ballast Water and Sediments. The study took into account only those questionnaires which included answers concerning ships with ballast tanks. After excluding documents not meeting the requirements, 1200 completed questionnaires were received. The questionnaire was divided into 2 parts. The first section concerned the current situation of the ships operation according to the type and size of ballast tanks, as well the Ships' region of operation in order to determine the significance of the ballast water problem. The second range of questions concerned seafarers' training and awareness of changes in legislation and the introduction of the International Convention for the Control and Management of Ships' Ballast Water and Sediments and their knowledge of potentially harmful organisms carried in ballast water (Appendix 1). The design of the survey also allowed for an examination of the seafarers' opinions and attitudes (such as their hopes and fears regarding the effectiveness of the introduced ballast water treatment solutions) to the new rules for the Control and Management of Ships' ballast water and sediments.

3. Results

3.1. Characteristics of the ships surveyed in terms of their use

The questionnaires were received from respondents who indicated that under the last three contracts they managed primarily seven types of ship, 50% of which were ships under 100 meters in length (600 ships), 33% were ships between 100 and 200 meters in length and 17% were ships over 200 meters (Fig. 1). The majority of the seafarers worked on ships operating exclusively in European areas (58% of all ships, including 600 ships under 100 metres and 96 ships between 100 and 200 metres long). In contrast, only 100 ships operated on the Europe-Asia-Africa-America route (10%) and 404 ships (32%) operated worldwide. Comparing the route of ships with the capacity of their ballast tanks, ships sailing exclusively in Europe accounted for as much as 71% of ships with ballast tanks no bigger than 5,000 m^3. On the other hand, ships sailing on routes between Europe and America, Europe and Africa or Europe and Asia had tanks between 5,000 m^3 and 20,000 m^3. In the case of ships sailing all over the world, the majority of them (as much as 90% of them) were ships with ballast tanks exceeding 20,000 m^3 (Fig. 2).

The results of the surveys showed that the larger the vessel is, the larger the ballast tanks are, which may lead to the increased number of non-native organisms being transported in ballast water.

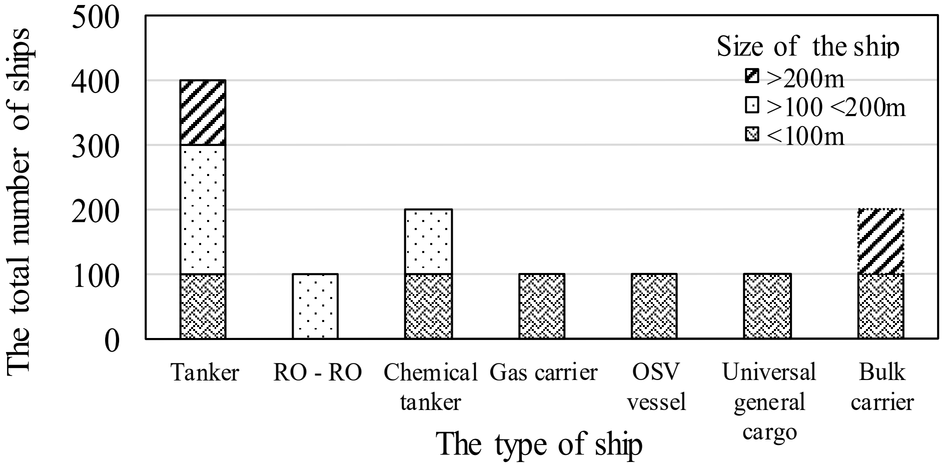

Fig. 1. Characteristics of the vessels mentioned in the survey in terms of type and length

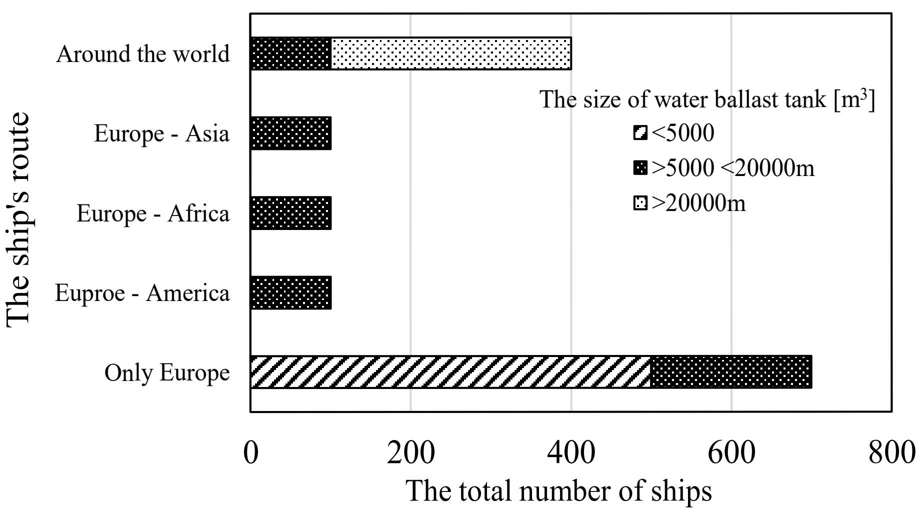

Fig. 2. Characteristics of the vessels mentioned in the survey in terms of routes and ballast tank volume

3.2. Assessment of seafarers' awareness of changes in legislation under theInternational Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention)

As many as 15% of the seafarers surveyed were not familiar with the recommendations of the International Convention for the Control and Management of Ships' Ballast Water and Sediments. The group of respondents who did not attempt to learn the BWM (Ballast Water Management) principles, in force since September 2017, were made up of seafarers who were not in charge of water treatment management (most often a seaman or a third officer). At the same time, half of all respondents negatively commented on the introduction of additional recommendations with regard to the control and management of the vessel's ballast water and sediments. As many as 20% of the 1200 respondents were not adequately trained for the proper treatment of ballast water and its sediments or were not sure whether they had received such training. Of all the seafarers who were familiar with the BWM rules, as much as 90% considered the threat of non-native species being transferred to new areas as still apparent. In the multiple choice question, they most frequently indicated that the threats to new habitats from ballast tanks were microorganisms (83%),_shellfish (66%), protozoa (50%) and parasites (50%). On the other hand, 10% of the same group of respondents stated that with the correct operation of the ballast water treatment method (BWT), the waters from ballast tanks do not pose a threat in terms of the transmission of non-indigenous aquatic species (Fig. 3).

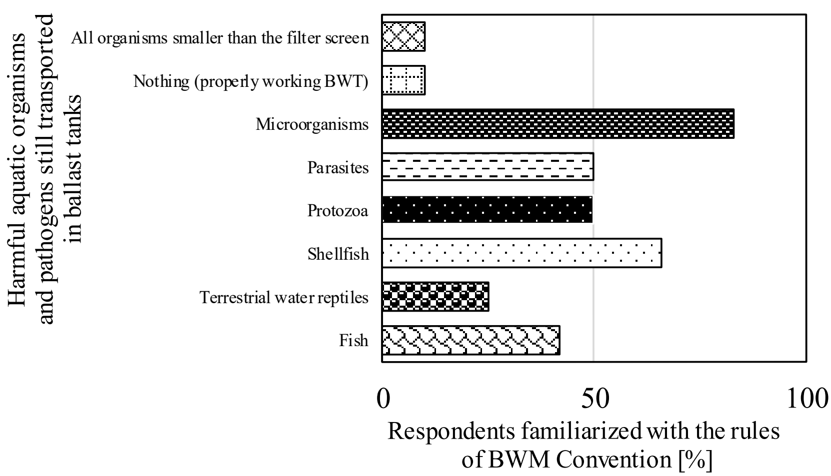

Fig. 3. Potentially harmful groups of aquatic organisms and pathogens transported in ballast tanks in the opinion of the surveyed seafarers familiar with the BWM Convention rules

When asked (a multiple choice question) about the time and place of changing the water in the ballast tanks, the surveyed seafarers most often indicated ports (50%), open waters (41.7%) and at the time of unloading (41.7%). At the same time, only 8.3% indicated places specially designated by the administration (e.g. Norway has specially designated areas where ballast water should be changed before it is emptied in a Norwegian port). In the respondents' answers to the question about the applied methods of ballast water treatment before its release, mixed systems which combine mechanical and chemical processes were mentioned most often (42%), biological and physical methods were indicated much less frequently (17% each) and only 8% of the respondents indicated an answer suggesting no treatment of ballast water (Fig. 4).

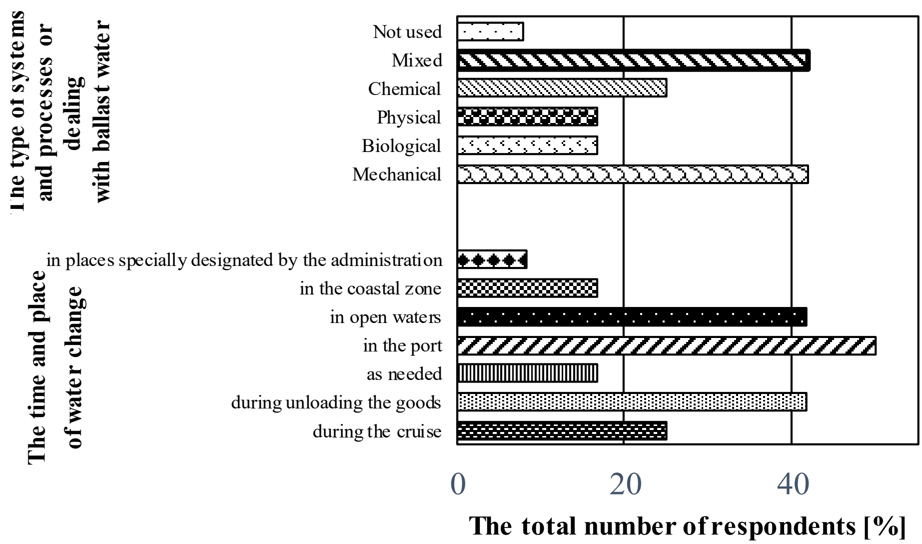

Fig. 4. Responses of respondents concerning treatment systems and processes and the place and time of ballast water exchange

3.3. Seafarers' hopes and concerns about the requirements of the BWM Convention

Out of 1,200 respondents, 600 did see a chance for the complete elimination of the transfer of harmful aquatic organisms and pathogens by using appropriate ballast water treatment systems (Fig. 5).

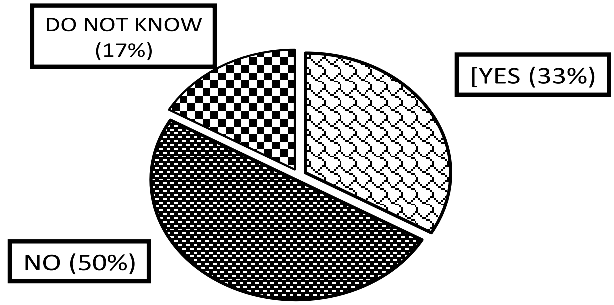

Fig. 5. Responses concerning the chance for complete elimination of the transfer of harmful aquatic organisms and pathogens with ballast water

Considering possible problems with the application of the new ballast water rules, as much as 40% of all seafarers were concerned about the increased number of duties by insufficiently trained crew. Almost as much as 35% declared the possibility of bypassing the regulations due to the overly complicated operation of ballast water treatment systems. 17% of respondents indicated economic issues, the long time needed to adjust ships to the new requirements, and additional problems during inspections as main concerns (Fig. 6).

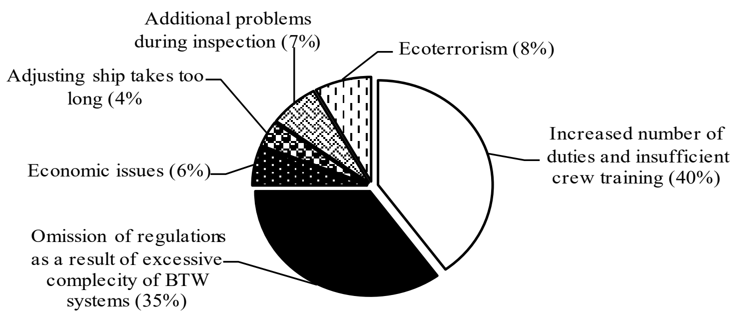

Fig. 6. Seafarers' concerns about the possibility of problematic situations arising from the introduction of new restrictions under the BWM Convention

A large group of respondents (80%) expressed confidence in the provisions for permanent prevention and final elimination of the transmission of harmful aquatic organisms and pathogens (Fig. 7). Some seafarers indicate that increasing environmental awareness and compliance with the BWM principles will lead to improved protection of aquatic ecosystems. However, as many as 33% of seafarers do not see any positive aspects in the introduction of new regulations in ballast water management (Fig. 7).

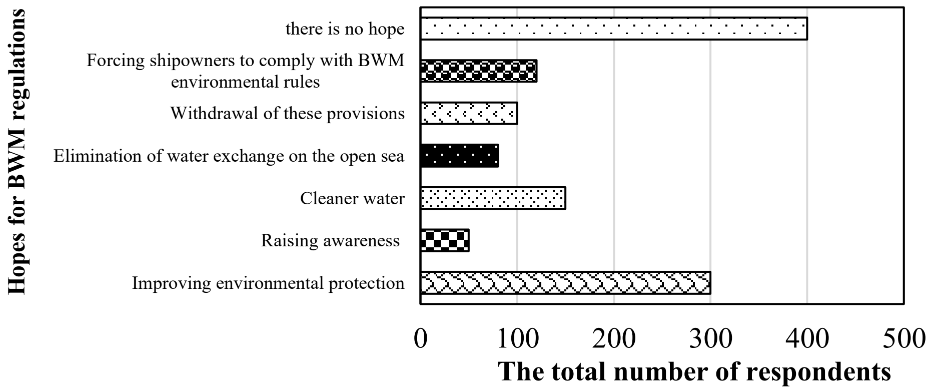

Fig. 7. Hopes of seafarers associated with the introduction of new restrictions on board the ship in accordance with the BWM Convention

4. Discussion

Globally, legislative work on regulations for the management of Ships' ballast water has been forced by the growing problem of non-native species being transported to new environments (Directive 2002/413/EC of 30 May 2002, HELCOM, International Convention for the Control and Management of Ships' Ballast Water and Sediment). According to information collected by HELCOM, 118 non-native species have been introduced into the Baltic Sea in the last 100 years (Fig. 8). Of these, as many as 90 have settled there permanently (HELCOM List of non-indigenous and cryptogenic species in the Baltic Sea).

This problem is not unique to the Baltic Sea, since as many as 7,000 species (Carlton 1999) are transferred in this way between ports around the globe. In the neighboring North Sea, as many as 150 non-native aquatic animal species have been identified (Gollasch et al. 2009), making it an area highly affected by the introduction of non-native species (Vila et al. 2010). It should be noted that the ports in the Baltic and North Sea are intensely connected via international maritime traffic, which may enhance the transfer and easy acclimatization of non-native species. However, the problem of ballast water transfer of allochthonous organisms does not only affect European ports, but also ports across the entire world (Ng et al. 2015, Kim et al. 2016, Kiu & Hall 2018, Li et al. 2018). That is why the problem of microorganisms that migrate to new environments in this way has been increasingly often researched (Atlung et al. 2012, Delacroix et al. 2013, Ziegler et al. 2018, Hess-Erga et al. 2019, Petersen et al. 2019).

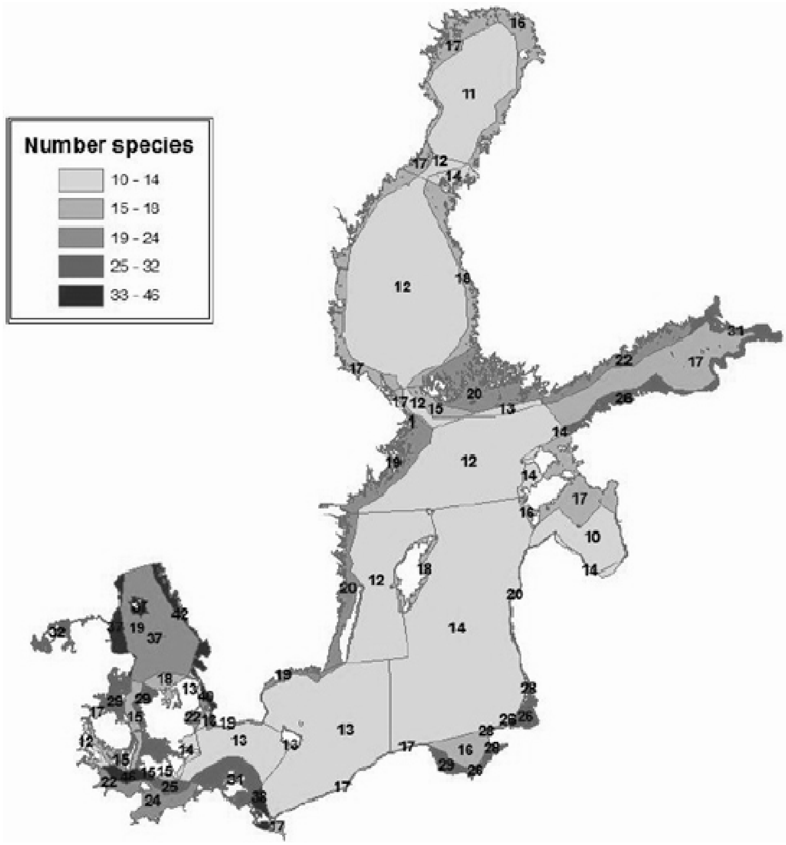

Fig. 8. Number of observed non-indigenous species in the Baltic Sea coastal and offshore areas. Source: HELCOM List of non-indigenous and cryptogenic species in the Baltic Sea

It is difficult to unequivocally determine the distribution of the populations of non-native animals carried by individual vessels. The abundance of organisms in the ballast water of ships sailing between the same ports varies depending on the season, the presence of organisms in the vicinity of the ship, and the security measures used on the ship (Golasch et al. 2000). In addition, different species have different tolerances to ballast tank conditions. Some can survive in ballast tanks for several days (Flagella et al. 2007) and therefore can be relocated to ports in close proximity to the point of departure. According to Carlton (1999), short-range vessels are a major vector for the transfer of non-native organisms. Some of these organisms, due to their shorter routes, may become invasive in marine and estuarine habitats, with negative ecological, economic and human health impacts (Anil et al. 2002) and effects on biodiversity and ecosystem services (Stachowicz et al. 2007). However, long-range vessels do not pose less of a threat to the transfer of allochthonous organisms to new environments. Although most of them are not able to survive long voyage times, those that manage to adapt to the adverse conditions in ballast tanks (especially microorganisms of unknown potential) become resistant and increase their survival capacity. Such adaptability may pose a much greater threat in terms of gaining the capacity to facilitate invasions than the mere transfer of non-native yet non-invasive organisms to new ecosystems (Gollasch et al. 2000, Gollash et al. 2009, Ng et al. 2015, Kim et al. 2016, Hess-Erga 2019). This situation makes ship passage routes a key element in combating the problem of transferring organisms to new ecosystems.

The problem related to the transport of non-native organisms with ballast water has still not been successfully resolved despite numerous studies on their appearance and ecology in new areas (Gollasch 2006, Czerniejewski & Filipiak 2001, Bauer & Woog 2008, Alexandrowicz & Alexandrowicz 2010, Brandorff 2011, Burton et al. 2011, David et al. 2019, Gollasch & David 2019). This is indirectly confirmed by the results of our survey, which shows that half of the respondents not only did not see a chance to eliminate the transmission of harmful aquatic organisms via ballast tanks, but as many as 40% of all seafarers are afraid of the increased number of duties associated with the operation of BWT systems which have to be performed by undertrained crew members.

The introduction of regulations for the control and proper handling of ship ballast water and its sediments has resulted in various types of ballast water treatment systems. According to the BWM Convention, these processes are procedures, activities and mechanisms designed to reduce or eliminate, in whole or in part, the risks associated with the carriage of non-indigenous species in ship ballast water. Those processes that have been approved and permitted under regulations D-2 and D-3 of that Convention can be divided into physical and chemical. The physical methods of ballast water treatment include water filtration, ultraviolet light irradiation, ultrasonic wave action, and circulation based on the ballast transfer process, during which the volume of water pumped through the tank should be at least three times the tank volume (Misorz 2017). However, pumping through less than three times the volume may be accepted provided the ship can demonstrate that at least 95 per cent volumetric exchange is met (Resolution MEPC.173(58)). The BWM Convention stipulates that ballast water exchange should be carried out by sequential, flow-through or dilution methods. On the other hand, chemical methods for ballast water treatment include disinfection processes that require the use of chemicals or biocides, e.g., chlorination, ozonation, chemical removal of sulfites and bisulfites (Misorz 2017, Hess-Erga 2019, Jung et al. 2020).

Continuous work on improvement of ballast water treatment processes as a consequence of eliminating undesirable aquatic organisms and pathogens have resulted in the creation of various BWT systems (Rahman 2017, David & Gollasch 2018, Gerhard et al. 2019, Kuroshi et al. 2019). According to the surveys, the commonly used ballast water treatment processes are mechanical, biological, physical and chemical, most often used in combination. In addition to those mentioned in the survey, other systems are used worldwide, such as UV lamps, filtration, ballast water heating, deoxidation and ozonisation (Rahman 2017, David & Gollasch 2018, Wan et al. 2018, Gerhard et al. 2019, Gollasch et al. 2019, Kuroshi et al. 2019).

However, according to Gollach and David (2019), and as confirmed by our survey, none of the systems are fully effective, as viable organisms still appear in the ballast water. Moreover, respondents indicated that in 8% of cases no BWT systems are used on their ships. Furthermore, Drillet et al. (2016) believe that the standards for the efficient operation of these systems include testing only for selected indicator organisms (e.g. pathogenic microorganisms), which is insufficient to create a full characterisation of the burden to the aquatic environment. This problem was examined by Hess-Erga et al. (2019), who correctly pointed out the lack of effectiveness of single ballast water treatment systems in the face of the diversity of organisms living in the tanks. Legal guidelines for ballast water treatment omit organisms smaller than 10 μm, which creates the risk of a lack of control of the unpredictable presence of harmful microorganisms. Most ballast water treatment systems in use utilize mechanical separation or filtration followed by a combination of chemical or physical post-treatment of tank water. Unfortunately, the common use of electrochemical or UV treatment in such conditions is hampered by the varying environment of ballast tanks and organic biocompounds. Hess-Erga et al. point out that insufficient inactivation of this group of organisms inhabiting ballast tanks could lead to potentially dangerous ecological consequences, where the success of invasive species may be aided by the microbial community that enters new environments with them. Therefore, they point out the need for intensified research on microbial invasion patterns in terms of their impact on ecosystems. Jung et al. (2020) also noted that validated BWT have failed to treat ballast water with a high density of organic matter. They also pointed out that for such ballast water, it is recommended to filter the water from the tanks during de-ballasting rather than vessel ballasting. In addition, they argue that ballast water should be re-treated when stored for long periods of time, due to the presence of high concentrations of suspended particles, which provide a specific medium for the growth of microorganisms colonizing ballast tanks. Jung et al. (2020) also draw attention to the need for regular training of the crew of ships that are equipped with ballast water treatment systems. Mere introduction of new regulations will not be sufficient if the crew is not fully prepared for the proper use of BWTs and, consequently, will not be able to carry out their proper operation and maintenance.

Another reason for the introduction of non-native species, in addition to the inefficiency of ballast water treatment systems, is the poor knowledge of BWM principles among seafarers (Rahman 2017, Wan et al. 2018, Gerhard et al. 2019, Golasch & David 2019). In our survey as much as 15% of seafarers declared no knowledge of BWM principles. For 85%, new regulations raised concerns. Equally important is the economic situation of shipowners obliged to decide which ballast water treatment systems will be most suitable for use in their ships (Tan 2015, Olenin et al. 2016, Wan et al. 2018, Gerhard et al. 2019). Many of the respondents noted that the most frequently installed BWT systems are of poor quality and prone to failure. These failures are not only due to the way the ballast water systems are constructed but also by dependence on the human factor. The results of the received questionnaires indicate that in many cases the principles of controlling and managing ships' ballast water and sediments are disregarded, which the respondents justified by the lack of readiness to implement such regulations. In addition, although the relevant bodies are required to manage the environmental programme under the BWM Convention, many seafarers complain about the lack of harmonisation of current national legislative restrictions (Verna & Harris 2016, Cohen et al. 2017, Gerhard & Gunscha 2018, Liu et al. 2019, Rak et al. 2019). Albert et al. (2013) indicate that the regulations established by the International Maritime Organisation (IMO) have not led to the unification of ballast water management standards and have even resulted in the establishment of completely different guidelines for individual countries. Similar suggestions were made by Gerhard et al. (2018) on the basis of legal regulations in the USA and Australia. Drillet et al. (2016) notes, in turn, that despite careful testing of the ballast water treatment systems (BWTS), it is not possible to ensure their effective operation at any given time for every type of water in the tanks. These problems are compounded by the fact that some seafarers prefer not to comply with the complex BWT rules by declaring that they are not familiar with the legislation in force today. Only respondents in the highest positions admitted that they pay special attention to all the work required of them concerning control and Management of Ships' ballast water and sediment.

5. Conclusions

The introduction of new legal standards such as the International Convention on the Control and Management of Ballast Water and Sediments represents a great opportunity for the protection of aquatic environments from non-native organisms. Adherence to these regulations may preserve the biodiversity of many ecosystems. Unfortunately, saving aquatic habitats is only possible if BWT systems meet minimum efficiency standards. Additionally, it is critical to ensure more precise training of crews who are to manage ballast water treatment systems.

Based on the obtained results of our survey, the vast majority of surveyed seafarers (85% of all respondents) knew the requirements of the International Convention for the Control and Management of Ships' Ballast Water and Sediments. However, this does not mean that they understand this legislative direction. Unfortunately, based on the survey data, a large proportion of the ships' crews (33%) were not convinced about the merits of improving the provisions on ballast water treatment. According to our respondents, it results in the introduction of overly complex and faulty BWM systems in the equipment of ships. Their concerns relate to the inadequate training of seafarers responsible for these systems and also burdensome additional inspections and other new obligations. On the other hand, seafarers in charge of the ballast water treatment systems see BWM regulations as a chance for improving the protection of the aquatic environment and progressively improving the process of ballast water exchange. Unfortunately, if seafarers are still not adequately informed and trained in terms of the requirements of BWT systems and the development of an effective system for the elimination of organisms carried in the ballast water, then despite the introduction of new regulations, the transport of non-native organisms in the ballast water of ships may still have a significant negative impact on the ecological status of aquatic ecosystems.

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References

Albert, R. J., Lishman, J. M., Saxena, J. R. (2013). Ballast water regulations and the move toward concentration-based numeric discharge limits. *Ecol. Appl., 23*(2), 289-300.

Alexandrowicz, W. P., Alexandrowicz, S. W. (2010). *Expansive migrations of molluscus during the historic period*. [W:] Mirek Z. (red.) Biological invasions in Poland. Wydawnictwo Instytutu Botaniki im. W. Szafera PAN w Krakowie 1: 23-48.

Altug, G., Gurun, S., Cardak, M., Ciftci, P. S., Kalkan, S. (2012). The occurrence of pathogenic bacteria in some ships' ballast water incoming fromvarious marine regions to the Sea of Marmara, Turkey. *Marine Environmental Research, 81,* 35-42.

Anil, A. C., Venkat, K., Sawant ,S. S., Dileep, Kumar ,M., Dhargalkar, V. K., Ramaiah, N., Harkantra, S. N., Ansari, Z. A. (2002). Marine bioinvasion: Concern for ecology and shipping. *Current Science, 83*, 214-218.

Bauer, H. G., Woog, F. (2008). Nichtheimische Vogelarten (Neozoen) in Deutschland. Teil I: Auftreten, Bestände und Status. *Vogelwate 46,* 157-194.

Brandorff, G. (2011). The copepod invader *Skistodiaptomus pallidus* (Herrick, 1879) (*Crustacea, Copepoda, Diaptomidae*) from North America in water bodies of Bremen, northern Germany. Aquatic Invasions 6.

Butron, A., Orive, E., Madariaga, I. (2011). Potential risk of harmful algae transport by ballast walters: the case of Bilbao Harbour. *Marine Pollution Bulletin 62,* 747-757.

Carlton, J. T. (1999). *The scale and ecological consequences of biological invasions in the world's oceans*. InInvasive species and biodiversity management, ed. O. T. Sandlund, P. J. Schei and A Viken,195-212. Dordrecht: Kluwer Academic Publishers.

Carney, K. J., Delany, J. E., Sawant, S., Mesbahi, E. (2011). The effects of prolonged darkness on temperate and tropical marine phytoplankton, and their implications for ballast water risk management. *Marine Pollution Bulletin, 62,* 1233-1244.

Cohen, A. N., Dobbs, F. C., Chapman, P.M. (2017). Revisiting the basis for US ballast water regulations. *Marine Pollution Bulletin, 118,* 348-353.

Czerniejewski, P., Filipiak, J. (2001). Krab wełnistoszczypcy (*Eriocheir sinensis Milne* – Edwards 1853) z Zalewu Szczecińskiego. Komunikaty Rybackie 60 (1): 28-31.

David, M., Gollasch, S. (2018). How to approach ballast water management in European seas. *Estuarine, Coastal and Shelf Science, 201*, 248-255.

David, M., Mageletti, E., Kraus, R., Marini, M. (2019). Vulnerability to bioinvasions: Current status, risk assessment and management of ballast water through a regional approach – the Adriatic Sea. *Marine Pollution Bulletin, 147*, 1-7.

Delacroix, S., Vogelsang, C., Tobiesen, A., Liltved, H. (2013). Disinfection by-products and ecotoxicity of ballast water after oxidative treatment – results and experiences from seven years of full-scale testing of ballast water management systems. *Mar. Pollut. Bull., 73,* 24-36. DOI: https://doi.org/10.1016/j.marpolbul.2013.06.014.

Drillet, G., Wisz, M. S., Lemaire-Lyons, Y. L. B., Baumler, R., Ojaveer, H., Bondad-Reantaso, M. G., Xu, J., Alday-Sanz, V., Saunders, J., McOwen, C. J., Eikaas, H. (2016). Protect aquaculture from ship pathogens. *Nature, 539*.

Flagella, M. M., Verlaque, M., Soria, A., Buia, M. C. (2007). Macroalgal survival in ballast watertanks. *Marine Pollution Bulletin, 54*, 1395-1401.

Gerhard, W. A., Gunscha, C. K. (2018). Analyzing trends in ballasting behavior of vessels arriving to the United States from 2004 to 2017. *Marine Pollution Bulletin, 135*, 525-533.

Gerhard, W. A., Lundgreenb, K., Drilletc, G., Baumlerd, R., Holbechb, H., Gunscha, C. K. (2019). Installation and use of ballast water treatment systems – Implications for compliance and enforcement. *Ocean and Coastal Management, 181*, 104907.

Gollasch, S., Rosenthal, H., Botnen, H., Hamer, J., Laing, I., Leppäkoski, E., Macdonald, E., Minchin, D., Nauke, M., Olenin, S., Utting, S., Voigt, M., Wallentinus, I. (2000). Fluctuations of zooplanktontaxa in ballast water during short-term and long-term ocean-going voyages. *International Review of Hydrobiology, 85,* 597-608.

Gollasch, S. (2006). Overview on Introduced Aquatic Species in European Navigational and Adjacent Waters. *Helgoland Marine Research, 60*, 84-89.

Gollasch, S., Haydar, D., Minchin, D., Wolff, W. J., Reise, K. (2009). *Introduced aquatic species ofthe North Sea coasts and adjacent brackish waters*. In Biological invasions in marine ecosystems: Ecological, management, and geographic perspectives, Ecological Studies 204, ed. G. Rilov and J. A.Crooks, 507-528. Berlin/Heidelberg: Springer-Verlag.

Gollasch, S., David, M. (2019). Chapter 13 – Ballast Water: Problems and Management [in:] World Seas: an Environmental Evaluation (Second Edition) Vol. III: Ecological Issues and Environmental Impacts; 237-250.

HELCOM. Source: http://www.helcom.fi/about-us/internal-rules/rules-of-procedure.

HELCOM List of non-indigenous and cryptogenic species in the Baltic Sea. Source: http://www.helcom.fi/Lists/Publications/Report%20on%20observed%20non-indigenous%20and%20cryptogenic%20species%20in%20the%20Baltic%20Sea.pdf

Hess-Erga, O. K., Moreno-Andrés, J., Enger, Ø., Vadstein, O. (2019). Microorganisms in ballastwater: Disinfection, community dynamics, and implications for management. *Science of the Total Environment, 657*, 704-716.

Jung, P. G., Hyun, B., Shin, K. (2020). Ballast Water Treatment Performance Evaluation under Real Changing Conditions. *J. Mar. Sci. Eng. 8*, 0817. DOI: 10.3390/jmse8100817

Kim, Y., Aw, T. G., Rose, J. B. (2016). Transporting ocean viromes: invasion of the aquatic biosphere. *PLoS One 11*, 1-18. DOI: https://doi.org/10.1371/journal.pone.0152671

Kiu, R., Hall, L.J. (2018). An update on the human and animal enteric pathogen Clostridium perfringens. *Emerging Microbes and Infections, 7*(141), 1-15. DOI: 10.1038/s41426-018-0144-8

Kuroshi, L., Òlçer, A. I., Kitada, M. (2019). A tripartite approach to operator-error evaluation in ballast water management system operation. *International Journal of Industrial Ergonomics, 69*, 173-183.

Li, C., Liu, B., Zhou, J., Wang, Z., Jiang, N. (2012). Investigation on bacterial diversity of ballast water from Ninbo port, China. *Ecological Science, 31*(6), 636-644.

Liu, T. K, Wang, Y., Ch., Su, P.H. (2019). Implementing the ballast water management convention: Taiwan's experience and challenges in the early stage. *Marine Policy 109,* 1-8.

Międzynarodowa Konwencja o Kontroli i Postępowaniu ze Statkowymi Wodami Balastowymi i Osadami z dn. 16 lutego 2004r. Source: http://library.arcticportal.org/1913/1/International%20Convention%20for%20the%20Control%20and%20Management%20of%20Ships%27%20Ballast%20Water%20and%20Sediments.pdf.

Misorz, T. (2017). Postępowanie z wodami balastowymi na statkach w żegludze międzynarodowej w świetle Konwencji BWM 2004. Prace Wydziału Nawigacyjnego Akademii Morskiej w Gdyni 32; 59-71, DOI: 10.12716/1002.32.05 (in Polish).

Ng, C., Le, T. H., Goh, S. G., Liang, L., Kim, Y., Rose, J. B., et al. (2015). A Comparison of Microbial Water Quality and Diversity for Ballast and Tropical Harbor Waters. *PLoS ONE 10*(11); e0143123. DOI: 10.1371/journal.pone.0143123

Normant-Saremba, M., Marszewska, L., Kerckhof, F. (2017). First record of the North American amphipod *Melita nitida* Smith, 1873 in Polish coastal waters. *Oceanological and Hydrobiological Studies, 46*(1), 108-115.

Petersen, N. B., Madsen, T., Glaring, M. A., Dobbs, F. C., Jørgensen, N. O. (2019). Ballast water treatment and bacteria: Analysis of bacterial activity and diversity after treatment of simulated ballast water by electrochlorination and UV exposure. *Sci Total Environ., 648*, 408-421

Pyłka-Gustowska, E. (2000). *Ekologia z ochroną środowiska*. Przewodnik. Wydawnictwo Oświata. Wydanie IV. Warszawa (in Polish).

Rahman, S. (2017). Implementation of Ballast Water Management Plan in Ships Through Ballast Water Exchange System. *Procedia Engineering, 194,* 323-329.

Rak, G., Zec, D., Markovčić, Kostelac, M, Joksimović, D., Gollasch, S., David, M. (2019). The implementation of the ballast water management convention in the Adriatic Sea through States' cooperation: The contribution of environmental law and institutions. *Marine Pollution Bulletin, 147*, 245-253.

Rastegary, M. (2017). The Ballast Water Management Convention and its Impacts on the Shipping Industry. *Payam Darya, 5*, 40-59.

Resolution MEPC.124(53). Guidelines for ballast water exchange (G6).

Stachowicz, J. J., Bruno, J. F., Duffy, J. E. (2007). Understanding the effects of marine biodiversityon communities and ecosystems. *Annual Review of Ecology, Evolution and Systematics, 38*, 739-766.

Tan, J. (2015). *Latest Update on the Ballast Water Management Convention 2004*. Legal Briefing, UK P&I CLUB.

Wan, Z., Chen, J., Sperling, D. (2018). Institutional barriers to the development of a comprehensive ballast-water management scheme in China: perspective from a multi-stream policy model. *Mar. Policy, 91*, 142-149.

Verna, D. E., Harris, B. P. (2016). Review of ballast water management policy and associated implications for Alaska. *Marine Policy, 70,* 13-21.

Vila, M., Basnou, C., Pysek, P., Josefsson, M., Genovesi, P., Gollasch, S., Nentwig, W., Olenin, S., Roques, A., Roy, D., Hulmes, P. E., DAISIE partners. (2010). How well do we understand the impacts of alien species on ecosystem services? A pan-European, cross-taxa assessment. *Frontiers in Ecology and the Environment, 8*, 135-144.

Ziegler, G., Tamburri, M. N., Fisher, D. J. (2018). Long-term algal toxicity of oxidant treated ballast water. *Mar. Pollut. Bull., 133*, 18-29 DOI: https://doi.org/10.1016/J.MARPOLBUL.2018.05.013.

Zvyagintsev, A. Y., Selifonova, J. P. (2010). Hydrobiological studies of the ballast waters of cargo chips in Russian sea ports. *Oceanology, 50*, 932-942.

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Heavy Metal Emissions from Linear Sources and Polluted Soil in The Capital City of Poland

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Abstract: Human activities such as transport contribute to the environmental degradation. Therefore, the aim of the study was to determine the level of contamination of soils, from different districts of big cities of central Europe, with heavy metals: zinc, lead, and nickel. The samples were taken from the top, sodded soil layer. Each single sample weigh was about 1 kg taken from 1 m^2 measuring station. Soil samples were dried at room temperature. The airborne dry soil was thoroughly mixed and sieved through a 1 mm nylon sieve. The study included analysis of which type of metals is washed out under the influence of abiotic factors (bioavailable forms) and demonstrating how spatial development affects the accumulation of selected heavy metals in the soil. The results indicated that heavy metals emitted to the ground layer of the atmosphere accumulate in the immediate vicinity of communication routes. Moreover, based on the analysis of interrelationships of zinc, lead, and nickel concentrations, it has been shown that there is a common source of their emission to soil. Furthermore, the thesis that the concentration of metals was dependent on the soil reaction was not confirmed.

Keywords: soil degradation; heavy metals contamination; zinc, lead and nickel contamination

1. Introduction

The constant development of urban agglomerations impose protection of natural environmental surrounding this area by improving the soil's condition, polluted from different sources, e.g. washing the soil with rainwater rich with heavy metals (Piecuch et al. 2015, Polanczyk et al. 2018, Peng et al. 2020). Soils are contaminated with various chemical compounds, e.g. atmospheric dust, sewage runoff, waste dumps, industrial settlers as well as waste sediments, sewage and liming of soils (Nathanail and Bardos 2004, Polanczyk et al. 2018). Urban soils accumulate pollution from many local sources, that have the potential to migrate inside soil (Pierzynski et al. 2005, Zieminska-Stolarska et al. 2015). The form of soil's contamination is strongly dependent on the source of emissions, the physical and chemical properties of soils, the amount and quality of colloids in soils, the pH, sorption properties, as well as the soil redox potential (Liu et al. 2019, Polanczyk et al. 2019). Drinking water resources should be particularly protected against the penetration of pollutants (Czapczuk et al. 2017).

Depending on the climatic conditions and the character of terrain, dust and aerosol particles can be transported by wind over long distances and then get into the soil in the form of dry precipitation, with rainfall, snowfall, and surface runoff. According to Kabaty-Pendias (Ebrahimi-Najafabadi et al. 2019) research, in Poland during the year falls: cadmium – 5 g/ha/year, copper – 39 g/ha/year, lead – 200 g/ha/year, zinc – 540 g/ha/year. For example, precipitation dust in Krakow consists mainly of fine particles of silicate enamel, sulphate calcium and iron oxides. Whereas tests of heavy metal content in precipitation dust carried out in residential and industrial districts of Lublin showed that the maximum concentrations of selected heavy metals were in: zinc – 3154 ppm, manganese – 2479 ppm, copper – 612 ppm, lead – 479 ppm and nickel – 132 ppm (Vehicles 2004). Concentration of heavy metals in rainwater is a sensitive indicator of atmospheric air pollution and is strongly correlated with dust pollution. Street dust is relatively rich in lead and other heavy metals. The lead content of Zurich's street dust is 2000 ppm, which is more than 20 times higher than the natural value (Zhang et al. 2019). Equally high concentrations of selected heavy metals were observed in precipitation dust collected along the Lazienkowska street in Warsaw. Lead aerosol, expelled from the exhaust system of vehicles, moves along with the air currents falling to the areas adjacent to the motorway traffic routes, the significant range of this precipitation is about 100 m. The movement of lead compounds from linear emission sources, which are communication routes, is forced mainly through air mass movements. Metals generated when burning gasoline are stable for 4 up to 7 days and then transform into less soluble forms such as sulfates, carbonates, phosphates and oxides (Pernille et al. 2006, Guan et al. 2018). The process of converting halogenated lead into insoluble forms strongly depends on climatic conditions. Despite restrictions on the use of heavy metal compounds in fuels, the greatest risk of soil pollution with heavy metals still comes from motor vehicles. The specificity of this threat is the banded arrangement of polluted areas. The content of heavy metals in soils adjacent to communication routes, parking areas as well as distance from the road (Martínez 2001). The level of the negative impact of road transport on the quality of the urban environment depends on the following factors: the number of vehicles, vehicle structure, speed, technical condition of the vehicle, the quality of fuel, traffic appearance as well as road quality. The source of lead compounds' emission are fuels. The introduction of lead tetraethyl and tetramethyl lead as a means of increasing octane number has caused that communication routes have become the main source of this metals (Zhao et al. 2019). Data in the literature indicate that communication sources account for 50 to 75% of lead emissions in urban areas (Backstrom et al. 2003). Despite the withdrawal from sales with the beginning of universal petrol replacing lead and restrictions to 0.005 mg/l at the producer and 0.013 mg/l at the distributor of lead compounds, there was no drastic decrease in the content of lead in soils. The reason for this is that the accumulation of metal in earlier years was so great that even limiting its content in fuel, did not cause a significant decrease its concentration in soil. In addition, lead-fueled cars, despite the change in gasoline used, contain in the engine installation residues of lead compounds accumulated in engine oils, lubricants and others (Ebrahimi-Najafabadi et al. 2019). The battery electrodes contain lead, zinc, iron, nickel, or cadmium. Lubricating oils contain heavy metals as well as oxidation and thermal decomposition products of oil and fuel. Zinc, calcium, lead, and magnesium oxides are used as additives to accelerate the vulcanization process of tires. For example, zinc oxide has been detected in the tire tread in an amount of 1-2%. When the tires wear off, it gets into the environment, thus increasing the level of zinc up to several hundred mg/kg in soils along roads (Öborn & Linde 2001). Corrosion of vehicle parts contributes to soil pollution with dust containing substances used to manufacture these parts. Traces of elements such as vanadium, nickel, iron, magnesium and others are also present in bitumens (Ashayeri & Keshavarzi 2019).

Therefore, the aim of the study was to determine the level of contamination of soils, from different districts of big city of central Europe, with heavy metals: zinc, lead, and nickel. In the introduction chapter analyzed problem was described. In the methodology the samples, applied devices and area of sample collecting was described. Finally, the results were presented in the results chapter and concluded in conclusion chapter.

2. Materials and methods

2.1. Characterization of the analyzed urban area

In the area of central Warsaw seven points for sample collection were chosen (Fig. 1). 1 – South Praga, Przyczółek Grochowski, al. The United States; a green belt between traffic lanes over the Gocławski Canal; From the north – allotments; from the south – Gocławskie Lake with adjacent green areas and newly built apartment blocks. Six-lane roadway. 2 – Center, Łazienki Królewskie near the Łazienki Ponds; From the east – Łazienki Ponds, park area. 3 – Mokotow, al. Independence at the height of the National Library; a green belt between the track and the lane; Buildings a few hundred meters from the road, park area. Six-lane road, track, bus stop. 4 – Center, intersection of Solidarnosci al. with Andersa street and Square Banking; Urban buildings, compact. The intersection of an eight-lane roadway with a six-lane roadway; track crossing; subway. 5 – Ochota, Wawelska street, approximately 50 m from the intersection with Grojecka street and approx. 100 m from the Aviator Monument; green belt between traffic lanes; Urban buildings, compact. Six-lane roadway. 6 – Ochota, Wawelska street, approximately 50 m from the intersection with Grojecka street and approx. 100 m from the Aviator Monument; the area behind compact buildings adjacent to Wawelska street. A green area between residential buildings, adjacent to a car park intended for residents. 7 – Downtown, Saxon Garden, central part; park area. Samples from measuring points 2 and 7 were taken to determine the geochemical background of the elements studied. Three conscript series were made: in March, April and May 2019.

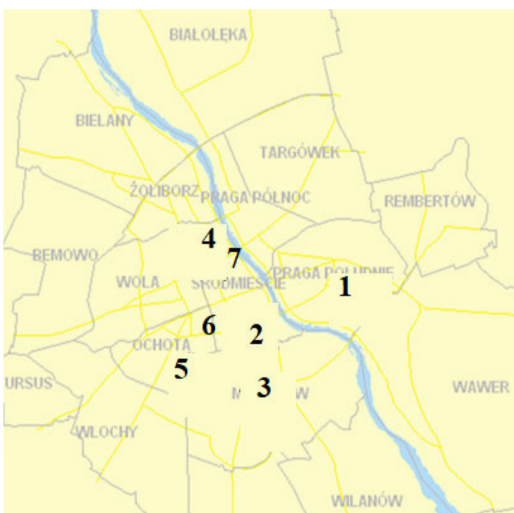

Fig. 1. Sampling points

Fig. 2a shows the collection point no. 2 and Fig. 2b its vicinity, i.e. Lazienkowska Route. On the other hand Fig. 3 shows the collection point no. 7.

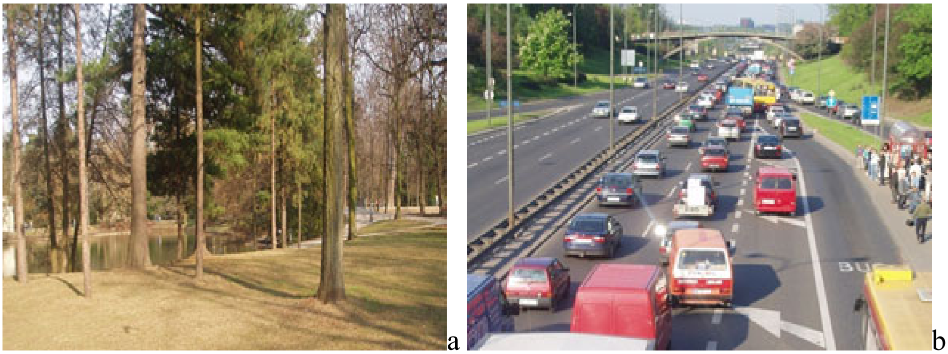

Fig. 2. a) Collection point no. 2; b) The vicinity of the Lazienkowska Route

Fig. 3. Collection point no. 7

2.2. Research methodology

In the laboratory scale spectrometer PU 9100X / 74 (Philips, England) was applied. The following reagents and solutions were applied: perchloric acid 70% (d = 1.67 g/ml), nitric acid 65% (d = 1.40 g/ml), acetic acid, glacial, part-d, deionized water as well as standard solutions: Zn: 1.5 mg/l, Pb: 5.0 mg/l, Ni: 5.0 mg/l.

Each time the sample of material was taken from the top (0-0.2 m), sodded soil layer. To obtain reliable results, each single sample weighing about 1 kg was a mixture of three smaller (about 300 grams) taken from a 1 m^2 measuring station. Soil samples were dried at room temperature. The airborne dry soil was thoroughly mixed and sieved through a 1 mm nylon sieve.

The wet clay mineralization variant based on concentrated nitric and perchloric acids was used to decompose the clay fraction of soil samples. Soil samples weighing 1 g were placed in 50 ml quartz flasks, to which 5 ml HNO_3 and 3 ml $HClO_4$ were added. Quartz coolers with a small amount of deionized water were placed in the neck of the flasks and heated on the burner until white fumes appeared. The mineralization time depend on the sample ranged from 40 to 90 minutes. The resulting solution was filtered on medium filters and then quantitatively transferred to 100 ml quartz volumetric flasks and made up to volume with deionized water. After wet mineralization, the content of zinc, lead and nickel in soil samples was determined directly by atomic absorption spectrometry with flame atomization. A 100 mm burner fed with a stoichiometric mixture of air and medical acetylene (acetylene A) was used. The flame temperature was 1200°C.

Hollow cathode lamps made by Philips were used as the radiation source. The spectrometer was program-controlled – Unicam Atomic Absorption – "Data Station ver. 1.7" from Unicam.

An attempt to assess the degree of toxicity was used according to the procedure recommended by the American Environmental Protection Agency (EPA), enabling the determination of toxicity and leaching potential of heavy metals from soils (TCLP). Soil samples were extracted with acetic acid solution.

The determined Corg content is the total amount of soil components that volatilize at 550°C during roasting. The dried soil sample with a mass was calcined in an electric furnace for 2 h. Then it was cooled in a desiccator and weighed.

3. Results and discussion

The highest concentration of lead (392 ±11.3 mg/kg s.m.) was recorded in samples taken near Lazienkowska Road, while the lowest (25.7 ±0.6 mg/kg s.m.) from the intersection area at Bankowy Square. The average lead concentration was observed in samples from the Lazienki Park and the Saxon Garden and was about 65 ±1.4 mg/kg s.m. While the highest value of zinc (728.2 ±22.1 mg/kg s.m.) were observed in samples from the area between residential buildings with the adjacent parking. Also, in this case, the metal concentration in the sample from Banking Square was lower than the concentration in the soil sample from control sites and reached the lowest value there. Relatively low concentrations were noted for nickel in all samples (Fig. 4-6). These Figures show the concentration of metals at the collection points.

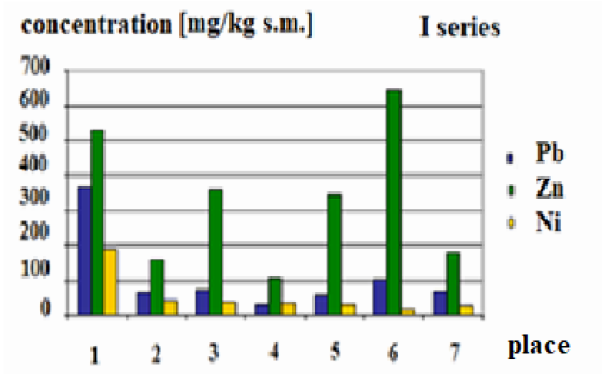

Fig. 4. Metal concentration in the soil for the first measurement series

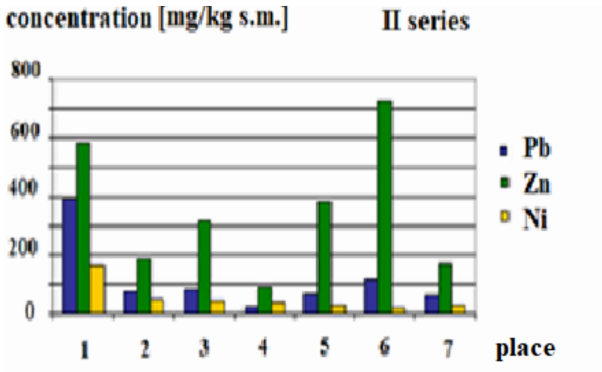

Fig. 5. Metal concentration in the soil for the second measurement series

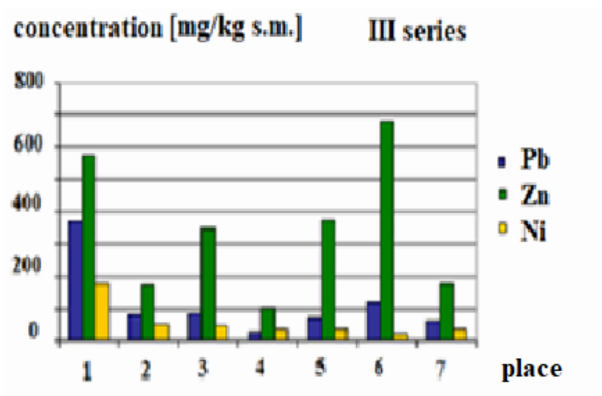

Fig. 6. Metal concentration in the soil for the third measurement series

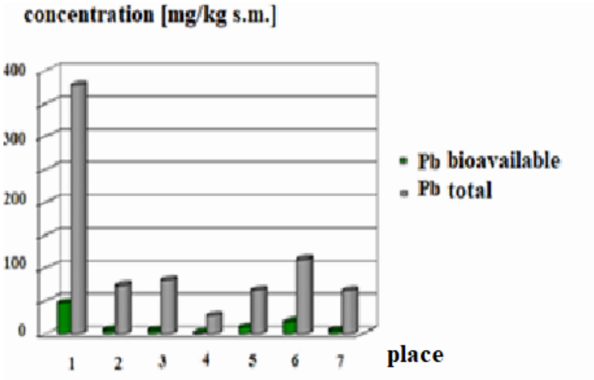

Fig. 7. Average content of lead in living organisms in relation to the average content of total lead (in mg/kg s.m)

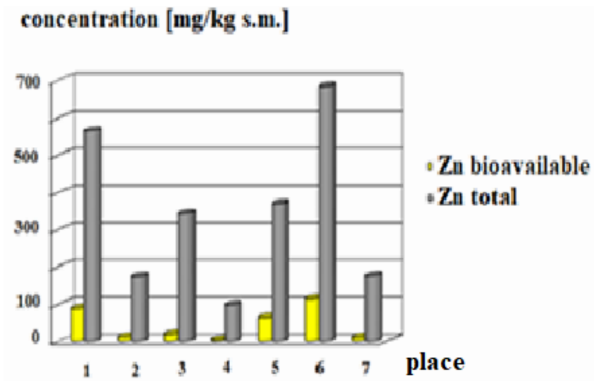

Fig. 8. Average content of zine in living organisms in relation to the average content of total zine (in mg/kg s.m)

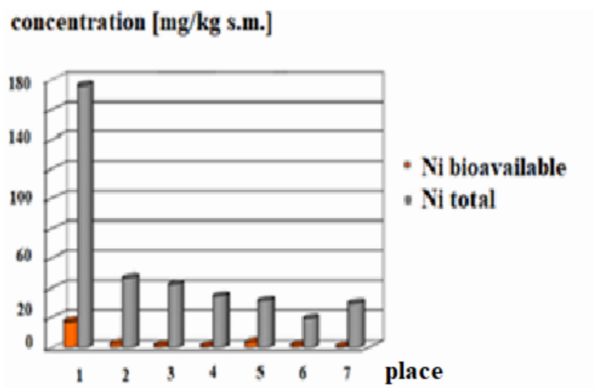

Fig. 9. Average content of nickel in living organisms in relation to the average content of total nickel (in mg/kg s.m.)

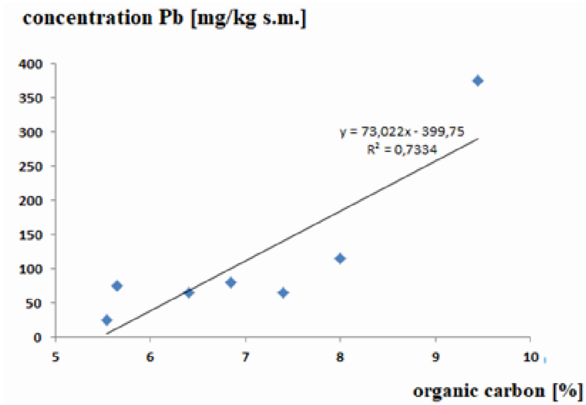

Fig. 10. Relationship between lead concentration and organic carbon content

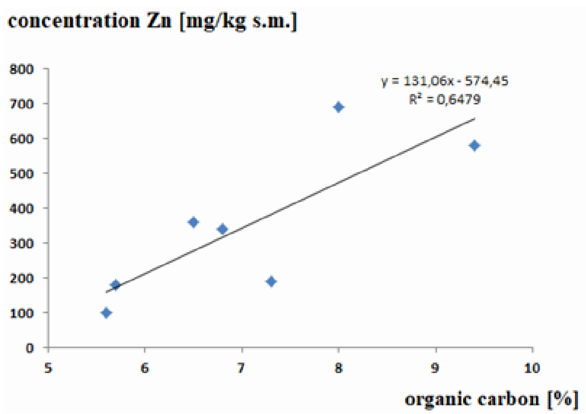

Fig. 11. Relationship between zinc concentration and organic carbon content

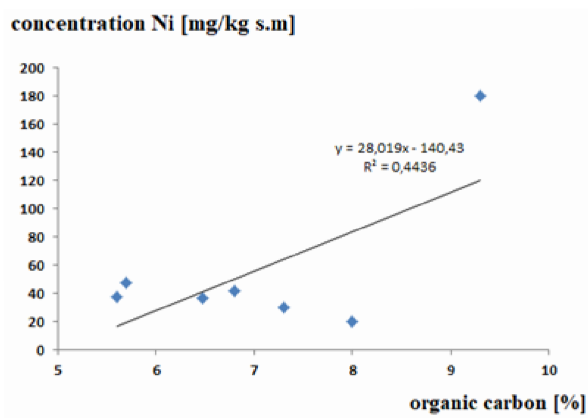

Fig. 12. Relationship between nickel concentration and organic carbon content

Analysis of concentration of selected metals in individual samples indicated that the highest concentrations of zinc are taken at place no. 1 with the highest traffic intensity and the strongest tendency to form traffic jams (Fig. 7 and Fig. 8). The values of lead emissions at the same site were in relation to the concentration of lead at site no. 5, which was at the same height as in station no. 6, but between lanes where lower Pb concentrations were recorded. At the same time, such a low (in comparison to no. 6) concentration of trace elements on a street with such a high traffic volume may indicate that along with the planting and care of greenery, the top layer of soil is replaced or mixed with its deeper layers, thus giving lower concentration values. A similar conclusion may be drawn when analyzing the results of samples taken from Banking Square. The determined concentrations are even lower than those in soil samples taken from areas recognized as reference points (background). Nickel soil pollution was negligible and oscillates within the range considered as a backdrop for urban areas. The general tendency indicates that in soils contaminated with one element, the content of other metals increased proportionally. The thesis that in the areas of anthropopressure, an increase in the concentration of one type of metals was in line with the general pollution of the soil environment. An analysis of the spatial arrangement of buildings gave grounds to conclude that in places where air traffic was restricted by buildings, the dust fall of heavy metals from motor vehicles was increased. The presented results of the reaction test showed that it did not have an impact on the level of soil pollution with heavy metals.

It was also observed that soil had limited capacity to absorb pollutant loads. It was investigated that the main problem of the automotive industry is the emission of zinc compounds. Moreover, the organic carbon content was in the range 5.0-10.3%, with the highest values obtained at place no. 1, and the lowest values in the Saxon Garden (control place). The soil organic carbon content was strongly correlated with the lead concentration (0.73), while the correlation coefficients for the other two metals were slightly lower and were: Zn (0.65) and Ni (0.44) (Fig. 10-12).

4. Conclusions

Dense network of communication routes and heavy traffic in Przyczolek Grochowski area caused that in the immediate vicinity elevated concentrations of the analyzed heavy metals were observed. This area has been identified as the most endangered among all measuring stations. However, due to the short-term scope of the analyzes, the test results may not be applicable to the long-term assessment of the degree of soil metal pollution. Moreover, heavy metals emitted to the ground layer of the atmosphere accumulate in the immediate vicinity of communication routes. Based on the analysis of interrelationships of zinc, lead, and nickel concentrations, it has been shown that there was a common source of their emission to soil.

Heavy metals are not biodegradable, they only change their forms under the influence of physical-chemical factors prevailing in soils. In areas exposed to anthropogenic pollution by heavy metals, the share of bioavailable forms of zinc, nickel and lead was higher than in control areas. While analysis of heavy metals in soils showed that road traffic was a common source of their emission.

References

Ashayeri, N. & Keshavarzi, B. (2019). Geochemical characteristics, partitioning, quantitative sourve apportionment, and ecological and health risk of heavy metals in sediments and water: A case study in Shadegan Wetland, Iran. *Marine Pollution Bulletin*.

Backstrom, M., Nilsson, U., Hakansson, K., Allard, B. & Karlsson, S. (2003). Speciation of heavy metals in road runoff and roadside total deposition. *Water, Air, and Soil Pollution, 24*.

C. o. E. P. E. f. R. Vehicles (2004). European Commission. Directorate General Transport and Environment.

Czapczuk, A., Dawidowicz, J. & Piekarski, J. (2017). Application of Multilayer Perceptron for the Calculation of Pressure Losses in Water Supply Lines. *Rocznik Ochrona Środowiska*, *11*.

Ebrahimi-Najafabadi, H., Pasdaran, A., Bezenjani, R. & Bozorgzadeh, E. (2019). Determination of toxic heavy metals in rice samples using ultrasound assisted emulsification microextraction combined with inductively coupled plasma optical spectroscopy. *Food Chemistry, 7*.

Guan, Q., Zhao, R., Pan, N., Wang, F. & Luo, L. (2018). Combining emission inventory and isotope ratio analyses for quantitative source apportionment of heavy metals in agricultural soil. *Chemosphere, 8*.

Liu, X., Ouyang, W., Shu, Y., Tian, Y. & Chen, W. (2019). Incorporating bio accessibility into health risk assessment of heavy metals in particulate matter originated from different sources of atmospheric pollution. *Environmental Pollution.*

Martínez, G. (2001). Distribution of the metals lead, cadmium, copper, and zinc in the top soil of Cartagena, Spain. *Water, Air, and Soil Pollution*.

Öborn, I. & Linde, M. (2001). Solubility and potential mobility of heavymetals in two contaminated urban soils from Stockholm. *Water, Air, and Soil Pollution*.

Peng, M., Zhao, C., Ma, H., Yang, Z., Yang, K., Liu, F., Li, K., Yang, Z., Tang, S., Guo, F., Liu, X. & Cheng, H. (2020). Heavy metal and Pb isotopic compositions of soil and maize from a major agricultural area in Northeast China: Contamination assessment and source apportionment. *Journal of Geochemical Exploration.*

Pernille, E. J., Ottosen, L. M. & Pedersen, A. J. (2006). Speciation of pb in industrially polluted soils. *Water, Air, and Soil Pollution*.

Piecuch, T., Andriyevska, L., Dabrowski, J., Dabrowski, T., Juraszka B. & Kowalczyk A. (2015). Treatment of Wastewater from Car Service Station. *Rocznik Ochrona Środowiska, 14*.

Polanczyk, A., Ciuka-Witrylak, M., Synelnikov, O. & Liok, V. (2018). *Analysis of sorption of vehicle liquids with sand that appear after car accidents reproduced in laboratory scale*. MATEC Web of Conferences, 8.

Polanczyk, A., Piechota-Polanczyk, A. & Dmochowska, A. (2019). The influence of the soil type on the permeability of petroleum derivatives. *Rocznik Ochrona Środowiska*, *13*.

Polanczyk, Majder-Lopatka, M., Salamonowicz, Z., Dmochowska, A., Jaosz, W., Matuszkiewicz, R. & Makowski, R. (2018). Environmental Aspects of Sorption Process. *Rocznik Ochrona Środowiska*, *13*.

Zhang, Y., Li, S., Lai, Y., Wang, L. & Chen, Z. (2019). Predicting future contents of soil heavy metals and related health risks by combining the models of source apportionment, soil metal accumulation and industrial economic theory. *Ecotoxicology and Environmental Safety, 11*.

Zhao, L., Hu, G., Yan, Y., Yu, R. & Yan, Y. (2019). Source apportionment of heavy metals in urban road dust in a continental city of eastern China: Using Pb and Sr isotopes combined with multivariate statistical analysis. *Atmospheric Environment, 11*.

Zieminska-Stolarska, A., Polanczyk, A. & Zbicinski, I. (2015). 3-D CFD simulations of hydrodynamics in the Sulejow dam reservoir. *Journal of Hydrology and Hydromechanics, 8*.

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Gas Formation Reactions in the Raw Mixture Based on TPP Ash

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Abstract: The article discusses the physicochemical mechanisms of the effect of chemical reagents on the processes of swelling of the raw mixture based on the ash of thermal power plants. The process of structure formation in such mixtures occurs as a result of physicochemical transformations of its constituent components. To intensify gas evolution and obtain materials of a porous structure, the presence of a gas former is necessary. The author has analysed the possibility of creating a porous structure in a raw mixture based on ash with the introduction of various gas formers or their formation as a result of exchange reactions. The main chemical compounds contributing to pore formation have been determined. To form a given structure, it is proposed to control chemical transformations at the stage of swelling. To study the processes of intensification of gas evolution, the author proposes to investigate the mechanisms of the influence of mineral fillers and chemical reagents on swelling processes based on the analysis of the Gibbs equation. The parameters of the Gibbs equation are obtained, by which it is possible to determine the probability of the occurrence of chemical reactions with the proposed chemical agents for the formation of gas bubbles with (pores) in the raw material.

Keywords: swelling, porous structure, ash of thermal power plants

1. Introduction

As a result of coal combustion at thermal power plants, a large amount of ash and slag waste is generated. The level of this waste disposal in Russia is about 4-5%; in developed countries – about 50%, in France and Germany – 70%, and in Finland – about 90% of their total amount (Lee et al. 2020). These countries use mainly dry ash, their disposal is encouraged by the national policy. Nowadays, the problem of ash and slag waste is becoming more acute, as it is generated in large volumes and have an utterly negative environmental impact. The waste accumulates in rising volumes, resulting to a rapid increase in environmental, social and economic costs due to the extremely low disposal level. Moreover, due to their physicochemical and physical composition, these materials are considered as unique resources to be used in various economic sectors with significant social, environmental and economic effects (Bielecka et al. 2020).

One of the possible solution to a problem is the development and implementation of effective thermal insulation porous materials based on ash containing raw mixture. Abundance of raw materials, relatively simple technology, low capital production costs, as well as attractive thermophysical characteristics could ensure wide use of these porous materials in industry. To ensure production of energy-efficient materials, features of the raw mixture swelling shall be studied in detail. Consequently, the production technology of ash-based porous thermal insulation structures shall be solved by studying the mechanism of a porous structure formation as a result of chemical reactions.

There are three main approaches to the elementary porous system formation. The first one considers the porous structure formation during a pseudo-continuous medium dispersion resulting from sublimation, condensation, crystallization and chemical reactions. The second approach is a porous system growth by adding porous systems of a smaller spatial scale (colloidal systems, bulk materials, etc.). There is an approach, where porosity is considered as fine-structure three-dimensional defects (metals, alloys, certain minerals). There is also a combined approach to a porous system formation, analysing more complex porous systems and their combinations (building materials, foam glass, insulation materials).

A porous system can be formed by diffusion accumulation of gases (diffusion genesis) and material destruction (destruction genesis). Diffusion accumulation of gases is a pore formation process during the release of gases in the material as a result of chemical reactions, difference in a substance saturation with gases in different physical states, transition to the gaseous state of one of the initial mixture components. The mechanism of a porous structure formation as a result of chemical reactions is based on the release of gases, accumulating in the least dense locations and forming gas bubbles. If the pressure in gas bubbles is higher than the sum of external and hydrostatic pressure, the liquid mixture of material boils. To intensify the pore formation process, the pressure is considerably reduced and the mixture starts boiling.

The formation of gases is also possible as a result of transition of one of the mixture components in the gaseous physical state (Pavlenko et al. 2019). At this, there gas accumulates and a pore is formed under the internal pressure action. Diffusion genesis also includes pore formation resulting from difference in the substance saturation in its solid and liquid state. Gas solubility in a liquid medium is higher than in a solid one. Therefore, dissolved gases are displaced during solution crystallization. If the solution surface has already crystallized, then an excess gas begins to accumulate upstream crystallization front, then it moves along with the crystallization front until its concentration exceeds the maximum possible concentration of dissolved gas in the solution. In all these cases of diffusion genesis (pore formation as a result of chemical reactions, difference in gas saturation of the substance in different physical states, resulting from evaporation of one of the initial mixture components) pore nucleation and its growth rate are the most important issues (Pavlenko et al. 2014). Although the pore nucleation location is fluctuating, the most viable pore nuclei are formed near structural imperfections. Such imperfections include the interface of different chemical structures, different physical states of one element; pores and cavities, formed as a result of the material destruction. In a liquid physical state, such imperfections diffuse in volume and can merge. To merge pore nuclei, energy shall be spent on the structure deformation.

2. Purpose of work and research methods

It is evident that ash shall not be considered as the industrial waste, but as a resource for production of new materials. One of TPP ash disposal methods is to use it in the technology of porous thermal insulation material production by means of thermal swelling of water soluble mineral raw mixture. To solve this task it is necessary to study main physico-chemical processes and transformations in the ash structure.

The structure in a mixture is formed as a result of physico-chemical transformations of ash components. Thermal swelling, the main process of structure formation and pore nuclei formation as its initial stage, result from chemical reactions in the mixture.

One of TPP ash disadvantages is its inconstant composition, depending on morphological characteristics of the burning fuel, milling fineness during its preparation, fuel ash-content, chemical composition of the fuel mineral part, temperature in the burning area, period of particles presence in this area, etc. Moreover, the ash, stored in ash dumps, is under constant chemical transformations, resulting in gradual change of its chemical composition.

TPP ash chemical composition was studied to determine its possible use as a raw material for production of building materials. According to standard modern methods, ash chemical composition is determined, it is presented in Table 1. Use of ash in its pure form is complicated by the negative impact of CaO (calcium (II) oxide), present in a free form in the burnt state. Hydration of CaO particles, often coated with a glassy shell, results in cracking and destruction of solidified material. The harmful impact of CaO can be neutralized by different means: physical, chemical and its use with cement. The positive effect in the latter case will be achieved as a result of dilution and containment of destructive phenomena using a set cement.

Table 1. Average content of TPP ash components

Substance	Formula	Content, wt.%
Silicon (IV) oxide	SiO_2	52.08
Aluminium (III) oxide	Al_2O_3	26.58
Iron (III) oxide	Fe_2O_3	13.0
Magnesium (II) oxide	MgO	2.4
Calcium (II) oxide	CaO	4.13
Manganese (II, III) oxide	Mn_3O_4	0.3
Titanium (IV) oxide	TiO_2	0.84
Chromium (III) oxide	Cr_2O_3	0.003
Sulfur (VI) oxide	SO_3	0.38
Phosphorus (V) oxide	P_2O_5	0.23
Potassium oxide	K_2O	1.5
Sodium oxide	Na_2O	0.5
Bound water	H_2O	0.2
Carbon (IV) oxide	CO_2	0.33
Calcination losses (at t = 950°C)	–	3.77

We analysed both methods in our work. As calcium oxide (CaO) content in ash is low (≈ up to 4%), each method may be relevant. During TIM production, to intensify gas emission we shall use NaOH alkali, which can be formed as a result of metabolic reactions. In our technologies alkalis can be added to the raw mixture as a separate component, its gradual formation is also possible in intermediate chemical reactions in the ash-based raw mixture. It would make it possible to control chemical transformations at the swelling stage. Formation of new compounds will promote a faster mixture plastification and its early consolidation. These properties can serve as a basis of a controlled process for a specified structure formation, which (as specified in the first section) is the purpose of this study.

Therefore, interaction of these chemical compounds accelerates CaO hydration, as well as formation of mixture hydrates.

Complex physicochemical and chemical processes in the interaction of clinker minerals with water occur according to the following equations:

- C_3S tricalcium silicate hydrolysis

$$3\,CaO\cdot SiO_2 + (n+1)H_2O = 2CaO\cdot SiO_2\cdot nH_2O + Ca(OH)_2, \quad (1)$$

- C_2S dicalcium silicate hydration

$$2\,CaO\cdot SiO_2 + nH_2O = 2CaO\cdot SiO_2\cdot nH_2O, \quad (2)$$

- C_3A tricalcium aluminate hydration

$$3CaO \cdot Al_2O_3 + 6H_2O = 3CaO \cdot Al_2O_3 \cdot 6H_2O, \quad (3)$$

- C_4AF tetracalcium (four-calcium) aluminoferrite hydrolysis

$$4CaO \cdot Al_2O_3 \cdot Fe_2O_3 + mH_2O = 3CaO \cdot Al_2O_3 \cdot 6H_2O + CaO \cdot Fe_2O_3 \cdot nH_2O. \quad (4)$$

The presence CaO compound in the system, which is in a free state, affects strength properties of the final product. During hydration with CaO transformations occur according to the following pattern:

$$CaO_{(sol.)} + nH_2O \rightarrow CaO + nH_2O\ (s.) \rightarrow Ca(OH)_2 + (n-1)H_2O(s.) \rightarrow$$
$$\rightarrow Ca(OH)_2 + (n-1)H_2O. \quad (5)$$

If the process takes place in the absence of excess water, then $Ca(OH)_2$ crystallizes rapidly and inside formed compound particles there is an increased internal stress, resulting in mixture cracking. To eliminate destructive phenomena in the cement, chemical additives are introduced into the mixture.

The solubility promoting compounds accelerate the swelling process and form soluble compounds with CaO: NaCl, $CaCl_2$, $MgCl_2$, NH_4Cl, $Ca(NO_3)_2$. Additives, slowing down CaO activity and forming sparingly soluble compounds on its surface, that prevent water access: $CaSO_4 \cdot 2H_2O$, Na_2SO_4. Chemical additives react with cement minerals, forming complex compounds: calcium hydrosulfoaluminates and hydrochloroaluminates $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot nH_2O$, $3CaO \cdot Al_2O_3 \cdot nCaCl_2 \cdot mH_2O$. These compounds increase the active surface of cement grains, the rate of cement interaction with water and strengthen a set cement.

The ash CaO interacts with portland cement clinker according to the following metabolic reactions:

$$3CaO \cdot Al_2O_3 + NaCl + 10H_2O = 3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O,$$
$$3CaO \cdot Al_2O_3 + 3CaSO_4 + 31H_2O = 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 31H_2O. \quad (6)$$

The strength of ash-containing concrete depends on the chemical and mineralogical composition of a cement clinker. At an early growth state, the concrete strength is facilitated by the increased content of alkali in the clinker, accelerating ash and cement chemical interaction (Polettini et al. 2009). Additives, such as $CaCl_2$ and $CaSO_4$, can be used to activate ash for use in cement systems (Poon et al. 2001). Addition of sodium chloride (NaCl) to a cement mixture in the amount of 1.2-1.5% promotes CaO hydration (Bellmann 2009).

U. A. Ayapov (Ayapov 1982) proposed to add sodium sulfate into the mixture (Na_2SO_4), which affects structure formation processes in a lime-ash binder system. The presence of a high content of Al_2O_3 in a system (18-24 wt.%), results in a shift of ionic equilibrium towards formation of sparingly soluble ettringite – calcium hydrosulfuminate ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot nH_2O$). It increases alkaline environment as a result of formation in a sodium hydroxide (NaOH) system, which enhances the effect of ash sulfate-alkaline activation, namely the destruction of Si-O-Al bonds, while ettringite crystals contribute to destruction of $Si(OH)_4$ (OH) and $Al(OH)_3$ gel colloidal film; chemical reactions accelerate on the ash grains surface, they are further enhanced by curing.

As a result of exchange reactions between sodium sulfate and cement hydration products, an additional amount of sulfate crystal hydrates is formed – gypsum ($CaSO_4 \cdot 2H_2O$) and alkali NaOH. When Portland cement sets in the air, it results in carbonization due to carbon (IV) oxide (CO_2) (concentration 0.03%)

$$\underset{\text{(crystal)}}{Ca(OH)_2 + CO_2 + nH_2O \rightarrow CaCO_3 + (n+1) \cdot H_2O,}$$

$$2NaOH + CO_2 + nH_2O \rightarrow Na_2CO_3 + 2H_2O. \quad (7)$$

Disodium trioxocarbonate (Na_2CO_3) interacts with gypsum first, as it is the most soluble product of Disodium trioxocarbonate (Na_2CO_3) hydration, under the action of NaOH, its solubility increases considerably:

$$CaSO_4\ 2H_2O + Na_2CO_3 \rightarrow CaCO_3 + Na_2SO_4 + aq. \quad (8)$$

Highly soluble in water sodium sulfate reacts again with calcium oxide to form gypsum and alkali.

The simplest way to increase the water resistance of a set cement is possible to be used with the introduction of additives of electrolyte salts, when additional crystal hydrates are formed. Salts-electrolytes (e.g.$NaNO_3$, Na_2SO_4, Na_2CO_3, dissolving in water, penetrate deep into the concrete structure and react with components of a set cement solidification products. Use of salts results in their interaction with a set cement components with formation of AFt and AFm phases and hydrosilicates. The mechanism of Na_2CO_3 (disodium trioxocarbonate) action can be represented as its reaction with calcium hydroaluminate in the presence of calcium hydroxide, followed by the formation of two sparingly soluble products, one of which is represented by a double salt:

$$Na_2\,CO_3 + C_4\,AH_{13} + Ca(OH)_2 + H_2O \rightarrow C_3ACaCO_3 \cdot 2H_2\,O + NaOH + CaCO_3. \quad (9)$$

A simple exchange reaction is also possible:

$$Na_2CO_3 + Ca(OH)_2 + H_2\,O \rightarrow CaCO_3 + NaOH. \quad (10)$$

Carbonization occurs in the surface layer. Formed $CaCO_3$ increases in volume and promotes strengthening of the outer concrete surface. Gradually, the system activates surface self-compaction processes with spontaneous slowing down of the carbonization phenomenon, resulting in a dense surface formation, it prevents CO_2 (carbon (IV) oxide) access, which is part of the air, into deep layers.

As ash contains up to 61% of aluminosilicate glass phase, similar reactions of interaction with Na_2SO_4 (sodium sulfate) will take place in ash-cement compositions. It is an obvious benefit, as theoretically we can influence kinetic parameters of the swelling process. Moreover, carbonized shrinkage during product carbonized shrinkage will partially compensate for their own expansion deformations by free lime quenching.

3. Experimental research

The impact mechanisms of mineral fillers and chemical reagents on swelling processes may be evaluated based on analysis of the combined equation of the first and second laws of thermodynamics.

$$\Delta G = P \cdot \Delta V + \sigma \cdot \Delta F + \mu \cdot \Delta n + \varphi \cdot \Delta q - T \cdot \Delta S = \Delta H - T\Delta S, \qquad (11)$$

where:
ΔG – Gibbs free energy allowing prediction of intensity and direction of changes in the system energy state,
ΔH – system enthalpy factor,
σ – the surface tension at the pore interface,
F – the pore surface area,
n – the rate of a volume change,
φ – the chemical potential of a pore-forming gas,
TΔS – an entropy factor.

The entropy factor changes with porous structure formation with the following work, performed by the system (a raw mixture):

- change of system volume,
- formation of a new surface and increase of surface tension during frame hardening,
- change of chemical potential, phase and component composition.

The entropy factor increases as a result of the porous structure formation, using technological techniques, described in the previous chapters.

Gibbs energy is represented by the following equation

$$G^{(1)} = \varphi \quad M^{(1)} + \sigma\Omega, \tag{12}$$

where: $M^{(1)}$ is the mass of a pore forming agent equal to $4\pi r^3/\upsilon'$,
Ω is the outer surface of a pore nucleus, $4\pi r^2$,
φ is the chemical potential of a pore-forming gas.

Gibbs energy of a system, consisting of the energy of a pore nucleus formation and a material porous structure

$$G = G^{(1)} + G^{(2)}, \tag{13}$$

where $G^{(2)}$ is Gibbs energy of the material.

Let us analyse the equilibrium state of this system. If system external pressure p', equal to gas pressure in a pore and temperature T' are constant, then equilibrium condition $dG = 0$ is represented by

$$dU^{(1)} + dU^{(2)} - T'\left(dS^{(1)} + dS^{(2)}\right) + p'\left(dV^{(1)} + dV^{(2)}\right) + \varphi^{(1)}dM^{(1)} + \\ +\varphi^{(2)}dM^{(2)} = 0, \tag{14}$$

where: U is internal energy; p' is external pressure (in this case mixture pressure).

Considering that

$$\left(\frac{\partial U}{\partial S}\right)_V = T; \left(\frac{\partial U}{\partial V}\right)_S = -p, \tag{15}$$

for a gas bubble according to Laplace formula

$$p^{(1)} = \left(p' + \frac{2\sigma}{r}\right), \text{ then}$$

$$dU^{(1)} + dU^{(2)} = T^{(1)}dS^{(1)} + T^{(2)}dS^{(2)} - \left(p' - \frac{2\sigma}{r}\right)dV^{(1)} - p'dV^{(2)}. \tag{16}$$

Considering that the system total mass is constant

$$\frac{2\sigma}{r}dV^{(1)} + \left(\varphi_\infty^{(1)} - \varphi^{(2)}\right)dM^{(1)} = 0. \tag{17}$$

For spherical pores

$$dV^{(1)} = 4\pi r^2 dr, \tag{18}$$

$$dM^{(1)} = \frac{4\pi r^2}{\upsilon^{(1)}}dr. \tag{19}$$

The above ratio can be written as

$$\left(\varphi_{\infty}^{(1)} - \varphi^{(2)} + \frac{2\sigma v^{(1)}}{r}\right) dr = 0 \tag{20}$$

or under condition dr ≠ 0,

$$\varphi^{(2)} - \varphi_{\infty}^{(1)}) = \frac{2\sigma v^{(1)}}{r}. \tag{21}$$

Let us assume instead $\varphi_{\infty}^{(1)}$ and $\varphi^{(2)}$ actual values of the pore-forming agent and material chemical potentials at a specified temperature and corresponding pressure equal to $\varphi^{(1)}\left(p^{(1)},\ T\right)$, T), $\varphi^{(2)}\left(p^{(2)},\ T\right)$. Similarly to a gas bubble in an infinite volume of liquid, decomposing $\varphi^{(1)}\left(p^{(1)},\ T\right)$ in a row by $p^{(1)} - p^{(2)}$, and $\varphi^{(2)}\left(p^{(2)},\ T\right)$ – in a row by orders $p^{(2)} - p^{(1)}$. We will obtain

$$\varphi^{(1)}\left(p^{(1)}, T\right) = \varphi^{(2)}\left(p^{(2)}, T\right). \tag{22}$$

From equation (22) it follows that the pore-forming agent and material chemical potentials have equal values. Thus, conditions of gas pressure equilibrium in the material during porous structure formation, taking into account the surface tension:

$$\{T^{(1)} = T^{(2)}, p^{(1)} - p^{(2)} = \frac{2\sigma}{r}, \varphi^{(1)}\left(p^{(1)}, T\right) = \varphi^{(2)}\left(p^{(2)}, T\right). \tag{23}$$

After differentiation of equation (11) by pressure *p* at *T* = *const* and given that $(\partial\varphi/\partial p)_T \ = \ v$, we obtain

$$\frac{1}{\rho^{(2)}} - v^{(1)} = -\frac{2v^{(1)}\sigma}{r^2}\left(\frac{\partial r}{\partial p}\right)_T + \frac{2\sigma}{r}\left(\frac{\partial v^{(1)}}{\partial p}\right)_T. \tag{24}$$

As $\frac{1}{\rho^{(2)}}$ is much lower than $v^{(1)}$, and $v^{(1)}$ at relatively low gas pressures can be considered equal to *RT/p*, then

$$\frac{RT}{p^{(1)}} = \frac{2v^{(1)}\sigma}{r^2}\left(\frac{\partial r}{\partial p}\right)_T - \frac{2\sigma}{r}\left(\frac{\partial v^{(1)}}{\partial p}\right)_T. \tag{25}$$

After integrating this equation by p ≥ 0 we obtain

$$\int \frac{RT}{p^{(1)}} dp = \int \frac{2v^{(1)}\sigma}{r^2}\left(\frac{\partial r}{\partial p}\right)_T dp - \int \frac{2\sigma}{r}\left(\frac{\partial v^{(1)}}{\partial p}\right)_T dp, \tag{26}$$

$$RT \cdot \left[ln\, ln\, (p^{(1)})\ + c\right] = -2\sigma \frac{v^{(1)}}{r}, \tag{27}$$

where c is the integration constant.

$$p^{(1)} = e^{-c} \cdot e^{-\frac{2\sigma v^{(1)}}{RT\ \ r}}$$

We obtain constant e^{-c} from equilibrium condition, given that at $r \to \infty$, $p = p_0$:

$$p^{(1)} = p_0 \cdot e^{-\frac{2\sigma \upsilon^{(1)}}{RT\ r}}. \tag{28}$$

After differentiating the equation of equality of potentials (23) by T and given that $(\partial\varphi/\partial p)_T = \upsilon$, $(\partial\varphi/\partial T)_P =$ -S we obtain

$$\left(\frac{\partial\varphi^{(1)}}{\partial p}\right)_T \frac{dp}{dT} + \left(\frac{\partial\varphi^{(1)}}{\partial T}\right)_P = \left(\frac{\partial\varphi^{(2)}}{\partial p}\right)_T \frac{dp}{dT} + \left(\frac{\partial\varphi^{(2)}}{\partial T}\right)_P, \tag{29}$$

$$dT = \frac{1}{s^{(2)} - s^{(1)}}\left(\frac{1}{\rho^{(2)}} \cdot dp^{(2)} - v^{(1)} \cdot dp^{(1)}\right). \tag{30}$$

As the material density is almost independent of the pressure at low gas pressures υ = RT/p, we obtain

$$T = \frac{1}{s^{(2)} - s^{(1)}}\left(\frac{p^{(2)}}{\rho^{(2)}} - RT\,ln\left|p^{(1)}\right|\right) + const. \tag{31}$$

Given P = const, $(\partial\varphi/\partial T)_P = -s$, we finally write

$$s^{(1)} - s^{(2)} = \frac{2\sigma v^{(1)}}{r^2}\left(\frac{\partial\ r}{\partial\ T}\right)_P + \frac{2\sigma}{r}\left(\frac{\partial\ v^{(1)}}{\partial\ T}\right)_P,$$

$$s^{(2)} - s^{(1)} = -\frac{2\sigma v}{rT}. \tag{32}$$

Considering (30):

$$T = \frac{1}{R\,ln\left|p^{(1)}\right|} \cdot \left(\frac{2\sigma v^{(1)}}{r} + \frac{p^{(2)}}{\rho^{(2)}}\right). \tag{31}$$

At $r \to \infty$ we obtain

$$\Delta T = \frac{1}{R\,ln\left|p^{(1)}\right|} \cdot \left(\frac{2\sigma v^{(1)}}{r} + \frac{p^{(2)}}{\rho^{(2)}}\right) - T_0, \tag{32}$$

where T_0 is a pore forming gas temperature.

Thus, all parameters for equation (11) are obtained, it is possible to determine probable chemical reactions and formation of gas bubbles (pores) in a raw material.

4. Conclusions

To intensify gas evolution in a mixture based on ash, the presence of a gas former is necessary, which can be formed as a result of exchange reactions. In ash and slag materials, the chemical and mineral-phase composition depends on the composition of the mineral part of the fuel, its calorific value, the combustion mode, the method of catching and removing incineration waste, and the place where raw materials are taken from the dumps. The use of additional gasifiers in certain technological modes contributes to the implementation of an intensive and controlled process of emission gases (for pore formation in the plastic raw material mixture). The mechanisms of the effect of mineral fillers and chemical reagents on the swelling processes can be estimated based on the analysis of the Gibbs equation, which makes it possible to predict the intensity and direction of changes in the energy state of the system. It will make it possible to determine the quantitative composition of a raw mixture with TPP ash addition and main technological modes of its swelling. The obtained results can be used to quantify components of a raw mixture for production of porous structures and perform further research to optimize the composition and technological modes of swelling.

References

Ayapov, U.A. (1982). Binders and concretes from mineral wastes of the industry of Kazakhstan /U.A. Ayapov S.A. Arkhabaev, Z.B. Shormanova. - A.: Nauka, 164.

Bellmann, F., Stark, J. (2009). Activation of blast furnace slag by a new method. *Cem. Concr. Res., 39*, 644-650.

Bielecka, A., Kulczycka, J. (2020). Coal Combustion Products Management toward a Circular Economy – A Case Study of the Coal Power Plant Sector in Poland. *Energies, 13*, 3603.

Koshlak, H., Pavlenko, A. (2019). Method of formation of thermophysical properties of porous materials. *Rocznik Ochrona Srodowiska, 21*(2), 1253-1262.

Lee, J., Kim, T., Sung, M., Vu, H.H.T., Shin, K.N., Ahn, J.W. (2020). An Integrative Approach to International Technology Transfer for Recycling Vietnam Coal Ash with Consideration of the Technological, Legal, and Network Perspectives. *Sustainability, 12*, 771.

Pavlenko, A., Koshlak, H. (2019). Heat and mass transfer during phase transitions in liquid mixtures. *Rocznik Ochrona Srodowiska, 21*(1), 234-249.

Polettini, A. (2009). Chemical Activation in View of MSWI Bottom Ash Recycling in Cement-Based Systems/A. Polettini, R. Pomi, E. Fortuna. *J. Hazardous Matter. 162*(2-3), 1292-1299.

Poon, C.S. (2001). Activation of fly ash/cement systems using calcium sulfate anhydrite (CaSO[4])/C.S. Poon, S.C. Kou, L. Lam, Z.S. Lin. *Cem. And Concr. Res. 31*(6), 873-881.

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Daily Suspended Sediment Prediction Using Seasonal Time Series and Artificial Intelligence Techniques

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Abstract: Estimating the amount of suspended sediment in rivers correctly is important due to the adverse impacts encountered during the design and maintenance of hydraulic structures such as dams, regulators, water channels and bridges. The sediment concentration and discharge currents have usually complex relationship, especially on long term scales, which can lead to high uncertainties in load estimates for certain components. In this paper, with several data-driven methods, including two types of perceptron support vector machines with radial basis function kernel (SVM-RBF), and poly kernel learning algorithms (SVM-PK), Library SVM (LibSVM), adaptive neuro-fuzzy (NF) and statistical approaches such as sediment rating curves (SRC), multi linear regression (MLR) are used for forecasting daily suspended sediment concentration from daily temperature of water and streamflow in the river. Daily data are measured at Augusta station by the US Geological Survey. 15 different input combinations (1 to 15) were used for SVM-PK, SVM-RBF, LibSVM, NF and MLR model studies. All approaches are compared to each other according to three statistical criteria; mean absolute errors (MAE), root mean square errors (RMSE) and correlation coefficient (R). Of the applied linear and nonlinear methods, LibSVM and NF have good results, but LibSVM generates a slightly better fit under whole daily sediment values.

Keywords: Prediction, Neuro-Fuzzy, Sediment Rating Curves, Support Vector Machines, Suspended Sediment

1. Introduction

Estimation of suspended sediment amount in streams and rivers correctly is a substantial value in the design and maintenance of hydraulic structures such as dams, bridges, etc. In particular, the sediment that accumulates in the water storage structures such as dam reservoir reduces the reservoir capacity. Decrease of the reservoir capacity causes shortening of the economic life of facilities. In order to prevent or even delay these damages, a passive storage called dead storage is determined in the dam reservoir. It is designed to remain under the water intake structure. The service life of a dam, namely its useful life, depends on the amount of storage. Therefore, it is important to accurately forecast the type and amount of sediments in dam projects.

In rivers, suspended sediments are also transported with water during stream-flow movement. These sediments are consisted of either erosion in river basin or by abrasion in the stream bed. Throughout river, scouring and accumulation in stream bed occur as a result of sediment movements. As a result of this scouring and accumulation, the shape of the river bed and morphological structure is expected to change. For the solution of these problems, suspended sediment estimations are needed.

Determination of suspended sediments by measurements is the most accurate method. However, this method takes time and is costly. In addition, there is no measurement of the amount of sediments in many observation stations, although water flow is measured. It is especially difficult to measure the amount of sediments in the stations in case of flooding.

Artificial intelligence techniques have been widely used to solve complex problems in recent years. Examples of these are; artificial neural networks (ANN) (Saplıoglu & Cimen 2010, Turhan & Cağatay 2016, Demirci et al. 2017, Unes et al. 2018a, 2018b, Turhan et al. 2019) and adaptive network-based fuzzy inference system (ANFIS) (Jang 1993, Ghavidel & Montaseri 2017, Ebtehaj & Bonakdari 2017, Demirci et al. 2018, Catal & Saplioglu 2018, Ehteram et al. 2021).

In the past, many researchers also applied artificial intelligence methods and obtained different results in order to explain the sediment amount problem and provide correct solutions. Kisi (2005) estimated the concentration of sediment in the stream using ANN. Mirbagheri et al. (2010) evaluated the applicability of the sediment rating curves (SRC), and fuzzy rule-based (NF) models in estimating the concentration of sediment in the rivers using the coefficient of determination and demonstrated that the NF model gives better results for predicting the sediment concentration. Fırat and Güngör (2010) used ANN and NF methods for sediment estimation. According to the results, they demonstrated that the NF approach provides high performance. Wieprecht et al. (2013) used an ANFIS to estimate bed load and total bed material load in the Rhine River. They used two-thirds of the available data sets (bed load and total bed material) for the training phase and the remaining one for the testing phase. They stated that the ANFIS modeling approach could be a good alternative for estimating bed load and total bed material load. Demirci and Baltaci (2013) investigated the viability of the SRC, multi linear regression (MLR), and fuzzy logic (FL) methods in estimating sediment concentration. FL model has shown good results in comparisons for both 5-year and 50-year sediment estimations. Demirci et al. (2015) used an ANN approach for forecasting sediment concentration in Little Coal river, West Virginia, in the USA. It was found that the ANN model gives better estimates than other techniques. Kitsikoudis et al. (2015), derived sediment transport formulas for sand-bed rivers. They used ANN, ANFIS, and genetic programming based symbolic regression methods to derive these formulas. Partovian et al. (2016), made a study on the daily sediment and flow model of the Minnesota River. They applied the previously measured data to ANN and ANFIS models. They compared it with MLR and auto-regressive moving average (ARMA) models to evaluate the performance of their models. According to their results, ANN and ANFIS models performed better than MLR model.

Kisi and Zounemat (2016) conducted studies to forecast the amount of sediment in 2 stations on the Muddy river in the USA. The input parameters were the daily flow rate and the amount of sediment concentration data in the study. They used ANN, NF, SRC, and CNF models (Clustered Neuro-Fuzzy model, developed from classic NF). The CNF method has been shown to provide better sediment estimation results than others. CNF method can be presented as an alternative to ANN, NF, SRC methods in sediment prediction. Seyedian and Rouhani (2015) studied the capabilities of the ANFIS to estimate daily sediment loads for four stations in the USA. They compared the ANFIS model they created with the SRC model in terms of error amounts (RMSE, MBE), and determination coefficient (R^2) values. They stated that the ANFIS model performed better than the SRC model. Tasar et al. (2017) used M5tree (M5T), ANN approaches, and statistical approaches to estimate sediment load. Gunawan et al. (2017) estimated sediment load using the backpropagation network (BPNN) scheme, which is an ANN method. As a result, they stated that this model performs better than other known calculation methods with its correlation coefficient (R) and mean square error (MSE) stability. Buyukyildiz and Kumcu (2017) studied to predict sediment load which gauged at Ispir Bridge station, Çoruh River in Turkey. Choubin et al. (2018), estimated river sediment using the classification and regression tree (CART) model with machine learning techniques. Emamgholizadeh and Demneh (2019), compared artificial intelligence models for the estimation of daily suspended sediment of Telar and Kasilian rivers in Iran. Results showed that ANN and ANFIS models were better performance than the other models. Salih et al. (2020), predicted suspended sediment load in river-based on river discharge information by using newly developed data mining models. Among the applied data mining models, the M5P model gave the best prediction result. Meshram et al. (2020), were used radial basis function (RBF), support vector machine (SVM), artificial neural networks (ANNs), and multiple model (MM)-ANNs to predict sediment yield. Results showed that the MM-ANNs model results gave best performance in all models.

This study aims to investigate the performance of data-driven methods, including two types of perceptron support vector machines with radial basis function kernel (SVM-RBF), poly kernel learning algorithms (SVM-PK), adaptive neuro-fuzzy (NF), and statistical approaches such as sediment rating curves (SRC), multi linear regression (MLR) in sediment concentration predictions in rivers. Furthermore, the LibSVM model, which is one of the new modeling techniques, was used for sediment estimation in this study.

2. Methods

2.1. Sediment Rating Curve

Conventional sediment rating curve (SRC) shows the connection between the sediment amount and the streamflow measured in any control section of the rivers. If *Q* indicates the streamflow and *S* indicates the concentration of sediment, the connection between these two variables;

$$S = aQ^b \tag{1}$$

where a and b are rating curve constant coefficients. Williams (1978) who examined the *S*-*Q* relationship given in Equation 1, proved that there is no uniform relationship. In some rivers, the *S*-*Q* relationship is followed by two different values. That is, the amount of sediment at different times in the stream can be different due to the hydrological causes for the same discharge value. In many cases, accurate sediments cannot be forecasted and are inadequate using these curves.

2.2. Multi Linear Regression

Multi linear regression (MLR) is a type of analysis for predicting a dependent variable, depending on 2 or more independent variables associated with the dependent variable (Berk, 2004). In MLR analysis, the relationship between further than one independent variable (x_1, x_2 ... x_n) and a dependent variable (y) is examined. That is, if the dependent variable "y" is assumed to be impressed by "n" independent variables such as x_1, x_2, x_3 … x_n . If the relationship between them is assumed to be linear, MLR equation "y" dependent variable can be expressed as:

$$y = a + b_1 x_1 + b_2 x_2 + \ldots + b_n x_n \tag{2}$$

When starting the regression analysis, the variables (two or more variables) to be searched first must be determined, an acceptance must be made then for the type of equation that shows the relationship between these variables.

2.3. Support Vector Machine

Support vector machine (SVM) is an approach of learning found by Cortes and Vapnik (1995) for solving the classification and regression problems. It is likely that classification of variables on a plane by drawing a boundary between them. The boundary which is drawn between variables must be as far as possible to each variable. The SVM defines how to draw this boundary between variables group. SVM studies according to statistical learning theory. A set of training data [$(x_1, y_1), (x_2, y_2), \ldots (x_n, y_n)$], where "$x_i$" value indicates that the input space of the sample and has a corresponding target "y_i" value. The SVM estimating function expressed as:

$$y = (K_{xi} \cdot W_{jk}) + b \tag{3}$$

Where the Kernel function is K_{xi}, b is bias term of SVM network and W_{jk} is called the Lagrange multipliers that obtain to the significance of the training data sets for the output data. The network architecture of SVM is given in Fig. 1.

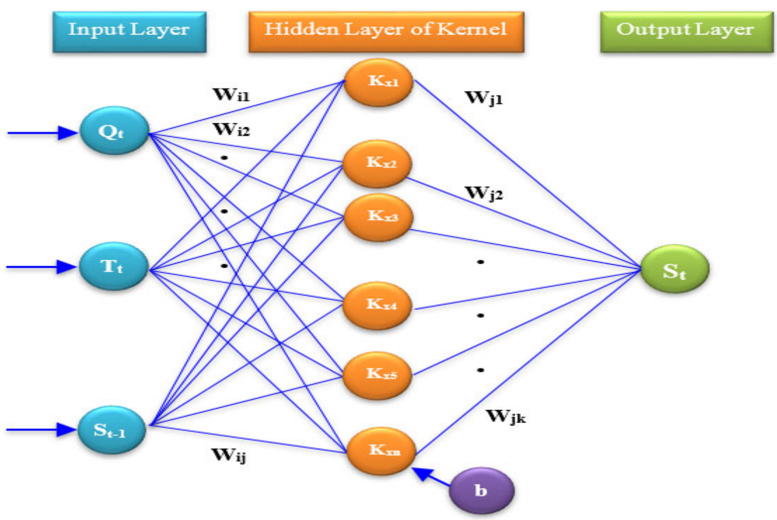

Fig. 1. Network architecture of SVM10 model

In the SVM model, firstly input data is determined and processing is started. Then Which Kernel type is decided (In this paper, radial basis function and polynomial Kernel is used). After decided Kernel type, parameters of kernel are obtained. Finally, Models trained and applied test results. All this SVM stage is given in Fig. 2.

The kernel function of non-linear radial basis (Hsu et al. 2003) is:

$$K_{xi} = e^{-\gamma \|x_i - y_i\|^2} \qquad \gamma > 0 \quad \text{and} \qquad i = 1,2,3,\ldots n \tag{4}$$

where γ is a user-defined parameter. The kernel function of polynomial (Hsu et al. 2003) is:

$$K_{xi} = (x.y + c)^d \qquad i = 1,2,3,\ldots n \tag{5}$$

where function degree define as d and c is constant parameter. If d = 1, function became linear condition.

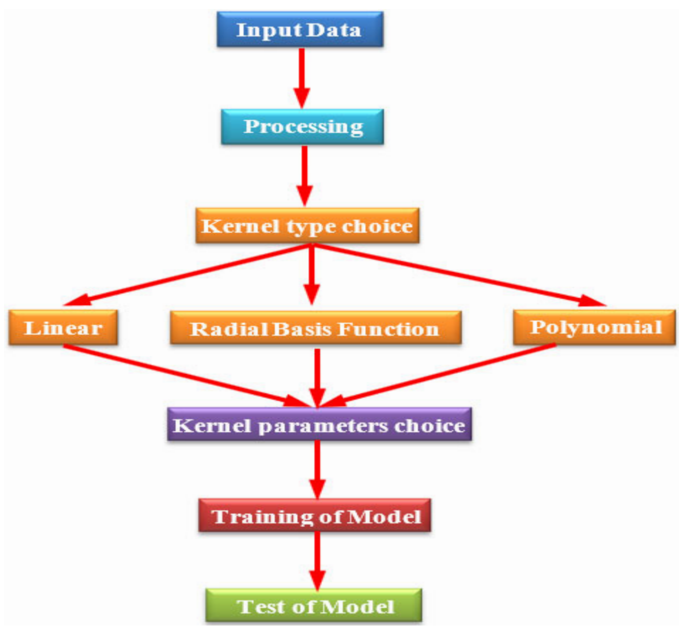

Fig. 2. SVM model stage

2.4. Library SVM

Library SVM (LibSVM) is one of the machine learning algorithms for support vector classification, regression (Chang & Lin 2002). C-SVC, nu-SVC, epsilon-SVR, and nu-SVR are the most commonly known LibSVM machine learning algorithms. It works with multi-class classification.

The difference between the LibSVM model from the classic SVM model is that SVM types can be selected. Once the SVM types have been determined, the processing steps are similar to the conventional SVM. In this model, nu-SVR SVM type and RBF Kernel type is selected. The RBF kernel portion was previously explained. Schölkopf et al. (1998) proposed a support vector classification algorithm called nu-SVR, which was self-adjusting the epsilon parameter. Nu-SVR provides a parameter that can set and control the number of support vectors based on the total number of samples in the data set.

2.5. Neuro-Fuzzy

Suitable methods for classical analysis (key curves, linear regression) cannot be applied successfully in the field of hydrology because hydrological events are dependent on many variables and have non-linear relationships. In order to analyze such hydrological events, simple, economical, and easy methods have been developed. Therefore, more accurate and efficient results can be obtained as the events are discussed in the perspective of fuzzy. Neuro-fuzzy (NF) is a very effective logical understanding that can be used for this approach (Üneş et al. 2015).

NF was initially represented by Jang (1993). The NF system works as a learning algorithm created with neural network functional rules. The parameters of neuro-fuzzy systems are obtained by neural network learning algorithms in fuzzy rule-based systems, and different analysis methods such as Sugeno can be applied. The NF with Sugeno type works according to "If-Then" rules and the NF structure uses the Sugeno-Fuzzy rules. It is possible to introduce fuzzy systems are logical models which is consisted of "If-Then" rules and membership functions. The Sugeno NF system, generated by two rules using three inputs, is shown in Fig. 3. Where, w_1 or w_2 is obtained by weighted mean of individual rule outputs. NF structure is shown in Fig. 4. NF is connected via directional links and contains several nodes. Every node has a node function that can be constant or adjustable parameters. During learning process, the fittest parameter values are obtained by adjusting training data. NF is a method with the basic learning rules that want to reduce the total of the squared errors between the network output data and the real output data.

Sugeno system in the first degree, two fuzzy If / Then rules with a typical set of rules can be specified as follows (Sayed et al. 2003).

1. Rule: If x is A_1, y is B_1 and z is C_1; then $f_1 = p_1x + q_1y + r_1z + s$
2. Rule: If x is A_2, y is B_2 and z is C_2; then $f_2 = p_2x + q_2y + r_2z + s$

where: A_1, B_1, C_1 and A_2, B_2, C_2 are linguistic labels (such as "low", "medium" or "high"), f_1 and f_2 denote, respectively, output functions of 1. and 2. rule, $\{p_i, q_i, r_i, s\}$ specified as result parameters.

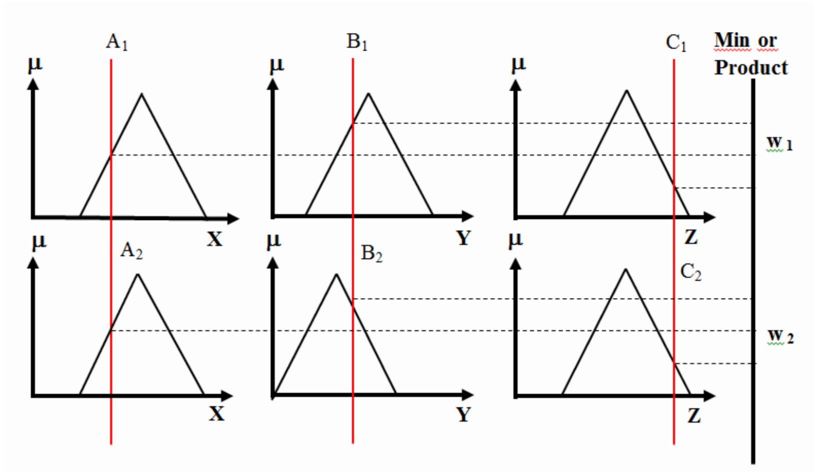

Fig. 3. Sugeno type fuzzy model generated by two rules using three inputs

With a Sugeno fuzzy inference system, NF network is generated. Researchers who want more information about NF can be found in Jang (1993).

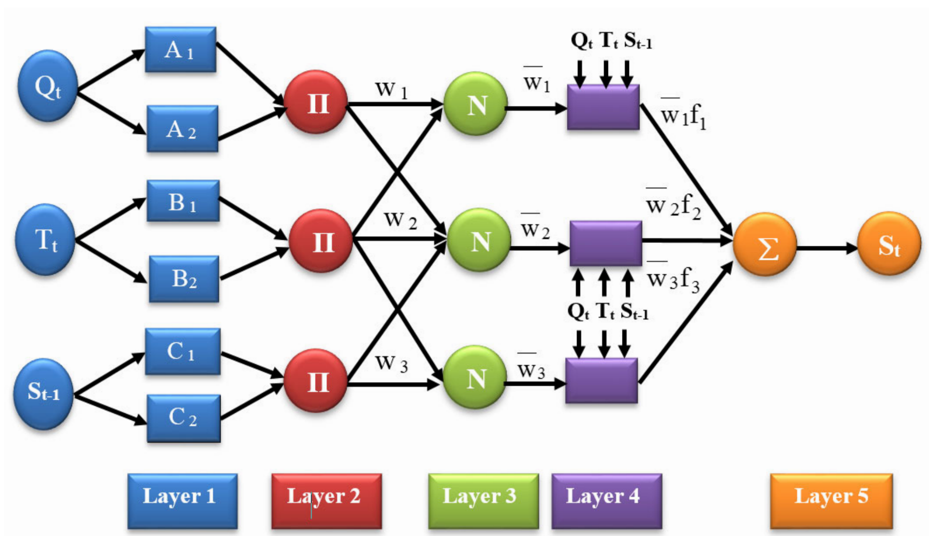

Fig. 4. Structure of the Neuro-Fuzzy (NF) system using three inputs

3. Study area

In this paper, Des Moines County area (Hydrologic Unit No: 18020109) in Iowa, United States was selected as the study area for estimating suspended sediment concentration amount. The Augusta station at the Skunk River has been studied (USGS Station No: 05474000]). Gage Datum at sea level is about 160 m (NGVD29, National Geodesy Vertical Datum). The location of the Augusta station at the Skunk River, which is the right tributary of Mississipi, is shown in Fig. 5.

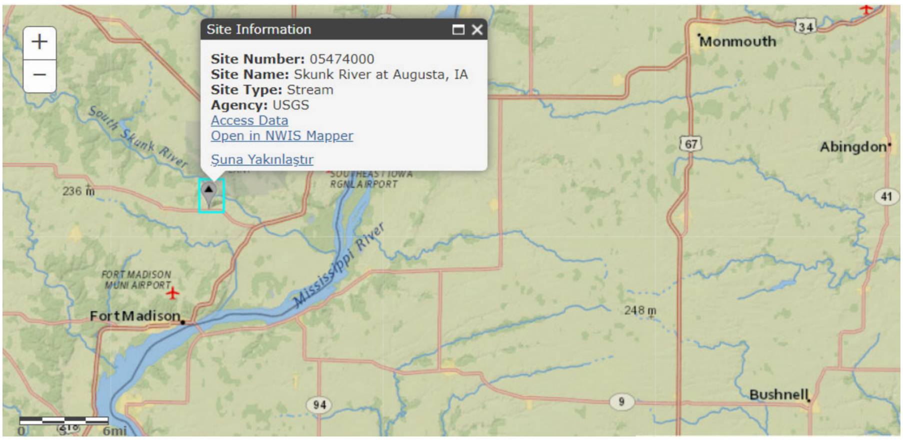

Fig. 5. Augusta station overviews on Skunk River (USGS)

4. Datasets

In this study, 3-year measurement data belonging to the Augusta station were used. Model performs was investigated by using daily average temperature of water, real-time streamflow, and sediment concentration data from Augusta Station at the Skunk River in the USA. A total of 1095 days of three years (2007-2009) was used for estimation. Daily mean temperature (T_{mean}), streamflow (Q) and sediment concentration (S) values are shown in Fig. 6, respectively.

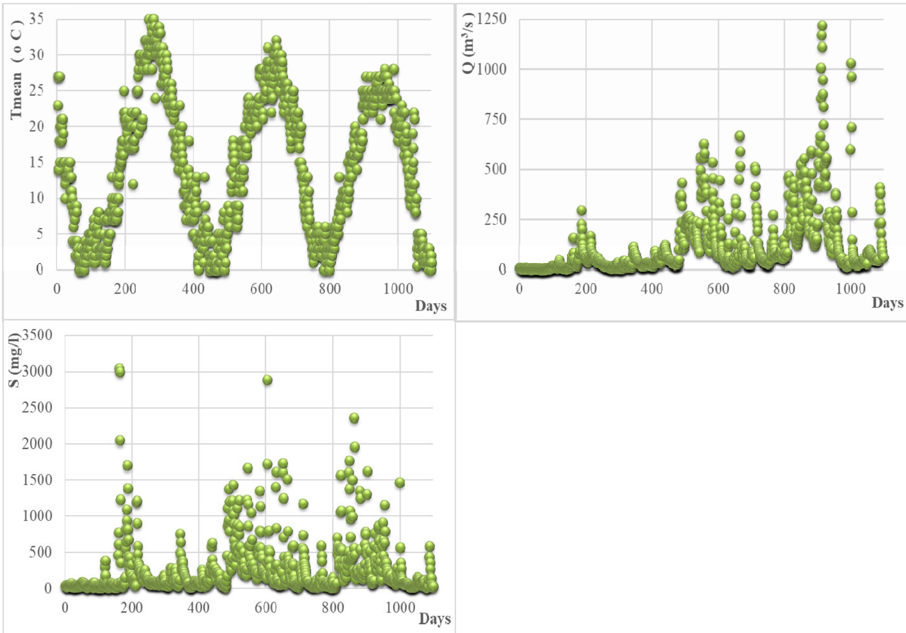

Fig. 6. Daily mean water temperature (T_{mean}), streamflow (Q), and sediment concentration (S) values for 3 years

5. Model results

5.1. Error analysis

The results of SRC, MLR, SVM-RBF, SVM-PK, LibSVM, and NF results for the models generated for 3 years data are as follows. For each model, the mean absolute errors (MAE), the root mean square errors (RMSE), and the correlation coefficients (R) between the models are also used to assess the performance of model estimations and observations. The MAE and RMSE were obtained as follows. The observed values were calculated.

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|Y_{i\,observed} - Y_{i\,estimate}\right| \tag{6}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Y_{i\,observed} - Y_{i\,estimate}\right)^2} \tag{7}$$

Here, N represents data numbers and Y_i sediment concentration data. The model results of the statistical criteria calculated in the study are given in Table 1.

5.2. Model results

In the Sediment Rating Curve (SRC), 3-year data were assessed. The SRC was drawn by fitting a curve to the flow rate (Q_t) and sediment concentration (S_t) data from the station. From the equation expressing this curve, sediment concentration data for SRC were obtained by setting the measured flow values at the gauge station instead of the unknown x value. The SRC for the training data is shown in Fig. 7.

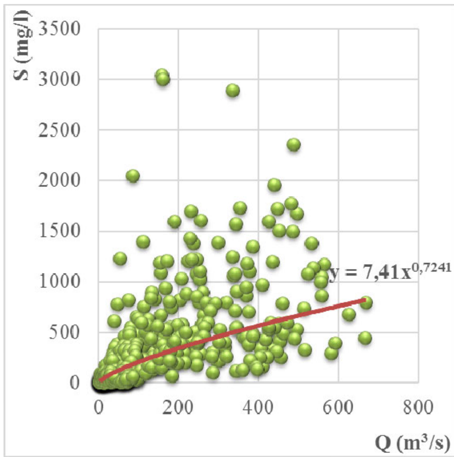

Fig. 7. Sediment Rating Curve (SRC) using train data

The established SRC model using training data is given in Equation 8 and this equation is also applied to the test data. Statistical results (RMSE, MAE and R) and inputs of SRC model are given in Table 1.

$$S_t = 7.4008 \text{ x } (Q_t)^{0.7241} \tag{8}$$

After determining the Sediment Rating Curve, a scatter plot is drawn for the test data. For the test phase, this scatter plot and distribution graph between measured values and the SRC results are shown in Fig. 8a.

The correlation coefficient, between measured values and SRC prediction results, R = 0.47 was obtained for the test. The sediment rating curve multiplies the observed value by the predicted value of real values. When the distribution graph for the test data is examined, it is seen that the SRC sediment estimated values differ than the actual values. According to the SRC results, SRC method has low R value for the test data and when the distribution graph is examined, it is seen that the desired estimates cannot be obtained and it is considerably lower than the station measurement data.

Table 1. Performances of SRC, MLR, SVM-RBF, SVM-PK, LibSVM, NF model for test data

Model No and Inputs		SRC			MLR			SVM-RBF		
Models	Model Inputs	RMSE (mg/l)	MAE (mg/l)	R	RMSE (mg/l)	MAE (mg/l)	R	RMSE (mg/l)	MAE (mg/l)	R
Model 1	Q_t	**278.77**	**163.19**	**0.47**	446.29	240.67	0.41	325.05	175.14	0.42
Model 2	Q_t, Q_{t-1}				437.52	223.22	0.55	333.82	181.58	0.39
Model 3	Q_t, Q_{t-1}, Q_{t-2}				441.91	224.55	0.54	324.08	178.40	0.40
Model 4	T_t				267.47	191.84	0.31	285.85	156.79	0.31
Model 5	T_t, T_{t-1}				266.79	191.65	0.32	284.52	156.40	0.31
Model 6	T_t, T_{t-1}, T_{t-2}				267.13	193.14	0.24	284.30	156.66	0.30
Model 7	S_{t-1}				172.65	87.13	0.75	**180.76**	**81.09**	**0.75**
Model 8	S_{t-1}, S_{t-2}				170.86	85.45	0.76	187.76	82.66	0.72
Model 9	S_{t-1}, S_{t-2}, S_{t-3}				168.09	83.86	0.77	187.66	82.71	0.72
Model 10	Q_t, T_t, S_{t-1}				222.63	122.34	0.69	213.61	112.07	0.66
Model 11	Q_t, Q_{t-1}, T_t, T_{t-1}, S_{t-1}, S_{t-2}				236.75	107.64	0.79	192.53	102.00	0.70
Model 12	Q_t, Q_{t-1}, T_t, T_{t-1}, T_{t-2} S_{t-1}, S_{t-2}				236.75	107.64	0.79	193.50	102.37	0.70
Model 13	Q_t, Q_{t-1}, T_t, T_{t-1},S_{t-1}, S_{t-2}, S_{t-3}				233.90	106.53	0.79	190.44	101.49	0.70
Model 14	Q_t, Q_{t-1}, T_t, T_{t-1}, T_{t-2}, S_{t-1}, S_{t-2}, S_{t-3}				**230.92**	**103.42**	**0.80**	190.45	101.52	0.70
Model 15	Q_t, Q_{t-1}, Q_{t-2},T_t, T_{t-1}, T_{t-2}, S_{t-1}, S_{t-2}, S_{t-3}				172.65	87.13	0.75	186.46	97.86	0.72

MAE: Mean absolute errors; **RMSE**: Root mean square errors **R**: Correlation coefficient

Table 1. cont.

Model No and Inputs		SVM-PK			LibSVM			NF		
Models	Model Inputs	RMSE (mg/l)	MAE (mg/l)	R	RMSE (mg/l)	MAE (mg/l)	R	RMSE (mg/l)	MAE (mg/l)	R
Model 1	Q_t	387.57	200.27	0.41	220.49	143.47	0.63	260.18	178.83	0.63
Model 2	Q_t, Q_{t-1}	385.81	190.90	0.52	155.90	108.75	0.84	182.53	121.09	0.85
Model 3	Q_t, Q_{t-1}, Q_{t-2}	394.10	193.27	0.51	165.37	107.42	0.83	219.16	153.48	0.81
Model 4	T_t	286.16	156.66	0.31	266.78	166.50	0.25	269.56	192.87	0.33
Model 5	T_t, T_{t-1}	284.95	156.46	0.32	266.36	166.52	0.25	281.84	209.67	0.19
Model 6	T_t, T_{t-1}, T_{t-2}	285.60	156.62	0.32	266.23	166.54	0.25	275.70	203.89	0.19
Model 7	S_{t-1}	174.57	73.66	0.75	168.69	72.62	0.77	166.42	85.06	0.78
Model 8	S_{t-1}, S_{t-2}	173.10	72.17	0.76	166.44	69.09	0.78	156.72	77.26	0.82
Model 9	S_{t-1}, S_{t-2}, S_{t-3}	169.48	69.78	0.77	166.32	68.83	0.78	164.80	79.48	0.81
Model 10	Q_t, T_t, S_{t-1}	177.54	84.29	0.74	215.12	77.02	0.81	169.07	102.82	0.80
Model 11	Q_t, Q_{t-1}, T_t, T_{t-1}, S_{t-1}, S_{t-2}	213.95	91.70	0.80	**121.38**	**64.39**	**0.90**	134.75	77.69	0.88
Model 12	Q_t, Q_{t-1}, T_t, T_{t-1}, T_{t-2} S_{t-1}, S_{t-2}	208.59	89.33	0.80	124.94	65.78	0.90	156.48	89.15	0.88
Model 13	Q_t, Q_{t-1}, T_t, T_{t-1},S_{t-1}, S_{t-2}, S_{t-3}	199.74	83.38	0.81	122.35	65.87	0.90	**131.25**	**73.71**	**0.89**
Model 14	Q_t, Q_{t-1}, T_t, T_{t-1}, T_{t-2}, S_{t-1}, S_{t-2}, S_{t-3}	201.30	83.86	0.81	122.97	65.57	0.89	147.00	80.75	0.89
Model 15	Q_t, Q_{t-1}, Q_{t-2},T_t, T_{t-1}, T_{t-2}, S_{t-1}, S_{t-2}, S_{t-3}	**180.72**	**79.41**	**0.83**	125.74	64.53	0.89	151.62	82.64	0.88

MAE: Mean absolute errors; **RMSE**: Root mean square errors; **R**: Correlation coefficient

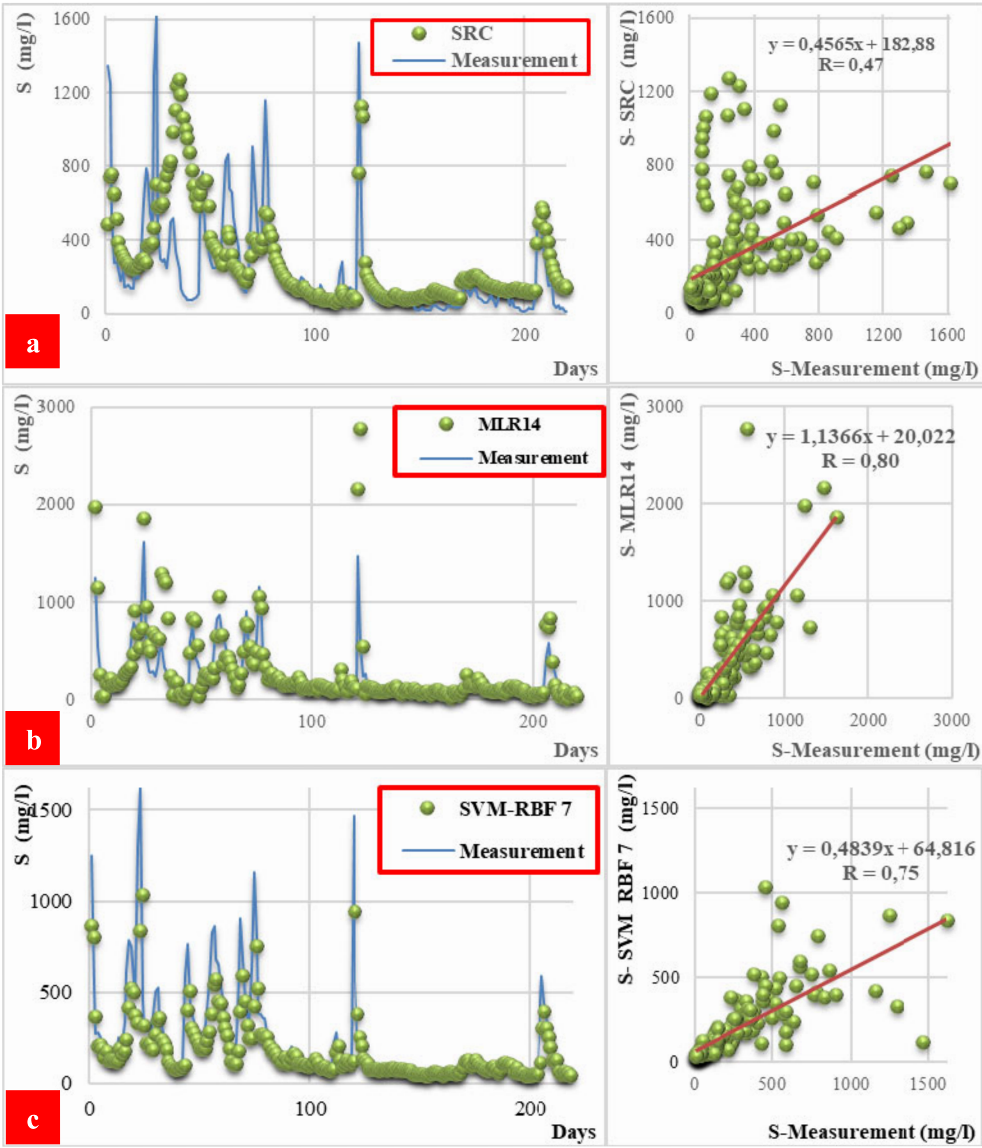

Fig. 8. Measurement and Model distribution-scatter graph for test data **a)** SRC **b)** MLR14 **c)** SVM-RBF 7

As for the Multi Linear Regression (MLR 1 to 15), 3-year data were assessed and the results were determined as follows. The mean temperature (T_t), the lagged time mean temperatures (T_{t-1}, T_{t-2}), the streamflow (Q_t), the lagged time stream-flows (Q_{t-1}, Q_{t-2}), and the lagged time sediment concentrations (S_{t-1},

S_{t-2}, S_{t-3}) at the time "t-1"; "t-2"; "t-3" were used as input values for the MLR model analysis.15 different models (MLR 1 to MLR 15) were used for MLR model studies. Statistical results (RMSE, MAE and R) and inputs of MLR model are given in Table 1.

According to Table 1, the best results in the MLR model belong to the "**MLR14**" model. The results of the MLR14 model are given below. The equation of MLR predictions is obtained by using training data in the MLR14 model and this equation is also applied to the test data. The equation used in MLR model estimation is given in Equation 15.

$$S_t = 232.21 + 3.43Q_t - 3.08Q_{t-1} - 3.7T + 4.14T_{t-1} + 0.27T_{t-2} + \\ + 0.7S_{t-1} + 0.05S_{t-2} + 0.06S_{t-3} \quad (9)$$

For the 3-year data generated, MLR 14 model was evaluated, and MLR 14 distribution and scatter graphs are shown, Fig. 8b.

In the scatter plot generated during the test phase, the correlation coefficient was obtained as R = 0.80. MLR1 test data estimations are lower than training data estimations. The MLR1 estimates in the test phase yield far-reaching estimates of actual values, although the daily sediment values yield better results than the SRC values. It has been observed that the MLR14 prediction values are smaller than the real sediment observation values in the scatter graphs.

For the SVM-RBF model analysis, as in MLR, the 3-year data are divided into training and test data. 15 different models (SVM-RBF 1 to SVM-RBF 15) were used for SVM-RBF model studies. Statistical results (RMSE, MAE, and R) and inputs of the SVM-RBF model are given in Table 1.

According to Table 1, the best results in the SVM-RBF model belong to the "SVM-RBF 7" model. The results of the SVM-RBF 7 model are given below. For the 3-year data generated, SVM-RBF 7 model was evaluated. Distribution and scatter graphs of the SVM-RBF 7 model are shown in Fig. 8c.

The correlation coefficient R = 0.75 was obtained for the graph generated for the test with the SVM-RBF 7 model results. The SVM-RBF 7 estimations at the test phase show better results than SRC model estimation values for the observed daily real-time sediment concentrations. But the MLR 14 model gave slightly better prediction results than the SVM-RBF 7.

For the SVM-PK model analysis, as in MLR and SVM-RBF, the 3-year data are divided into training and test data. 15 different models (SVM-PK 1 to SVM-PK 15) were used for SVM-PK model studies. Statistical results (RMSE, MAE, and R) and inputs of these models are given in Table 1.

According to Table 1, the best results in the SVM-PK model belong to the **"SVM-PK 15"** model. The results of the SVM-RBF 7 model are given below. Distribution and scatter graphs of the SVM-PK 15 model are shown in Fig. 9a. below, respectively.

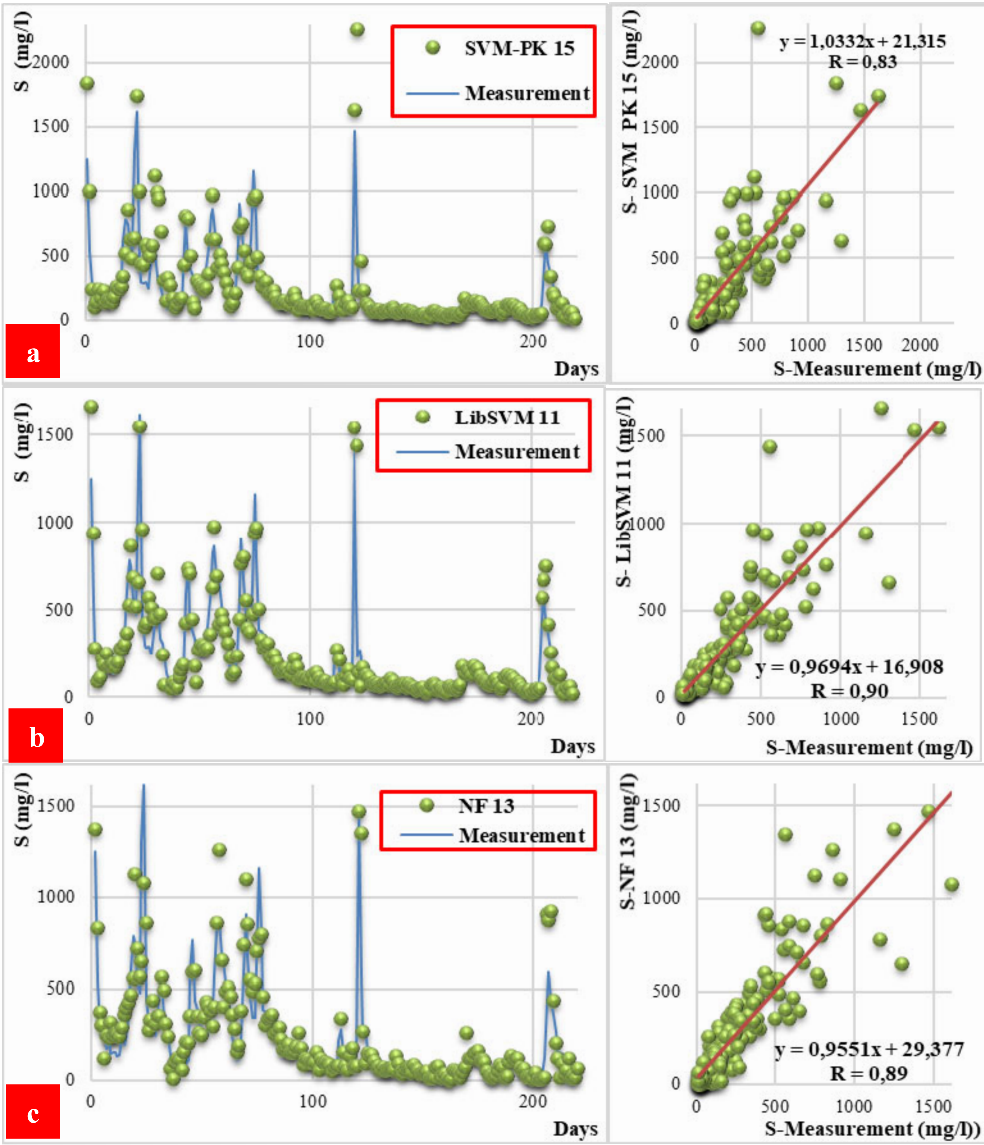

Fig. 9. Measurement and Model distribution-scatter graph for test data **a)** SVM- PK 15 **b)** LibSVM 11 **c)** NF 13

In the scatter plot generated during the test phase, the correlation coefficient was determined as R = 0.83. The SVM-PK 15 estimations at the test phase show better results than the other models (SRC, MLR 14, SVM-RBF 7) values for the observed daily real-time sediment concentrations. The SVM-PK 15 model predictions have close to the actual sediment measurements.

For the LibSVM model analysis, as in MLR; SVM-RBF, and SVM-PK, the 3-year data are divided into training and test data. 15 different models (LibSVM 1 to LibSVM 15) were used for LibSVM model studies. Statistical results (RMSE, MAE and R) and inputs of these models are given in Table 1.

According to Table 1, the best results in the LibSVM model belong to the **"LibSVM 11"** model. The results of the LibSVM 11 model are given below. Distribution and scatter graphs of the LibSVM model are shown in Fig. 9b. below, respectively.

The correlation coefficient R = 0.90 was obtained for the graph generated for the test with the LibSVM 11 model results. The LibSVM 11 estimations at the test phase show better results than the other models (SRC, MLR 14, SVM-RBF 7 and SVM-PK 15) values for the observed daily real-time sediment concentrations.

In NF analysis, Gaussian parabolic 3x3x4x4x3x4x3 Membership Functions (MFs) and Grid Partition section were analyzed with 300 iterations, assuming the output as linear. For the NF model analysis, as in MLR; SVM-RBF, SVM-PK and LibSVM the 3-year data are divided into training and test data. 15 different models (NF 1 to NF 15) were used for NF model studies. Statistical results (RMSE, MAE and R) and inputs of these models are given in Table 1.

According to Table 1, the best results in the NF model belong to the **"NF 13"** model. The results of the NF 13 model are given below. Distribution and scatter graphs of the NF 13 model are shown in Fig. 9c. below.

The correlation coefficient R = 0.89 was obtained for the graph generated for the test with the NF 13 model results. The NF 13 estimations at the test phase show better results than the other models (SRC, MLR 14, SVM-RBF 7, and SVM-PK 15) values for the observed daily real-time sediment concentrations. It is seen that NF and LibSVM models have low error rates and a high correlation when a general evaluation is carried out.

5.3. General evaluation

Sediment amounts from 875-day observations used in the training of the NF model were also trained for MLR, SVM models as input set. Then, the models created were applied to the inputs of the test data generated from 220-day observations. The model results were compared with the measured values. The correlation coefficient variation of prediction models are given in Fig. 10.

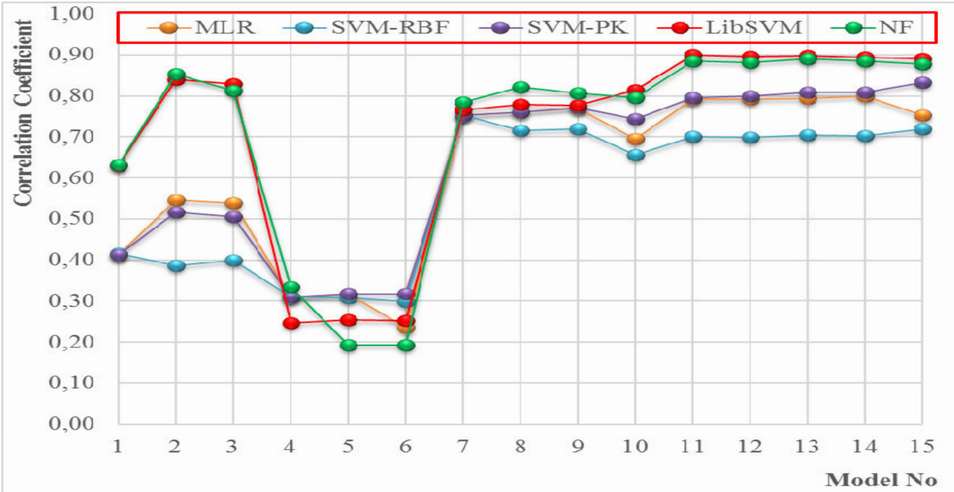

Fig. 10. Correlation coefficient variations according to SRC, MLR, SVM, and NF models

The model with the best result according to Table 1 is obtained when RMSE, MAE have the smallest, and R has the largest value. According to RMSE, MAE, and R, the SRC model (278,77-163,19-0,47) has the lowest success rate. The MLR 14 (230,92-103,42-0,80) model performed better than the SRC model. The SVM-PK 15 (180,72-79,41-0,83) model performed better than the SRC, MLR 14, and SVM-RBF 7 model. The NF 13 (131,25-73,71-0,89) and LibSVM 11 (121,38-64,39-0,90) models were found to perform better than the other classical methods at all estimation performance evaluations.

6. Conclusions

In the present study, the potential of sediment rating curve (SRC), multi linear regressions (MLR), neuro-fuzzy (NF) and support vector machines with radial basis function kernel (SVM-RBF), support vector machines with the poly kernel (SVM-PK), LibSVM for the predicting of daily suspended sediment concentration is questioned by comparing the results with the observed suspended sediment concentration. Daily mean temperature, real-time streamflow, sediment concentration, 3-year data from the Skunk River Augusta station in the US were used. As a result of this study, it is possible to draw the following conclusions:

For the 3-year data, the best results according to the correlation coefficient and error analysis criteria were obtained in the neuro-fuzzy and LibSVM models. But, the LibSVM approach slightly better than the NF model for forecasting daily sediment concentrations. The worst estimation results in all criteria were obtained in the sediment rating curve model.

The MLR model could not find the desired accuracy in the same question due to the nonlinearity of the suspended sediment behavior while explaining empirical relationships.

Support vector machines with poly kernel model has better performance than SRC, MLR, and SVM RBF models

The neuro-fuzzy and LibSVM models whose inputs are the air temperature, streamflow, lagged time stream-flows and suspended sediment concentrations performed the best among the input combinations tried in this paper. This indicates that all these variables are needed for better suspended sediment modeling.

As a result, it is demonstrated in this paper that the neuro-fuzzy and LibSVM models can be an applicable and alternative method for suspended sediment prediction in future studies.

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Conflicts of interest: none

References

Berk, R. A. (2004). Regression analysis: A constructive critique (Vol. 11). Sage.

Buyukyildiz, M., & Kumcu, S. Y. (2017). An estimation of the suspended sediment load using adaptive network based fuzzy inference system, support vector machine and artificial neural network models. *Water resources management, 31*(4), 1343-1359. DOI: https://doi.org/10.1007/s11269-017-1581-1.

Çatal, Y., & Saplioğlu, K. (2018). Comparison of adaptive neuro-fuzzy inference system, artificial neural networks and non-linear regression for bark volume estimation in brutian pine (Pinus brutia Ten.). *Applied ecology and environmental research, 16*(2), 2015-2027.

Chang, C.C., & Lin, C.J. (2002). Training v-support vector regression: theory and algorithms. *Neural computation, 14*(8), 1959-1977.

Choubin, B., Darabi, H., Rahmati, O., Sajedi-Hosseini, F., & Kløve, B. (2018). River suspended sediment modelling using the CART model: A comparative study of machine learning techniques. *Science of the Total Environment, 615*, 272-281.

Cortes, C., Vapnik, V. (1995) Support-vector networks. *Mach Learn, 20*, 273-297. DOI: https://doi.org/10.1007/BF00994018

Demirci, M., & Baltaci, A. (2013). Prediction of suspended sediment in river using fuzzy logic and multilinear regression approaches. *Neural Computing and Applications, 23*(1), 145-151. DOI: https://doi.org/10.1007/s00521-012-1280-z

Demirci, M., Üneş, F., & Saydemir, S. (2015). Suspended sediment estimation using an artificial intelligence approach. In Sediment matters, 83-95. Springer, Cham. DOI: https://doi.org/10.1007/978-3-319-14696-6_6

Demirci, M., Unes, F., Kaya, Y. Z., Mamak, M., Tasar, B., & Ispir, E. (2017). *Estimation of groundwater level using artificial neural networks: a case study of Hatay-Turkey*. In "10th International Conference Environmental Engineering".

Demirci, M., Unes, F., Kaya, Y. Z., Tasar, B., & Varcin, H. (2018). Modeling of dam reservoir volume using adaptive neuro fuzzy method. *Aerul si Apa. Componente ale Mediului*, 145-152.

Ebtehaj, I., & Bonakdari, H. (2017). Design of a fuzzy differential evolution algorithm to predict non-deposition sediment transport. *Applied Water Science, 7*(8), 4287-4299.

Ehteram, M., Ahmed, A. N., Latif, S. D., Huang, Y. F., Alizamir, M., Kisi, O., ... & El-Shafie, A. (2021). Design of a hybrid ANN multi-objective whale algorithm for suspended sediment load prediction. *Environmental Science and Pollution Research, 28*(2), 1596-1611.

Emamgholizadeh, S., & Demneh, R. K. (2019). A comparison of artificial intelligence models for the estimation of daily suspended sediment load: a case study on the Telar and Kasilian rivers in Iran. *Water Supply, 19*(1), 165-178.

Firat, M. & Güngör, M. 2010. Monthly total sediment forecasting using adaptive neuro fuzzy inference system. *Stochastic Environmental Research and Risk Assessment, 24*, 259-270. DOI: https://doi.org/10.1007/s00477-009-0315-1

Ghavidel, S. Z. Z., & Montaseri, M. (2014). Application of different data-driven methods for the prediction of total dissolved solids in the Zarinehroud basin. *Stochastic environmental research and risk assessment, 28*(8), 2101-2118.

Gunawan, T. A., Kusuma, M. S. B., Cahyono, M., & Nugroho, J. (2017). The application of backpropagation neural network method to estimate the sediment loads. In *MATEC Web of Conferences, 101*, 05016. EDP Sciences.

Hsu, C. W., Chang, C. C., & Lin, C. J. (2003). A practical guide to support vector classification.

Jang, J. S. (1993). ANFIS: adaptive-network-based fuzzy inference system. *IEEE transactions on systems, man, and cybernetics, 23*(3), 665-685. DOI: https://doi.org/10.1109/21.256541

Kişi, Ö. (2005). Daily river flow forecasting using artificial neural networks and autoregressive models. *Turkish Journal of Engineering and Environmental Sciences, 29*(1), 9-20.

Kisi, O., & Zounemat-Kermani, M. (2016). Suspended sediment modeling using neuro-fuzzy embedded fuzzy c-means clustering technique. *Water resources management, 30*(11), 3979-3994. DOI: https://doi.org/10.1007/s11269-016-1405-8

Kitsikoudis, V., Sidiropoulos, E., & Hrissanthou, V. (2015). Assessment of sediment transport approaches for sand-bed rivers by means of machine learning. *Hydrological sciences journal, 60*(9), 1566-1586.

Meshram, S. G., Singh, V. P., Kisi, O., Karimi, V., & Meshram, C. (2020). Application of artificial neural networks, support vector machine and multiple model-ANN to sediment yield prediction. *Water Resources Management, 34*(15), 4561-4575.

Mirbagheri, S. A., Nourani, V., Rajee, T. & Alikhani, A. (2010). Neuro-fuzzy models employing wavelet analysis for suspended sediment concentration prediction in rivers. *Hydrological Sciences Journal 55,* 1175-1189. DOI: https://doi.org/10.1080/02626667.2010.508871

Partovian, A., Nourani, V., & Alami, M. T. (2016). Hybrid denoising-jittering data processing approach to enhance sediment load prediction of muddy rivers. *Journal of Mountain Science, 13*(12), 2135-2146.

Salih, S. Q., Sharafati, A., Khosravi, K., Faris, H., Kisi, O., Tao, H., ... & Yaseen, Z. M. (2020). River suspended sediment load prediction based on river discharge information: application of newly developed data mining models. *Hydrological Sciences Journal, 65*(4), 624-637.

Saplıoğlu, K., & Çimen, M. (2010). Yapay sinir ağlarını kullanarak günlük yağış miktarının tahmini. *Mühendislik Bilimleri ve Tasarım Dergisi, 1*(1), 14-21.

Sayed, T., Tavakolie, A. & Razavi, A. 2003. Comparison of adaptive network based fuzzy inference systems and B-spline neuro-fuzzy mode choice models. *Journal of Computing in Civil Engineering 17,* 123-130. DOI: https://doi.org/10.1061/(ASCE)0887-3801(2003)17:2(123)

Schölkopf, B., Bartlett, P., Smola, A. & Williamson, R. 1998. *Support vector regression with automatic accuracy control*. In ICANN 98, 111-116. Springer, London.

Seyedian, S. M., & Rouhani, H. (2015). Assessing ANFIS accuracy in estimation of suspended sediments. *Građevinar, 67*(12), 1165-1176.

Taşar, B., Kaya, Y. Z., Varçin, H., Üneş, F. & Demirci, M. (2017). Forecasting of suspended sediment in rivers using artificial neural networks approach. *International Journal of Advanced Engineering Research and Science, 4*(12).

Turhan, E., & Çağatay, H. Ö. (2016). Eksik akım verilerinin tahmin modelinin oluşturulmasında yapay sinir ağlarının kullanımı: Asi Nehri-Demirköprü akım gözlem istasyonu örneği. *Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi, 31*(1), 93-106 (in Turkish).

Turhan, E., Keleş, M. K., Tantekin, A., & Keleş, A. E. (2019). The investigation of the applicability of data-driven techniques in hydrological modeling: The case of seyhan basin. *Rocznik Ochrona Środowiska, 21*, 29-51.

Üneş, F., Joksimovic, D. & Kisi, O. 2015. Plunging flow depth estimation in a stratified dam reservoir using neuro-fuzzy technique. *Water Resources Management 29,* 3055-3077. DOI: https://doi.org/10.1007/s11269-015-0978-y

Üneş, F., Doğan, S., Taşar, B., Kaya, Y., & Demirci, M. (2018a). The Evaluation and Comparison of Daily Reference Evapotranspiration with ANN and Empirical Methods. *Natural and Engineering Sciences, 3*(3), 54-64.

Üneş, F., Bölük, O., Kaya, Y. Z., Taşar, B., & Varçin, H. (2018b). Estimation of Rainfall-Runoff Relationship Using Artificial Neural Network Models for Muskegon Basin. *International Journal of Advanced Engineering Research and Science, 5*(12), 198-205.

USGS.gov | Science for a changing world [WWW Document], n.d. URL https://www.usgs.gov/

Wieprecht, S., Tolossa, H. G., & Yang, C. T. (2013). A neuro-fuzzy-based modelling approach for sediment transport computation. *Hydrological sciences journal, 58*(3), 587-599.

Williams, J. R. (1978). A sediment graph model based on an instantaneous unit sediment graph. *Water Resources Research, 14*(4), 659-664. DOI: https://doi.org/10.1029/WR014i004p00659

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Environmental Costs Generated by Road Freight Transport in Poland

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Abstract: The sector of transport, on the one hand, contributes to the socio-economic development; on the other hand, it is the source of multiple external effects with a significant and adverse impact on the society and economy. In spite of many years' experiences in the study of external costs of transport, there are still large discrepancies in research approaches and methods. This article reviewed available studies in the scope of the estimation of external costs in transport and presented own estimations of the level of costs of climate change and air pollution generated by road freight transport in Poland. The estimation of external costs was conducted based on a method developed by Martinio et al. The obtained results of the study confirm the significant adverse effect of road freight transport on the environment. The results may be useful in the selection of appropriate transport policy instruments.

Keywords: road freight transport, external costs, costs of climate change, air pollution

1. Introduction

Problems connected with the protection of the natural environment against the harmful impact of the economic activity carried out by humans is one of the most significant challenges of today. These issues pertain to the exploitation of natural resources, pollution of the environment, climate change, destruction of natural habitats of numerous plant and animal species, as well as risks to entire ecosystems (Radim et al. 2019). These changes also result in increasing threat to the safety of people, their well-being and health (Pawłowska 2018).

Already in 1990s, transport was recognised as one of the most cumbersome sectors of human activity. Unfortunately, this tendency continues. In the aspect of transport, on top of risks connected with disturbing the balance in ecosystems, there are also the issues of transport accidents and related material and human losses (Pawłowska 2017). In terms of policies, the problems mentioned above have been addressed through the concept of sustainability, which is present in most of the programming documents of the European Union, both on the level of the entire economy of the group and in sectoral programmes. The concept of sustainability of transport is a response to the failures of the transport policy of the second half of the 20th century. Unsustainable transport causes pollution of the natural environment, absorbs enormous amounts of energy, and the increase of investments in this sphere does not cause the expected improvement of the quality of provided services (Baran & Górecka 2019, Jacyna et al. 2018). The aim of this article is to review available studies in the scope of estimation of external costs in transport and to present the results of own estimations of the level of costs of the climate change and air pollution generated by road freight transport in Poland. The obtained results of the research may be useful in the selection of appropriate transport policy instruments.

2. Literature review

In Poland, transport is a very important sector of economy, which is demonstrated e.g. by its 7.8% share in the GDP (Quarterly national accounts…, GUS 2020). The development of the transport sector is very closely connected with the process of socio-economic development on a feed-back basis. Transport connects markets, allows production to be increased, activates regions surrounding its infrastructure (Koźlak 2012). Transport is also the source of many major external effects that are negative for the society and the economy, resulting in significant social costs. The external effects of transport refer to a situation in which the user of transport does not pay all the costs connected with the transport process (including environmental costs, costs of congestion or road accidents) or does not receive full benefits connected with them (EC 1995).

Most of all, transport uses vast areas for the development of transport infrastructure, both non-linear and linear one, as well as seriously pollutes the atmospheric air, water and soil. Furthermore, transport activity distorts the natural terrain and landscape, leading to defragmentation of the ecosystem; it damages the structure of the bedrock, destroys plants and threatens animals. Transport has an adverse effect on human organisms by causing risks to their health and life. Generally, we can differentiate four areas in transport in which external effects occur (Rothengater 2000, Gołębiowski et al. 2020). Firstly, the expansion of infrastructure may lead to both positive and negative external effects, which are not taken into account in market transactions. Secondly, users within the transport sector can affect each other, leading to unintended interactions rendering the sector ineffective. Thirdly, the financial structure of payments for the use of the infrastructure may prove falsified due to the unjust division of financial flows, i.e. tax-payers pay much more than the value of public services resulting from the functioning of the infrastructure, while private users pay less than the actual costs of using the infrastructure. The fourth area pertains to the fact that the activity carried out on or thanks to the transport infrastructure affects third parties from outside the transport sector, e.g. through noise, accidents, air pollution (Pawłowska 2018).

Apart from the above-mentioned categories, also significant are the costs of up- and downstream processes. This group of costs includes the costs of air pollution and climate change generated by the production of electricity and fuels for transport, costs of emissions connected with the production and maintenance of means of transport and transport infrastructure, and costs of managing waste generated by the transport activity (Burdzik et al. 2014).

Since the start of 1990s, the estimation and internalisation of external costs of transport have been important subjects of studies. In recent years, many studies under numerous research projects – both on a EU level and the level of individual EU countries – have been conducted with an aim to develop the methods of estimation of the external costs of transport. Table 1 presents a summary of major studies focusing on the costs of climate change and air pollution generated as a result of the activity of various branches of transport.

Table 1. Summary of studies and research in the scope of external costs of air pollution and climate change generated by transport

Year	Institution conducting the works/Authors	Branch of transport	Scope of research	Climate change	Air pollution
2018	UBA	road	Germany	+	+
2016	CE Delft	transport	EU 28	+	+
2015	Petruccelli U.	road, railway	UK, Italy, Germany	+	+
2014	Ricardo-AEA	all	EU	+	+
	Mindur L. et al.	road, railway	Poland	+	+
	Huderek-Głapska S.	all	EU	+	+
2012	Trela M.	road	Poland		+
	Poliński J.	road, railway	Poland	+	+
	Becker J. et al.	road	UE 27		+
2011	European Commission	all	EU	+	+
	HEIMTSA	road, railway	EU		+
	CE Delft, INFRAS, Frauhafner, Delft JSI	all	EU	+	+
2010	Martinio A. et al.	all	EU	+	+
	NERI	road	EU		+
	Victoria Transport Policy Institute	road	EU	+	+

Table 1. cont.

Year	Institution conducting the works/Authors	Branch of transport	Scope of research	Climate change	Air pollution
2008	CE Delft (IMPACT)	all	EU	+	+
	CE Delft (OECD)	all	EU	+	+
	Fondazione Eni Enrico Mattei	road, railway, sea, air	Italy	+	+
	Leeds University (GREACE)	all	UE 25	+	+
	LEBER/INFRAS	road, railway	Basque Country	+	+
2005	WHO	all	EU		+
	Bickel P. et al. (HEATCO)	road, railway	UE 25		+
2004	Van Essen H.P. et al.	road, railway, air	UE 15		+
	CE Delft	all	Netherlands	+	+
2004/ 2000	INFRAS/IWW	all	EU 15, Norway, Switzerland	+	+
2002	Leeds University (UNITE)	road, urban rail, water, air	EU 15, Hungary, Estonia, Switzerland	+	+
2001	Weinreich S. et al. (RECORDIT)	all	3 European corridors	+	+
	COWI	road, railway	Estonia	+	+
	Leeds University (CAPRI)	road, railway, air	EU	+	+
	Boiteux Report	road, railway	France	+	+
	Commission of the European Communities	all	EU	+	+
2000	Nash C. et al. (PETS)	road, railway, air	EU	+	+
	INFRAS/IWW	all	EU	+	+
	Experts assuming advisory roles of the High Level Group for charging for the transport infra-structure	road, railway	EU		+
	KBN	road, railway	Poland	+	+
1998	Sansom T. et al. (ITS)	road, railway	UK	+	+
	ECTM	road, railway	EU 15, Norway, Switzerland	+	+
1992	European Commission	all	EU	+	+
	European Commission	all	EU	+	+

Source: Zych-Lewandowska et al. 2020

3. Aim, materials and methods

The aim of the article was to estimate the level of costs of climate change and air pollution generated by road freight transport in Poland, using the method proposed by Martinio et al. (2009). It has been found that the method of Martinio et al. (2009) is the most appropriate approach to the estimation of external effects, standing out against the previously published proposals (cf. Table 1). This document was ordered by the EU Committee on Transport and developed by TRT Transporti e Territorio, a company specialising in research projects in the scope of economics and transport, including: planning, modelling, quantitative analyses and economic evaluation of transport. The work of Martinio et al. (2009) summarises research available at the time in the scope of the analysis of external costs of transport and, additionally, the manual IMPACT (*Maibach* et al. 2008) and the transport package of the European Commission (Green Transport Package 2008).

The basic assumption of the applied method of Martinio et al. (2009) is the division of external costs into six groups: accidents, climate change, air pollution, noise, congestion, other (Table 2). In terms of research, this article focuses on an analysis of external costs connected with the environment, i.e. costs of air pollution and climate change generated by road freight transport.

The research facility was selected on purpose. The research concerned the sector of road freight transport. The choice was affected by the fact that road transport in Poland in 2018 performed 85.5% of the total shipping work. The research covered the period 2005-2016. The scope of research started in 2005 due to Poland's accession to the European Union and the necessity for state agencies to collect statistical data necessary for conducting this research. The source material for the study was data from Statistics Poland and the National Emissions Balancing and Management Centre.

Table 2. Division of external effects into groups in line with the recommendations of the EU Committee on Transport

External effect	Cost components	Basic factors influence on cost
accidents	– material losses, – administrative costs, – medical costs, – production losses, – risk value,	– kind/characteristics/maintenance of vehicles, – speed of vehicles, – traffic, – time of day, – weather conditions, – deployment of infrastructure, its technology and maintenance,
air pollution	– costs of human health, – costs of material losses, – crop losses,	– population density and settlement density, – density of receptors close to emission sources, – sensitivity of the area, – level of emissions,

Table 2. cont.

External effect	Cost components	Basic factors influence on cost
climate change	– costs of prevention aimed at reducing the risk of climate change, – costs of losses caused by the increase of temperature,	– kind of vehicle and its equipment, – speed, – driving style, – fuel consumption and carbon content in the fuel,
congestion	congestion: – costs of time, – operational costs, deficiency: – costs of delays, – costs of lost opportunities,	congestion: – kind of infrastructure, – traffic intensity and capacity depending most of all on the time of day, place, accidents and the kind of structure of the infrastructure, deficiency: – kind of infrastructure, – level of traffic and capacity depending most of all on the time of day and place,
noise	– nuisance, – medical costs,	– time of day, – density of receptors close to emission sources, – existing noise levels,

Source: Martinio et al. 2009

4. Research results

According to Martinio et al. (2009), climate change, also referred to as the global warming, means “a change in the concentration of greenhouse gases causing a gradual warming at the surface of the Earth, mainly due to human activity.” According to the study, the costs of climate change include: costs of losses in agricultural production, changes in the availability of water resources and the rise in the sea level, health effects, increase in transport emissions, and costs of coal use.

According to Maibach et al. (2008), the level of external costs of climate change is proportional to the volume of freight and fuel consumption, and is estimated based on the amount of CO_2 emissions. These emissions depend on: the type of vehicle and its equipment, characteristics of emissions depending on the speed of the vehicle, driving style, fuel consumption and type of vehicle.

In the EU countries, transport accounted for 33.4% of CO_2 emission (Statistical Pocketbook 2020). Aside from the listed variables affecting this value, it can be concluded that it also depends on the location. According to Gradziuk and Gradziuk (2016), in the territory of the analysed rural municipalities, transport accounted for 47% of CO_2 emission, i.e. much more than the

European average, as the location where transport takes place has a direct effect on the above-listed properties, most of all on the driving style.

Martinio et al. (2009) presented suitable indicators for the estimation of the external costs of climate change caused by heavy goods vehicles transporting freight (Table 3). As part of the research, the external costs of climate change caused by road transport were estimated. Data from Table 4 was used, which included the volume of freights in consecutive years, which was then multiplied by appropriate indicators from Table 3. Calculation results are presented in Table 5. Due to the availability of data, the costs were aggregated to average values by dividing them into freight areas.

The costs of climate change in Poland caused by road freight transport, after an initial growing trend in 2008-2011, levelled off at the about PLN 2.5 bn a year (Table 5). These costs varied depending on the place of carriage, i.e. whether within a city, outside a city or on a motorway. In the studied period, the average cost of climate change caused by road transport on motorways was PLN 170 m, and was the lowest in comparison with other roads; its growth dynamics, however, was the largest. The highest costs were caused by inter-city transport, conducted not on motorways but on other roads, which were used for transporting the most goods. The level of costs of climate change on other roads reached on average PLN 1.5 bn annually. This was mainly caused by the lack of an appropriate number of express roads. Furthermore, the external cost of one vehicle-kilometre is higher on other roads than on motorways due to, e.g. a different driving mode (fewer instances of slowing down, accelerating and stopping at junctions, etc.), but also a closer proximity of human settlements, which can be directly affected by air pollution. In urban areas in Poland, the level of generated external costs of climate change can be deemed average compared with other analysed areas (it amounted to about PLN 750 m).

Air pollution is mostly made up of the emission of: nitric oxides, non-methane volatile organic compounds (NMVOCs), sulphur dioxides as well as $PM_{2.5}$ and PM_{10} particulate matter. Other pollutants include: carbon monoxide, ammonia, heavy metals (cadmium, mercury, lead, arsenic, chromium, zinc, copper, nickel), persistent organic pollutants (POP: dioxins, furans and polychlorinated biphenyls, hexachlorobenzene, benzo(a)pyrene and polycyclic aromatic hydrocarbon (PAH)), as well as total dust (TSP, which also contains $PM_{2.5}$ and PM_{10}) and carbon black dust. A detailed analysis in the case of road transport focused on the first group of compounds considered by Martinio et al. (2009) as the most significant one.

The main factors affecting the emission of pollutants by transport include: fuel composition, engine characteristics and maintenance, kind and basic characteristics of the vehicle, distribution of transport infrastructure, speed, congestion. The basis for the analysis of the external costs of air pollution by road transport were the multipliers recommended by the EU (Table 6).

Table 3. Indicators for the estimation of the external costs of CO_2 emissions for heavy goods vehicles in road transport divided into transport areas, mass of the vehicle and fulfilled fuel consumption standard

Mass of vehicle	EURO standard	Value of indicators by area [euro cent/ vehicle-kilometre]				
		metropolitan	city	inter-city	motorways	average
< 7.5 t	EURO 0	1.3	1.3	1.2	1.2	1.2
	EURO 1	1.1	1.1	1.0	1.0	1.0
	EURO 2	1.1	1.1	1.0	1.0	1.0
	EURO 3	1.1	1.1	1.1	1.1	1.1
	EURO 4	1.1	1.1	1.0	1.0	1.0
	EURO 5	1.1	1.1	1.0	1.0	1.0
7.5-16 t	EURO 0	2.0	2.0	1.8	1.7	1.7
	EURO 1	1.8	1.7	1.6	1.5	1.5
	EURO 2	1.7	1.7	1.5	1.4	1.5
	EURO 3	1.8	1.8	1.6	1.5	1.5
	EURO 4	1.6	1.6	1.5	1.4	1.4
	EURO 5	1.7	1.7	1.5	1.4	1.4
16-32 t	EURO 0	2.0	2.0	1.8	1.7	1.7
	EURO 1	1.8	1.8	1.6	1.5	1.5
	EURO 2	1.7	1.7	1.5	1.4	1.4
	EURO 3	1.8	1.8	1.6	1.5	1.5
	EURO 4	1.6	1.6	1.5	1.4	1.4
	EURO 5	1.7	1.7	1.5	1.4	1.4
> 32 t	EURO 0	2.9	2.9	2.5	2.3	2.3
	EURO 1	2.6	2.6	2.2	2.0	2.0
	EURO 2	2.5	2.5	2.2	2.0	2.0
	EURO 3	2.6	2.6	2.2	2.0	2.0
	EURO 4	2.4	2.4	2.1	1.9	1.9
	EURO 5	2.5	2.4	2.1	1.9	1.9

Source: Maibach et al. 2008

Table 4. Traffic in freight transport in Poland in the years 2008-2015

Type of road	Level of road freight traffic in years [millions of vehicle-kilometres]							
	2008	2009	2010	2011	2012	2013	2014	2015
Motorways	1,577	2,320	2,765	2,917	2,892	2,962	2,982*	2,986*
City roads	8,639	8,671	9,761	10,215	10,090	10,269	10,524	1,010
Other roads	19,527	18,832	21,112	22,067	21,760	22,115	21,999*	21,763*

* Data estimated based on data from Statistics Poland from corresponding years.
Source: own study based on data from Statistics Poland

Table 5. External costs of climate change caused by road freight transport in Poland in 2008-2015 divided into areas of transport

Type of road	External costs of climate change (PLN m) in given years:								Dynamics 2008/2015 (%)
	2008	2009	2010	2011	2012	2013	2014	2015	
Motor-ways	103	151	181	190	188	193	194	194	128
City roads	673	676	761	796	786	800	820	843	124
Other roads	1,354	1,305	1,463	1,530	1,508	1,533	1,525	1,509	115
Total	2,130	2,132	2,405	2,516	2,482	2,526	2,539	2,546	119

Source: own study

Table 6. Values recommended for the estimation of the costs of air pollution caused by transport

Specification	Values of indicators for pollutants [EUR/tonne]								
Pollutant	NO_x	NMVOCs	SO_2	$PM_{2.5}$			PM_{10}		
Context	N/A	N/A	N/A	Metropolitan area	Urban area	Non-built up area	Metropolitan area	Urban area	Non-built up area
Multiplier	3,900	600	5,600	174,500	56,000	52,400	69,800	22,400	20,900

Source: Martinio et al. 2009

The estimation of the level of the external costs of pollution in transport in Poland used the data of the National Centre for Emissions Management (KOBiZE), which concerned the amounts of emission of compounds broken into individual branches of economy. The amounts of pollution emitted by road freight transport in consecutive years and the external costs of this emission are presented in Table 7 and 8.

Total emissions of road freight transport in 2016, respectively: NO_x: about 150 k tonnes; NMVOCs: about 12 k tonnes; $PM_{2.5}$ and PM_{10}: about 5 k tonnes; SO_x: about 0.12 tonnes (Table 7). Road transport is an insignificant emitter of sulphur oxide, because the combustion of diesel and petrol fuel produce only trace amounts of sulphur. The conducted analyses confirm the downward trend in the emission of pollutants in road transport in the years 2005-2016, both in terms of volume and generated external costs. However, in 2016 there was a noticeable increase in the emission of the compounds in question. According to the National Centre for Emissions Management, it resulted from an increased amount of fuel consumed by road transport.

Table 7. Emissions of SO_x, NO_x, NMVOCs, $PM_{2.5}$ and PM_{10} caused by road freight transport in 2005-2016 in Poland

Year	Emission of a compound in given years [tonnes]				
	NO_x	NMVOCs	SO_x	$PM_{2.5}$	PM_{10}
2005	146,315.68	18,134.81	0.10	6,399.46	6,399.46
2006	162,252.54	20,548.24	0.10	7,225.93	7,225.93
2007	178,109.03	20,477.62	0.11	7,663.32	7,663.32
2008	168,503.95	17,969.19	0.11	6,830.44	6,830.44
2009	172,530.34	18,417.27	0.12	7,023.98	7,023.98
2010	168,313.28	15,629.97	0.12	6,237.34	6,237.34
2011	169,146.54	14,715.14	0.12	5,987.20	5,987.20
2012	155,500.96	13,774.20	0.11	5,480.27	5,480.27
2013	133,487.70	11,886.67	0.10	4,541.05	4,541.05
2014	131,159.97	11,077.65	0.10	4,305.54	4,305.54
2015	126,585.68	10,237.45	0.11	3,982.07	3,982.07
2016	148,022.24	11,692.65	0.12	4,669.48	4,669.48
Dynamics 2016/2005	101%	64%	120%	73%	73%

Source: own study based on KOBiZE

Table 8. External costs of the emission of compounds by road freight transport in 2005-2016 (PLN m)

Year	External costs of the emission of compounds by road freight transport (PLN m)						Unit costs PLN/ tkm
	NO_x	NMVOCs	SO_x	$PM_{2.5}$	PM_{10}	Total	
2005	2,459.42	46.90	0.38	2,600.95	1,039.83	6,147.10	0.051
2006	2,727.30	53.14	0.35	2,936.86	1,174.12	6,891.42	0.050
2007	2,993.83	52.96	0.35	3,114.62	1,245.19	7,406.61	0.046
2008	2,832.38	46.47	0.30	2,776.12	1,109.86	6,764.83	0.039
2009	2,900.06	47.63	0.29	2,854.78	1,141.31	6,943.78	0.036
2010	2,829.18	40.42	0.27	2,535.06	1,013.49	6,418.15	0.030
2011	2,843.18	38.05	0.28	2,433.40	972.84	6,287.48	0.028
2012	2,613.82	35.62	0.26	2,227.36	890.47	5,767.28	0.025
2013	2,243.79	30.74	0.24	1,845.63	737.86	4,858.03	0.019
2014	2,204.67	28.65	0.21	1,749.91	699.59	4,682.82	0.018
2015	2,127.78	26.47	0.20	1,618.45	647.03	4,419.74	0.016
2016	2,488.11	30.24	0.20	1,897.83	758.73	5,174.91	0.017
Dynamics 2016/2005	101%	64%	53%	73%	73%	84%	33%

Source: own study

A significant element of the analysis is the estimation of not only total emissions, but also unit emissions, i.e. expressed as tonne-kilometres, because only such approach presents the real level of the impact of road transport on the environment and allows it to be compared with other branches. Unit external costs of air pollution generated by road freight transport decreased year after year (Table 8). This trend continued, even though the volumes of freight in Poland increased each year. It may mean that the quality of the means of transport improved. In the case of road transport, it would be a constantly increasing share of newer vehicles, meeting the more and more restrictive engine standards. However, an analysis of the age of heavy goods vehicles does not confirm that, instead pointing to the ageing of the HGV fleet (Statistics Poland 2016). Therefore, the decrease of emissions in road transport must have been caused not by changes in the fleet of vehicles, but rather in the infrastructure. The increase of the length of express roads and motorways in Poland in the period from 2005 to 2016 was significant (motorways from 552 km to 1,637 km – increase by almost 300%; express roads from 258 km to 1,534 km – increase by almost 600%). Since the level of fuel consumption – and, consequently, the emission of pollutants – is directly affected by the traffic flow, then the expansion of the network of express roads could have been the cause of the decrease in the unit emissions of pollutants in road transport.

5. Conclusions

The achievement of sustainable transport development appears as the main priority of the transport policy in today's world. The EU has caused the development of specific methodological assumptions in the scope of the estimation of the external costs of transport, which may support further steps of internalisation of external costs and reform of transport charges. However, it is not possible to precisely identify the structure of the external costs of transport and to estimate their values as a function of time, because, on the one hand, the estimates of the external costs of transport entail a large error margin, and on the other hand there is a lack of access to required data which could be used for estimation. However, some methods of estimation of these costs can deliver estimated values of costs. In Poland, there are few publications and studies of the full estimate of the external costs of transport. In consideration of the above, and assuming that the analysis of external costs may become a significant element of transport costs, and, consequently, of logistics in the areas of deliveries, production and distribution, this article presented an estimation of external environmental costs of road freight transport.

Road transport accounts significant percentage of total emissions of harmful compounds. The results of the conducted studies, when compared to the previous research of the authors (Zych-Lewandowska et al. 2020, Zych-

Lewandowska 2020), demonstrate that, in terms of the emissions of SO_x, NO_x, NMVOCs, $PM_{2.5}$ and PM_{10}, road transport is in a much worse position than rail transport. This means that rail transport has a decisively less adverse effect on human health and natural environment than road transport.

In order to reduce the adverse external effects of road transport, various actions are undertaken. For the purpose of reducing the emission of harmful gases and particulate matter, exhaust emission standards (EURO) are introduced for new vehicles sold in the European Union (Merkisz et al. 2012). Furthermore, the automotive market presents new technologies for powering vehicles with alternative fuels, which have a smaller impact on the environment. Electric vehicles are introduced as well. Currently, they are not a popular choice due to their limited performance, range, charging time and, most of all, high costs of production of such cars as well as the necessity to adjust the infrastructure to them. However, the BEV (Battery Electric Vehicle) technology is the most discussed concept, which gives hope for the reduction of emissions of harmful pollutants to the environment.

The prevailing unfavourable branch structure of shipping, which is decisively dominated by road transport with its still growing share in shipping, impedes the achievement of the desired effects of actions taken. In addition, the continuing growing trends in the transport of passengers and goods result in the effects of actions taken being largely countered by the increased carriage work of both the goods and passenger transport.

References

Baran, J., Górecka, A. (2019). Economic and environmental aspects of inland transport in EU countries. *Economic Research-Ekonomska Istraživanja, 32*(1), 1037-1059. DOI: 10.1080/1331677X.2019.1578680

Burdzik, R., Kabot, M., Cieśla, M. (2014). Classification and internalisation of external cost in road transport. *Logistyka, 4*, 1723-1732 (in Polish).

European Commission, EC (1995). Green Paper: Towards fair and efficient pricing in transport. Policy options for internalising the external costs of transport in the European Union. COM (95)691 final. Brussels.

Gołębiowski, P., Żak, J., Jacyna-Gołda, I. (2020). Approach to the proecological distribution of the traffic flow on the transport network from the point of view of carbon dioxide. *Sustainability, 12*(17), 6939. DOI: 10.3390/su12176936

Gradziuk, P., Gradziuk, B. (2016). Low-Carbon Economy – A New Challenge for Rural Communes. *Wieś i Rolnictwo, 1*, 105-123. DOI: 10.7366/wir012016/06 (in Polish).

Green Transport Package of 8 July 2008, European Commission 2008.

Jacyna, M., Wasiak, M., Lewczuk, K., Chamier-Gliszczynski, N., Dąbrowski, T. (2018). Decision Problems in Developing Proecological Transport System. *Rocznik Ochrona Środowiska, 20*(2), 1007-1025.

Koźlak, A. (2012). *A modern transport system as a factor in the development of regions in Poland*. Gdańsk: Publishing House of the University of Gdańsk (in Polish).

Maibach, M., Schreyer, C., Sutter, D., van Essen, H.P., Boon, B.H., Smokers, R., Schroten, A., Doll, C., Pawłowska, B., Bąk, M. (2008). Handbook on estimation of external costs in the transport sector. Produced within the study Internalization Measures and Policies for All external Costs of Transport (IMPACT), Delft.

Martinio, A., Maffii S., Sitran, A., Giglio, M. (2009). The Calculation of External Costs in the Transport Sector A comparative analysis of recent studies in the light of the Commission's 'Greening Transport Package. Brussels.

Merkisz, J., Pielcha, J., Nowak, M. (2012). Exhaust emissions from vehicles in real traffic conditions on the example of Poznan agglomeration. *Postępy Nauki i Techniki, 15*, 103-105 (in Polish).

Pawłowska, B. (2017). *An overview of the progress towards sustainable transport development by using TERM indicators*. W: M. Suchanek (red.), Sustainable transport development innovation and technology. Proceedings of the 2016 TranSopot Conference, Springer, 27-46.

Pawłowska, B. (2018). External costs of transport in Poland. *Scientific Review – Engineering and Environmental Sciences, 27*(1), 28-41. DOI: 10.22630/PNIKS. 2018.27.1.4 (in Polish).

Quarterly national accounts of gross domestic product 2015-2019 (2020). Warszawa: GUS (in Polish).

Radim, L., Baran, J., Wysokiński, M., Gołasa, P., Bieńkowska-Gołasa, W., Golonko, M., Chamier-Gliszczyński, N. (2019). Economic and Environmental Efficiency of the Chemical Industry in Europe in 2010-2016. *Rocznik Ochrony Środowiska, 21*, 1393-1404.

Roman, M., Górecka, A., Domagała, J. (2020). The Linkages between Crude Oil and Food Prices. *Energies, 13*(24), 1-18. DOI: 10.3390/en13246545

Rothengater, W. (2000). *External Effects of Transport.* W: J.B. Polak, A. Heertje (red.), Analytical transport economics. An International Perspective, Cheltenham: Edward Elgar Publishing, 79-116.

Statistical Pocketbook. EU Transport in figures (2020). EU.

Statistics Poland (2016).

Zych-Lewandowska, M. (2020). *Negative externalities of freight transport in Poland and methods of reducing them.* Warszawa: Publishing House of SGGW (in Polish).

Zych-Lewandowska, M., Domagała, J., Klepacki, B. (2020). *Negative externalities of transport in economic theories and methods of their estimation.* Warszawa: Publishing House of SGGW (in Polish).

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The Influence of the Przebędowo Reservoir on the Water Quality of the Trojanka River in the First Years of its Functioning

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Abstract: Agriculture, mainly biogenic compounds (nitrogen and phosphorus) and plant protection products are one of the sources of environmental pollution. The sources of pollution are both farm buildings and intensively used agricultural land. Therefore, a crucial element of the environment contributing to the improvement of surface water quality are the aforementioned shallow reservoirs covered by vegetation that act as biofiltres or reservoirs such as dammed reservoirs. The analysed reservoir is located in the Greater Poland Province, about 25 km to the north from Poznań, in Murowana Goślina commune. The research on the analysed reservoir was conducted during the growing seasons, from 2016 to 2018, at three measurement and control points: at the Przebędowo reservoir inflow, it the Przebędowo reservoir and at the Przebędowo reservoir outflow. They included determining 4 groups of physico-chemical indicators supporting biological elements, including indicators characterising aerobic conditions, salinity, acidification (pH) and indicators characterising biogenic conditions. Based on the conducted research, a great influence of the reservoir was proven, especially in the context of the concentration of dissolved oxygen at the outflow, where, concerning this indicator, the reservoir was classified as water quality class I. The presented research results also confirmed that in the context of the complexity of hydrological and physico-chemical processes taking place in dammed reservoirs, it is necessary to continuously control them both in terms of water quantity and quality.

Keywords: small-scale water retention, dammed reservoirs, water quality

1. Introduction

Changes in the quality of surface water of a catchment are particularly visible in small water reservoirs. The factors that influence the size of the biogenic compounds and their migration in surface water are the development of the catchment, the size and depression of the land, the type and degree of vegetation cover, population density, sanitation infrastructure, level and method of fertilisation, livestock density and others (Giercuszkiewicz-Bajtlik 1990, Ilnicki 2002). Concerning the functions of reservoirs, there are also two vital aspects, from which conflicting purposes of its use emerges. On the one hand, reservoirs are an important element of industrial infrastructure and indispensable source of water for cities and settlements but, on the other hand, because of their impact on the environment, they are also a vital element of the ecosystem (Wicher 2004). However, reservoirs which have a dam (dammed reservoirs), apart from their basic functions, also improve the purity of surface water. After damming, sedimentation and retention of up to 90% of mineral and organic particles that are in the water flowing into a reservoir occurs. Nonetheless, one cannot unequivocally determine whether reservoirs improve or deteriorate the water quality as these issues are very complex (Wiatkowski et al. 2010).

Agriculture, mainly biogenic compounds (nitrogen and phosphorus) and plant protection products are one of the sources of environmental pollution. The sources of pollution are both farm buildings and intensively used agricultural land (Saunders et al. 2001, Elser et al. 2007, Chislock et al. 2013). Chemical compounds from applied mineral fertilisers and plant protection products, leaking septic tanks and sewage systems are washed away by rain and directed to surface waters. Reduction of the amount of these pollutions can be achieved by suitable management of agriculture, building a treatment plant. However, even with such management, some of the compounds that get into the soil during fertilisation will always be washed away by precipitation water and will enter surface waters. Therefore, a crucial element of the environment contributing to the improvement of surface water quality are the aforementioned shallow reservoirs covered by vegetation that act as biofiltres or reservoirs such as dammed reservoirs. According to Galicka et al. (2007) dammed reservoirs can periodically retain up to 90% of the total amount of matter flowing into them. Wiatkowski (2008, 2010) states that after flowing of the water of the Prosna river through the Psurów reservoir, one could spot a significant reduction of phosphates (by 21%), nitrates (V) (by 26%), nitrates (III) (by 9%) and ammonia (by 5%).

The influence of a dammed reservoir on water quality in the rivers located below it depends on the amount of stored water and the flow as well as on the time of water retention and the location of the reservoir (on the water-course or as a side-reservoir). Reservoirs with a long time of retention of water are "trap" for the river nutrient material such as phosphorus and nitrogen and limit the amount of mineral suspensions. Depending on the depth and location of discharge, reservoirs can lower the water temperature in summer (deep reservoirs with a long time of water retention, in which stratification occurs and water discharge is below the thermocline) or raise it (shallow reservoirs with a long time of water retention). Water leaving deep reservoirs with a discharge below the thermocline on a short section below the dam has a low oxygen concentration. Some dammed reservoirs retain the water of poor quality (with a high content of phosphorus and nitrogen compounds) and introduce biological contaminants, namely large amount of phytoplankton into the river below, causing the algal bloom. The phenomenon caused by the algal bloom of water occurs in small and medium rivers with shallow reservoirs with a long time of retention.

Storage reservoirs in Poland are located mainly in catchments that are characterised by agricultural use, mostly in the lower or middle course of the river. Certainly, this is related to the problems with their functioning and exploitation. Such reservoirs are exposed to excessive accumulation of biogenic compounds, mainly organic and inorganic nitrogen and phosphorus compounds (as it was mentioned earlier). The result is the deterioration of the quality of the stored water and eutrophication (Przybyła et al. 2014).

The aim of this study was to assess the impact of Przebędowo reservoir on the water quality of the Trojanka river in the first years of its functioning.

2. Materials and methods

The analysed reservoir is located in the Greater Poland Province, about 25 km to the north from Poznań, in Murowana Goślina commune (Fig. 1). According to natural regions of Poland based on physical geography (Kondracki 2000), the area of research, characterised by the early post-glacial landscape, is located in the Greater Poland Lakeland (Polish: Pojezierze Wielkopolskie) in the area of the Poznań Warta Gorge (Polish: Poznański Przełom Warty) (315.52). The discussed catchment area of about 100^2 is covered mainly by forests, and to a lesser extent, arable lands in the area adjacent to the reservoir. The structure of land use according to Corine Land Cover 2018.

The Przebędowo reservoir was constructed in the valley of the Trojanka river at km 6+915-8+371 of its course, by the Provincial Management of Drainage, Irrigation and Infrastructure in Poznań and commissioned in November 2014. The reservoir is 1450 meters long and 120 meters wide. The front dam is class IV and is 334 meters long. It should be noted that the Trojanka river acts as a local wildlife corridor for a river system. The river is vital for the connection of the area of Puszcza Zielonka Landscape Park (established in 1994) Special Area of Conservation Natura 2000 "Uroczyska Puszczy Zielonki" and the Warta river to which it flows. Due to this fact, the reservoirs maintain connections between area of the Trojanka river above the damming and the Warta river valley. The main task of the reservoir is to store water for agricultural purposes, as well as to improve ambient and water conditions on adjacent agricultural land and to protect the area below the dam and area adjacent to the reservoirs from flooding and fire. 13 meters wide ecological buffer zone (biogeochemical barrier) was established around the reservoir and it serves as a transition zone between the reservoirs and the agricultural land in order to limit the flow of biogenic compounds (nitrogen, phosphorus) and plant protection products from the adjacent areas.

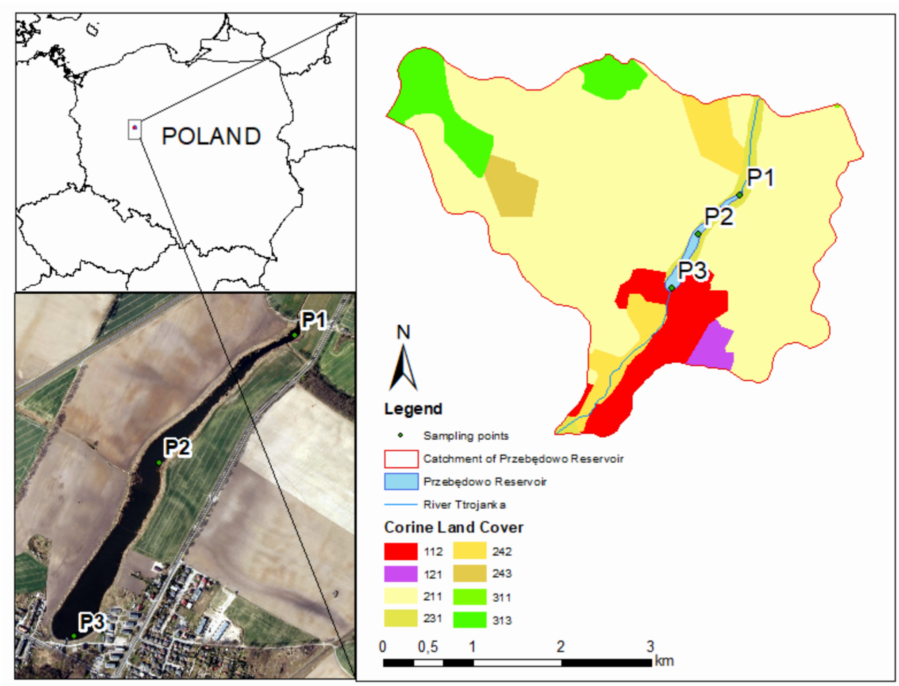

Fig. 1. Location of the Przebędowo Reservoir with water sampling points (P1 – inflow, P2 – reservoir, P3 – outflow) and use of the catchment area

The research on the analysed reservoir was conducted during the growing seasons, from 2016 to 2018, at three measurement and control points: at the Przebędowo reservoir inflow (Trojanka river), it the Przebędowo reservoir and at the Przebędowo reservoir outflow (Trojanka river). The tests of water samples were collected once a month and carried out in the laboratory of the Institute of Land Improvement, Environmental Development and Geodesy of the Poznań University of Life Sciences. They included determining 4 groups of physico-chemical indicators supporting biological elements, including indicators characterising aerobic conditions (dissolved oxygen content and biochemical oxygen demand $_5$), salinity indicators (calcium, magnesium, sulfates and electrolytic conductivity), acidification (pH) and indicators characterising biogenic conditions (ammoniacal nitrogen, nitrate nitrogen (V) nitrate nitrogen (III) and phosphate (V)) in accordance with applicable standards.

Fig. 2. 13 meters wide ecological buffer zone (biogeochemical barrier)

Statistical inference about the significance of the differences in the values of indicators between the measurement and control points was carried out with the non-parametric Mann-Whitney U test at the significance level $\alpha = 0.05$. This test was chosen due to the lack of normal distribution of most of the analyzed indicators.

The analysis of the ecological status of Trojanka river was carried out in accordance with the Regulation of the Ministry of Marine Economy and Inland Navigation of 11 October 2019 (hereinafter referred to as "the Regulation") on the classification of the ecological status, ecological potential and chemical status, method of classifying the status of a body of surface water, as well as environmental quality standards for priority substances. The ecological status was determined by characterising surface water quality for the abiotic 17 type (lowland sandy river) of a body of surface water, which is the Trojanka river, taking into account the physicochemical elements included in the Regulation.

3. Results and discussion

Analysing the indicators characterising the aerobic conditions, namely the concentration of dissolved oxygen, one can conclude that the average values of this indicator in the discussed vegetation periods of the analysed extent of time, at the inflow of the Przebędowo reservoir and in the reservoir itself were 6.37 and 6.64 g·dm^{-3} respectively, and are lower than the requirements of the Regulation for water quality class II, for which the limit value is set at 6.80 mg·dm^{-3}. However, at the outflow of the reservoir, the average content of oxygen dissolved in water was 7.57 mg·dm^{-3} and exceeded the limit for class II. The water flowing out from the reservoirs can be classified as water quality class I regarding dissolved oxygen concentration (Fig. 3). Nonetheless, the extreme values of the discussed indicator were: min. – 4.0 mg·dm^{-3}, and max – 12.8 mg·dm^{-3} respectively. The analysis of the water in the reservoir shows their good oxygenation. Slightly different results were obtained by Bogdał et al. (2015) at the Goczałkowice reservoir, where the average values of dissolved oxygen concentration at the outflow were lower than at the inflow (inflow – 9.51 mg·dm^{-3}; outflow – 8.46 mg·dm^{-3}). According to these authors, such results were due to the blooming of cyanobacteria.

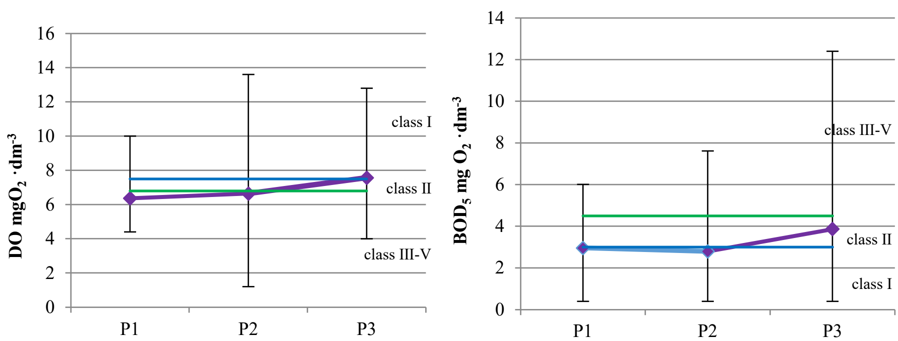

Fig. 3. The content of dissolved oxygen and biochemical oxygen demand $_5$ in the Trojanka river and the Przebędowo reservoir on the three measurement points, during the growing seasons 2016-2018 (average values of indicators)

The analysis of the second indicator characterising aerobic conditions, which is BOD_5, allowed to determine that in the discussed period its values at the inflow ranged from 0.4 to 6.01 mg·dm^{-3}, and the average was 2.96 mg·dm^{-3}, which classifies it as the water quality class I. 2). The quality of waters below the reservoir deteriorated, the value of BOD_5 ranged from 0.4 to 12.4 mg·dm^{-3}, and the average was 3.86 mg·dm^{-3}, which, concerning the analysed growing seasons, would classify it as the water quality class II. Similar values were obtained by J. Kanclerz et al. (2014) on the Stare Miasto reservoir. There, the waters on the inflow were also classified according to BOD_5, as water quality class I, while after flowing through the reservoir, the water quality deteriorated and was also classified as water quality class II.

In general, one can state that the load of organic matter in the Trojanka river and the analysed reservoir that influence oxygen consumption in the self-purification process was irregular.

The results of research conducted in the laboratory and its analysis proved that waters at all three measure points (P1, P2, P3) had a slightly alkaline pH, with the average of P1 = 8.48; P2 = 8.59; P3 = 8.52 respectively, which classified those as water quality class III-V (Fig. 4). The results obtained were consistent with the results of Kanclerz et al. (2014) on Stare Miasto reservoir, where the authors also found a slightly alkaline pH of the waters of the Powa river (the average pH was 8.3), however, according to then binding Regulation of 2011, the waters of the Powa river were classified as water quality class I – of very good quality. Currently, for water quality class I and II, the pH values should be between 7.0 and 7.9.

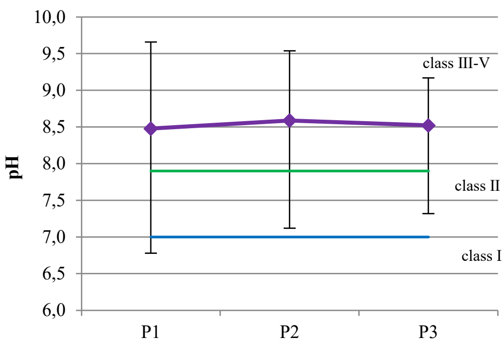

Fig. 4. The pH in the waters of Trojanka river and the Przebędowo reservoir at three measurement points, during the growing seasons 2016-2018 (average values of indicators)

The analysis of indicators characterising salinity of water in the aforementioned measurement points showed that the average values of calcium in the water during the growing seasons in years 2016-2018 were very similar to each other: inflow – 111.33 mg·dm^{-3}; reservoir – 108.0 mg·dm^{-3} and outflow – 110.11 mg·dm^{-3} (Fig. 5) and, according to the Regulation, exceeded values necessary for classification as water quality class II.

Also, no major differences were found in the values of chlorides between the measuring points analysed. The average value of these elements in the analysed years was: at the inflow 34.72 mg·dm^{-3}; in the reservoir 35.14 mg·dm^{-3} and at the outflow 39.86 mg·dm^{-3} (Fig. 5) and according to the Regulation, exceeded the value necessary for classification as water quality class II which is 33.7 mg·dm^{-3}. Based on the obtained results, the quality of water was classified as class III-V.

In the research conducted by Przybyła et al. (2014) on the Jutrosin reservoir, the authors obtained slightly better results in relation to the aforementioned indications, as the concentration of chlorides allowed to classify the quality of water as class I and the concentration of calcium allowed to classify the quality of water as class II.

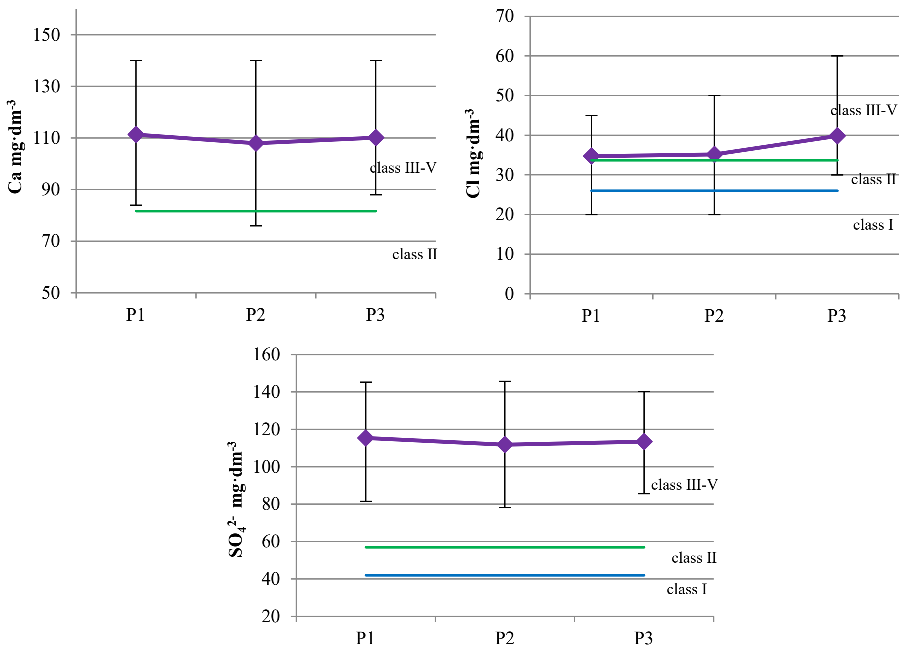

Fig. 5. The content of calcium, chlorides and sulphates (VI) in the waters of Trojanka river and the Przebędowo reservoir at three measurement points, during the growing seasons 2016-2018 (average values of indicators)

The analysis of another indicator characterising salinity of water, i.e. sulphates (VI) proved that, in the discussed period, the lowest values of 78.19 mg·dm^{-3} were recorded in the reservoir, while at the inflow and the outflow from the reservoir values were 81.48 mg·dm^{-3} and 85.59 mg·dm^{-3} respectively (Table 1). The obtained results allowed to classify those waters, in respect of the content of sulphates, as water quality class III-V. The average values of this indicator were: P1 – 115.4 mg·dm^{-3}; P2 – 111.85 mg·dm^{-3}; P3 – 113.39 mg·dm^{-3}. According to the Regulation, the limit value for classification as water quality class III-V is 57 mg·dm^{-3} (Fig. 5).

Table 1. Minimum, maximum, average and median of the physico-chemical indicators in the measurement points in the Trojanka river during the growing seasons 2016-2018

Indicator	Control and measurement points		
	Inflow (P1)	Reservoir (P2)	Outflow (P3)
/1/	/2/	/3/	/4/
Dissolved oxygen DO (mg O_2 · dm^{-3})	4.4-10 6.37 (6.10)	1.2-13.6 6.64 (6.32)	4.0-12.8 7.57 (6.81)
Biochemical oxygen demand, BOD_5 (mg O_2 · dm^{-3})	0.4-6.01 2.96 (2.65)	0.4-7.62 2.79 (2.28)	0.4-12.4 3.86 (3.11)
Acidification (pH)	6.78-9.66 8.48 (8.75)	7.12-9.54 8.59 (8.75)	7.32-9.17 8.52 (8.68)
Calcium Ca (mg · dm^{-3})	84.0-140.0 111.33 (116.0)	76.0-140.0 108.0 (108.0)	88.0-140.0 110.11 (110.0)
Magnesium Mg (mg · dm^{-3})	4.86-21.89 13.78 (14.59)	7.30-19.46 13.24 (12.16)	9.73-24.32 14.59 (13.38)
Chlorides Cl (mg · dm^{-3})	20.0-45.0 34.72 (35.0)	20.0-50.0 35.14 (35.0)	30.0-60.0 39.86 (40.0)
Nitrate nitrogen (V) $N\text{-}NO_3$ (mg · dm^{-3})	0.02-7.6 1.49 (1.05)	0.02-4.1 1.06 (0.9)	0.02-3.4 1.01 (0.85)
Nitrate nitrogen (III) $N\text{-}NO_2$ (mg · dm^{-3})	0.005-0.09 0.05 (0.05)	0.005-0.15 0.03 (0.025)	0.01-0.09 0.04 (0.02)
Ammoniacal nitrogen $N\text{-}NH_4$ (mg · dm^{-3})	0.01-0.15 0.04 (0.04)	0.01-0.12 0.03 (0.01)	0.01-0.14 0.04 (0.01)
Sulphates (VI) SO_4^{2-} (mg · dm^{-3})	81.48-145.26 115.4 (123.45)	78.19-145.67 111.85 (114.5)	85.59-140.32 113.39 (118.51)
Phosphate (V) $P\text{-}PO_4$ (mg · dm^{-3})	0.01-0.25 0.08 (0.05)	0.01-0.34 0.08 (0.02)	0.01-0.38 0.10 (0.07)
Electrolytic conductivity EC (µS · cm^{-1})	402.0-714.0 565.22 (555.0)	426.0-674.0 519.22 (514.0)	447.0-725.0 556.94 (548.5)

In the research of Bogdała et al. (2015) on the Goczałkowice reservoir, the authors obtained results allowing them to classify the water, in respect to the average or even maximum values of content sulphates as water quality class I. It may have resulted from the fact that, unlike Przebędowo reservoir, in the catchment of Goczałkowice reservoir, there are no arable lands as well as the parts of the area surrounding it is the protected area of Natura 2000.

The analyses carried out on another crucial indicator of salinity of water, which is the content of magnesium, showed that at each measurement point both minimum and average values of magnesium were at a low level during the test period which allows to classify the water quality as class I. However, by analysing the results, one might conclude that the values of magnesium increased with the flow of water between the points. The lowest value above the reservoir was 4.86 $mg \cdot dm^{-3}$, and in the reservoir itself 7.30 $mg \cdot dm^{-3}$. At the outflow, the lowest value was 9.73 $mg \cdot dm^{-3}$. The maximum values were as follows: inflow 21.89 $mg \cdot dm^{-3}$, reservoir 19.46 $mg \cdot dm^{-3}$, outflow 24.32 $mg \cdot dm^{-3}$ (Table 1). The average values were: inflow13.78 $mg \cdot dm^{-3}$, reservoir 13.24 $mg \cdot dm^{-3}$, outflow 14.59 $mg \cdot dm^{-3}$ (Fig. 6). It should be noted that, according to the Regulation, the limit value for classifying as water quality class I is 18.4 $mg \cdot dm^{-3}$.

The last analysed indicator that measures salinity was the electrolytic conductivity. During the research, it ranged from 402 to 714 $\mu S \cdot cm^{-1}$ for the waters at the inflow of the Przebędowo reservoir and from 426 to 674 $\mu S \cdot cm^{-1}$ for the waters stored in the reservoir and from 447 to 725 $\mu S \cdot cm^{-1}$ for the waters at the outflow of the reservoir (Table 1). It was found that the average values of electrolytic conductivity at the analysed measurement points allow to classify the waters at the inflow as water quality class II, the waters in the reservoir as class I and the waters at the outflow as class II (Fig. 5).

Such a tendency of fluctuation of average values of electrolytic conductivity, and consequently, convergent results, were also obtained by Kozłowski et al. (2017), at the Cedzyna reservoir on the Lubrzanka river. On the mentioned reservoir, the average values were: inflow – 272 $\mu S \cdot cm^{-1}$; reservoir – 222.9 $\mu S \cdot cm^{-1}$; outflow – 229.4 $\mu S \cdot cm^{-1}$.

The last group of analysed physico-chemical indicators is that characterising biogenic conditions.

The first analysed indicator in this group of compounds were phosphates. According to Pawełek et al. (2005), the presence of these compounds in the surface water is due to the soil erosion, sewage inflow, dissolution of all kinds of minerals as well as precipitation.

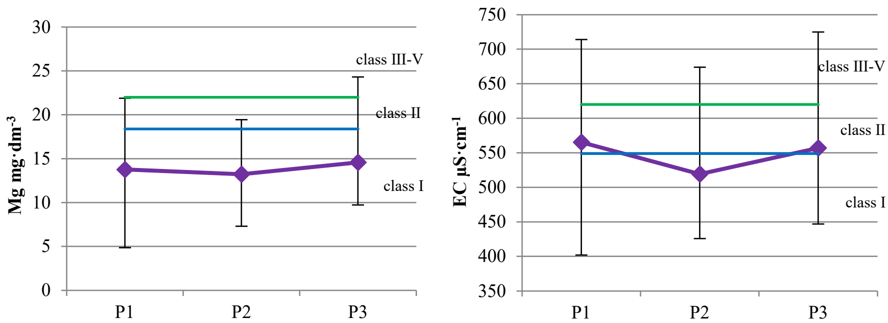

Fig. 6. The content of magnesium and specific electrolytic conductivity in the waters of the Trojanka river and the Przebędowo reservoir at three measurement points, during the growing seasons 2016-2018 (average values of indicators)

Average phosphate values at the inflow of the Przebędowo reservoir and in the reservoir itself were 0.08 mg·dm^{-3}, while at the outflow 0.10 mg·dm^{-3} (Fig. 7). Average phosphate values for the water samples tested during the research period are within the limit value defined by the Regulation for water quality class II, i.e. between 0.065 mg·dm^{-3}, and 0.101 mg·dm^{-3}. The highest (maximum) values for the individual measurement points were: at the inflow 0.25 mg·dm^{-3}, in the reservoir – 0.34 mg·dm^{-3} at the outflow 0.38 mg·dm^{-3} .

Slightly higher values of phosphate were obtained by Pawełek et al. (2008) at the inflow of the Dobczycki reservoir. In their research, the authors analysed the concentration of biogenic compounds in the water of the streams flowing into the reservoir. Average phosphate values for the Dębnik and Wolnica tributaries were 0.136 mg·dm^{-3} and 0.142 mg·dm^{-3}.

Another analysed indicator characterising biogenic conditions was nitrate nitrogen (V). It is a form of nitrogen that is not bound by sorbent soil and therefore is easily washed out. During the research, the average values of the analysed indicator above, below and in the reservoir itself were: P1 – 1.49 mg·dm^{-3}; P2 – 1.06 mg·dm^{-3}; P3 – 1.01 mg·dm^{-3}, which allowed to classify this water, regarding this parameter, as class I (Fig. 7). According to the regulation, the limit value for water quality class I for nitrate nitrogen (V) is 2.2 mg·dm^{-3}.

The results obtained regarding nitrate nitrogen (V) were largely comparable to the results of Kanclerz et al. (2010) obtained from the Stare Miasto reservoir, where the average values of the discussed indicator were also within the limit value of water quality class I.

Indicators characterising ammoniacal nitrogen constitute an important element of assessing the quality of water in reservoirs which catchments are used for agricultural purposes. According to the Regulation, the limit value for the water quality class I for the aforementioned indicator is 0.25 mg·dm^{-3}. In the analysed period, on the reservoir in question, the maximum values did not exceed this limit and were: at the inflow – 0.15 mg·dm^{-3}, in the reservoir – 0.12 mg·dm^{-3}, at the outflow – 0.14 mg·dm^{-3} (Table 1). Average values of ammoniacal nitrogen: P1 – 0.04 mg·dm^{-3}; P2 – 0.03 mg·dm^{-3}; P3 – 0.04 mg·dm^{-3} (Fig. 7).

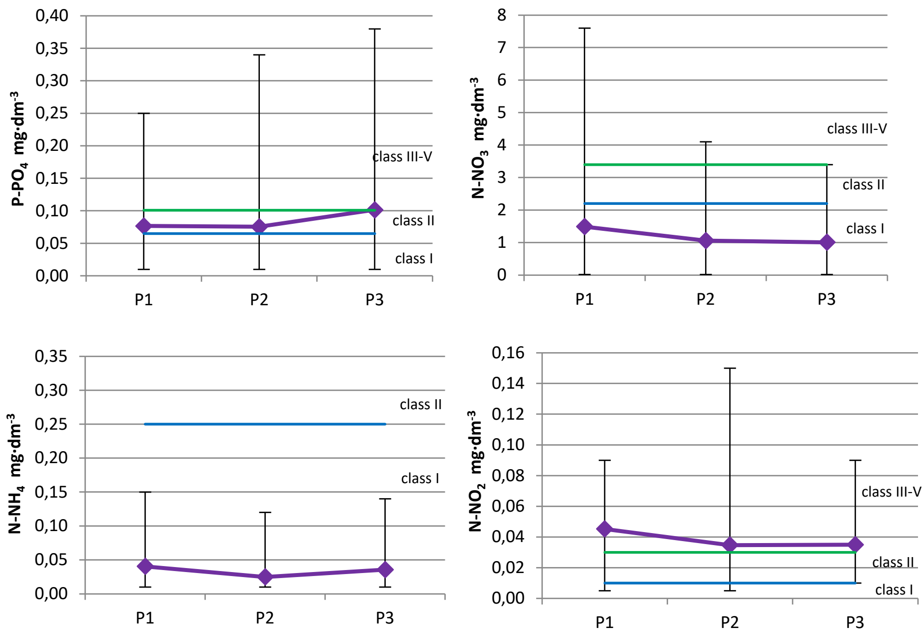

Fig. 7. The content of phosphate (V), nitrate nitrogen (V), ammoniacal nitrogen and nitrate nitrogen (III) in the waters of the Trojanka river and the Przebędowo reservoir at three measurement points, during the growing seasons 2016-2018 (average values of indicators)

Similar results were obtained by Szczykowska (2013), during the analysis of the water quality of the Koryncin reservoir. Ammoniacal nitrogen concentration was relatively low and allowed to classify this as water quality class I. However, the author emphasized that during the winter period, the values of this indicator might be increased, which is largely due to the intake of water from under the ice layer, when processes of ammonification of organic matter of sediments take place. Nonetheless, the observed increase in the value of ammoniacal nitrogen in the spring period might be related to the slopewash in the indirect and direct area of the catchment of the reservoir.

The last analysed indicator was nitrate nitrogen (III). The results obtained in the research period showed that the values of the indicator ranged from 0.005 to 0.9 mg·dm^{-3} concerning the waters at the inflow of the Przebędowo reservoir, from 0.005 to 0.15 mg·dm^{-3} concerning the waters stored in the reservoir and from 0.01 to 0.09 mg·dm^{-3} concerning the waters at the outflow of the reservoir (Table 1). The average values for individual measurement points were: P1 – 0.05 mg·dm^{-3}; P2 – 0.03 mg·dm^{-3}; P3 – 0.04 mg·dm^{-3}. According to the Regulation, the obtained results of the average concentration of the analysed indicator allow to classify these waters as water quality class III-V.

Analysing the average values of nitrate nitrogen (III) it was found that the value of the indicator in the reservoir itself is lower than in the waters at the inflow and the outflow. These results are consistent with the ones of Wiatkowski (2008) obtained on the Młyny reservoir on the Julianpolka river in which the author determined that the average values of this indicator were lower in the reservoir itself than in the waters at the inflow and the outflow.

Statistical analysis performed with the Mann-Whitney U test showed that the values of the two examined indicators differed significantly between the measurement and control points (Table 2). Statistically higher values of dissolved oxygen in water and chlorides were found in point 1 (inflow) compared to point 3 (outflow).

Table 2. Importance of the water indicators' values between the measuring-control points P1 and P3 of the Przebędowo Reservoir – Mann-Whitney's nonparametric test*

Index	Unit	Median of sample points		Test probability, *p*
		Inflow (P1)	Outflow (P3)	
Dissolved oxygen DO	(mg O_2 · dm^{-3})	6.10	6.81	0.037
Biochemical oxygen demand BOD_5	(mg O_2 · dm^{-3})	2.65	3.11	0.734
Acidification	pH	8.75	8.68	0.518
Calcium Ca	(mg · dm^{-3})	116.00	110.00	0.786
Magnesium Mg	(mg · dm^{-3})	14.59	13.38	0.738
Chlorides Cl	(mg · dm^{-3})	35.00	40.00	0.020

Table 2. cont.

Index	Unit	Median of sample points		Test probability, *p*
		Inflow (P1)	Outflow (P3)	
Nitrate nitrogen (V) $N\text{-}NO_3$	$(mg \cdot dm^{-3})$	1.05	0.85	0.459
Nitrate nitrogen (III) $N\text{-}NO_2$	$(mg \cdot dm^{-3})$	0.05	0.02	0.387
Ammoniacal nitrogen $N\text{-}NH_4$	$(mg \cdot dm^{-3})$	0.04	0.01	0.462
Sulphates (VI) SO_4^{2-}	$(mg \cdot dm^{-3})$	123.45	118.51	0.707
Phosphate (V) $P\text{-}PO_4$	$(mg \cdot dm^{-3})$	0.05	0.07	0.653
Electrolytic conductivity EC	$(\mu S \cdot cm^{-1})$	555.00	548.50	0.460

*Statistical values in red mean statistically significant differences at $p < 0.05$

4. Conclusions

1. The research has shown that the parameters characterising aerobic conditions and biogenic conditions with the exception of nitrate nitrogen (III) meet the requirements necessary to classify this reservoir as water quality class II. However, other elements, indicators of salinity and acidification do not meet the requirements necessary to classify this reservoir as water quality class II. Based on the analysis of average values of physico-chemical parameters, the ecological status of the Trojanka river at the inflow and the outflow of the reservoir does not meet the requirements necessary to classify it as water quality class II. Therefore, the ecological status of the waters of the Trojanka river was classified as below good.
2. Out of 12 tested physicochemical indicators of the Trojanka river water, the values of only 2 indices were statistically higher at the outflow from the reservoir.
3. Based on the conducted research, a great influence of the reservoir was proven, especially in the context of the concentration of dissolved oxygen at the outflow, where, concerning this indicator, the reservoir was classified as water quality class I. This situation might be influenced by located on the reservoir discharge and spillway structure with damming height of 3.8 m, which makes the oxygenation process more intensive.

4. The Przebędowo reservoir is a new one as it was commissioned in November 2014. Also, its ecosystem does not yet have its internal mechanisms that transform the excess of the biogenic compounds. This makes the reservoir susceptible to water quality fluctuations. Over the years one can expect the quality parameters to be better.

References

Bogdał, A., Kowalik, T., Witoszek, K. (2015). Wpływ Zbiornika Goczałkowickiego na zmianu jakości wód w rzece Wiśle. *Inżynieria Ekologiczna. 45*, 124-134 (in Polish).

Chislock, M. F., Doster, E., Zitomer, R. A., & Wilson, A. E. (2013). Eutrophication: causes, consequences, and controls in aquatic ecosystems. *Nature Education Knowledge, 4*(4), 10.

Czamara, W., Czamara, A., Wiatkowski, M. (2008). The use pre-dams with plant filtres to improve water quality in storage reservoirs. *Arch. Environ. Prot., 34*, 79-89.

Elser, J. J., Bracken, M. E., Cleland, E. E., Gruner, D. S., Harpole, W. S., Hillebrand, H., ... & Smith, J. E. (2007). Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecology letters*, *10*(12), 1135-1142.

Galicka, W., Kruk, A., Zięba, G. (2007). Bilans azotu i fosforu w zbiorniku Jeziorsko. *Nauka Przyr. Technol. 1*(2), #17 (in Polish).

Giercuszkiewicz-Bajtlik, M. (1990). *Prognozowanie zmian jakości wód stojących*. Instytut Ochrony Śroodowiska, Warszawa (in Polish).

Górniak, A. (2006). Ekosystem zbiornika Siemianówka w latach 1994-2004 i jego rekultywacja. Publishing House of the University of Bialystok, Poland (in Polish).

Kanclerz, J., Wicher-Dysarz, J., Dysarz, T., Sojka, M., Dwornikowska, Ż. (2014). Wpływ Zbiornika Stare Miasto na jakość wody rzeki Powy. *Nauka Przyr. Technol. 8*(4), #54 (in Polish).

Kanownik, W., Kowalik, T., Bodgał, A., Ostrowski, K., Rajda, Wł. (2011). Jakość i walory użytkowe wód odpływających ze zlewni zbiorników małej retencji planowanych w rejonie Krakowa. Wyniki badań przeprowadzonych w ramach projektu rozwojowego nr R12 001 02 sfinansowanego przez Ministerstwo Nauki i Szkolnictwa Wyższego [Quality and utility value of water flowing from the catchment of planned small retention reservoirs near Kraków. Results of studies conducted within the R&D project no. R12 001 02 financed by the Ministry of Science and higher Education], 36 (in Polish).

Kondracki, J. (2000). *Geografia regionalna Polski*. PWN, Warszawa (in Polish).

Kozłowski, R., Przybylska, J., Kaleta, J. (2014). Wpływ zbiornika zaporowego Cedzyna na wybrane parametry jakości wody rzeki Lubrzanki w okresie letnim. *Monitoring Środowiska Przyrodniczego, 19*(1), 81-89 (in Polish).

Pasternak, K. (1968). Skład chemiczny wody rzek i potoków o zlewniach zbudowanych z różnych skał i gleb. *Acta Hydrobiologica, 10*, 1-25 (in Polish).

Pawełek, J., Spytek, M. (2005). *Substancje biogenne w dopływach zbiornika Dobczyckiego*. Infrastruktura i Ekologia Terenów Wiejskich, PAN, 4/2005 99-113 (in Polish).

Pawełek, J., Spytek, M. (2008). *Stężenie związków biogennych w wodzie potoków dopływających do zbiornika Dobczyńskiego*. Infrastruktura i Ekologia Terenów Wiejskich, PAN, 5/2008 179-190 (in Polish).

Pęczuła, W., Suchora, M. (2011). Analiza przyczyn występowania złej jakości wody w zbiorniku retencyjnym w Kraśniku w pierwszych latach jego funkcjonowania. *Prz. Nauk. Inż. Środ. 54*, 321-332 (in Polish).

PN-91 C-04537-09:1973 Woda i ścieki. Badania zawartości związków fosforu. Oznaczanie fosforanów ogólnych metodą kolorymetryczną lub ekstrakcyjno-kolorymetryczną.

PN-C-04576-08:1982 Woda i ścieki. Badania zawartości związków azotu. Oznaczanie azotu azotanowego metodą kolorymetryczną z salicylanem sodowym.

PN-EN 1899-2:2002 Jakość wody. Oznaczanie biochemicznego zapotrzebowania tlenu po n dniach (BZTn) - Część 2: Metoda do próbek nierozcieńczonych.

PN-EN 26777:1999 Jakość wody. Oznaczanie azotynów. Metoda absorpcyjnej spektrometrii cząsteczkowej.

PN-EN 27888:1999 Jakość wody. Oznaczanie przewodności elektrycznej właściwej.

PN-EN 25813:1997 Jakosc wody. Oznaczanie stężenia tlenu rozpuszczonego.

PN-EN ISO 9963-1:2001 Jakość wody. Oznaczanie zasadowości. Część 1: Oznaczanie zasadowości ogólnej i zasadowości wobec fenoloftaleiny.

PN-ISO 7150-1:2002 Jakość wody. Oznaczanie azotu amonowego. Część 1. Manualna metoda spektrometryczna.

PN-ISO 9280: 2002 Jakość wody. Oznaczanie siarczanów(VI) - Metoda grawimetryczna z chlorkiem baru

PN-ISO 9297:1994 Jakość wody. Oznaczanie chlorków - Metoda miareczkowania azotanem srebra w obecności chromianu jako wskaźnika (Metoda Mohra).

PN-ISO 8288:2002 Woda i ścieki – badania zawartości metali metodą absorpcyjnej spektrometrii atomowej - Oznaczanie cynku, miedzi, ołowiu, kadmu, niklu, kobaltu, żelaza i manganu w wodzie z zastosowaniem wstępnego zagęszczenia metodą chelatowania i ekstrakcji.

Przybyła, Cz., Kozdrój, P., Sojka, M. (2014). Ocena jakości wód w lateralnych zbiornikach Jutrosin i Pakosław w pierwszych latach funkcjonowania [Assessment of water quality in the Jutrosin and Pakosław lateral reservoirs in the first years of their operation]. *Inżynieria Ekologiczna, 39*, 123-135 (in Polish).

Puczyńska, I., Skrzypski, J. (2009). Integracja działań biologicznych i technicznych jako podstawa intensyfikacji procesów samooczyszczania się zbiorników zaporowych (na przykładzie zbiornika Sulejowskiego) [Integration of biological and engineering measures as the basis for intensification of self-purification in dam reservoirs (based on the Sulejowski reservoir)]. *Ecological Chemistry and Engineering S, 16*(S2), 221-23 (in Polish).

The Regulation of the Ministry of Marine Economy and Inland Navigation of 11 October 2019 on the classification of the ecological status, ecological potential and chemical status, method of classifying the status of a body of surface water, as well as environmental quality standards for priority substances.

Saunders, D. L., & Kalff, J. (2001). Nitrogen retention in wetlands, lakes and rivers. *Hydrobiologia, 443*(1), 205-212.

Szczykowska, J., Siemieniuk, A., Wiater, J. (2013). Problemy ekologiczne zbiorników małej retencji na Podlasiu. *Ekonomia i Środowisko, 4*(47) (in Polish).
Wiatkowski, M. (2008). *Wstępne wyniki badań jakości wody dopływającej i odpływającej ze zbiornika Psurów na rzece Prośnie*. W: Meteorologia, hydrologia, ochrona środowiska – kierunki badań i problemy. Red. A. Dubicki. Monogr. IMGW: 407-414.
Wiatkowski, M. (2010). Zmiany wybranych wskaźników jakości wody rzeki Prosny przepływającej przez zbiornik Psurów. *Proc. ECOpole 4*(2), 495-500.
Wiatkowski, M. (2010). Ocena jakości wody zbiornika Komorów na potoku Milikówka. *Infrastruktura i ekologia terenów wiejskich, 8*(2), 51-64 (in Polish).
Wicher, J. (2004). *Akumulacja rumowiska w nizinnych zbiornikach wodnych*. Maszynopis. Katedra Inżynieriii Wodnej i Sanitarnej UP, Poznań (in Polish).
Wicher-Dysarz, J., Kanclerz, J. (2012). Funkcjonowanie małych zbiorników nizinnych z wydzieloną częścią wstępną na przykładzie zbiorników Jezioro Kowalskie i Stare Miasto. *Rocznik Ochrona Srodowiska, 14*(1), 885-897 (in Polish).

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Mycological Air Quality at Animal Veterinary Practice

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Abstract: The objective of the study was to characterize the mycological quality of air at animal veterinary practice in Krakow. Bioaerosol measurements were performed during the summer season of 2017. The samples of outdoor and indoor air at animal veterinary practice were collected using a 6-stage Andersen`s air sampler. The highest concentration of fungal aerosol was observed in the treatment room. The analysis showed various fungal contamination in different measuring points at different measuring times of the day. Based on the analysis of bioaerosol particle size distribution it was found that the largest "load" of fungi, isolated form the air, can reach (in the human respiratory tract) to the region of the throat, trachei and primary bronchi. The predominant fungi in indoor air was *Penicillium* spp. and *Cladosporium cladosporoides.* Fungi that can cause dermatophytoses have also been isolated from indoor air: *Microsporum canis* and *Trichophyton verrucosum.* The study confirmed that the animal veterinary practice can be a workplace related to exposure to microbial agents.

Keywords: bioaerosol, fungi, air quality, animal veterinary practice

1. Introduction

In recent years, people spend between 80-95% of their time indoors. It should be emphasized that indoor air quality is one of the most significant factors affecting the human health. One of the biotic contaminants of air are fragments of fungal mycelia and fungal spores. Biological particles can be released into the air from any natural or non-natural surfaces. Fungi can get into the atmosphere from plant and soil, due to wind or thermal convection processes or after emissions from natural water reservoirs. Human activity also has a big impact on the qualitative and quantitative composition of the biological aerosol (Bowers et al. 2012, Polymenakou 2012). The main source of fungi in indoor air are living organisms: people, animals, plants, as well as construction materials in buildings or external air getting inside the rooms. The penetration of atmospheric air into the rooms of the building is the main process that causes biological contamination of this environment with fungal spores (Chmiel et al. 2015, Małecka-Adamowicz et al. 2019).

Fungi that are part of bioaerosols can't grow during airborne transport but they are able to survive in the air for some time – it depends on their properties or environmental conditions (eg. access to nutrients, physical and chemical factors of environmental stress, the particle size – the small components of bioaerosol retain their viability in the environment longer than larger microbes). Fungal spores can survive in the air for a long time, when the most sensitive, vegetative forms of bacteria die quickly (Gatchalian et al. 2010, Menetrez et al. 2010, Puspita et al. 2012, Galperin & Yutin 2013).

The fungi present in the air can cause adverse health effects like irritations, infections, allergies, and serious toxic effects. In addition, a large number of fungi produce mycotoxins (secondary metabolites) and can affect human health (Thorne et al.1992, Kalogerakis et al. 2005, Ajoudanifar et al. 2011, Breza-Boruta 2015, Frączek et al. 2018). Biological factors can be a serious problem of occupational medicine and public health, and exposure to biological factors is related to specific professions. Environment of veterinary institutions and carrying out duties by vet or veterinary technician are considered to be related to exposure to harmful biological agents (Harper et al. 2013, Rim & Lim 2014, Grzyb & Pawlak 2020). Especially, direct contact between veterinarians and diagnosed animals is associated with the risk of biological contamination. In veterinary practice, not only animals are sources of microorganism contamination, but also people or the components of the indoor environment (Sitkowska et al. 2015).

Due to the fact that the microbiological quality of air is a very important factor in the workplace, the aim of this study was to characterize this property of air at the animal veterinary practice based on the number and species composition of the fungal population.

2. Materials and methods

The study was carried out in the summer of 2017 at the premises of the animal veterinary practice in Krakow (Poland). The veterinary practice takes care of pets, mainly dogs and cats. The samples of air were collected in two series, in duplicate at four measuring points. The selected rooms were those in which animals were housed or through which there was a regular flow of animals on a daily basis (treatment room – with a volume of 40 m^3 of air, a room with cages in which animals are housed after treatments – 30 m^3 of air, and waiting room – 36 m^3 of air) inside the building. During the measurements there were two dogs in the room with cages (every time). Air samples were collected before opening, five hours after opening (half of the working time of the veterinary practice) and after the veterinary practice work. Five hours after opening, there were a total of five animals in the building (two dogs in the waiting room with the owners – two people, one dog in the treatment room with the owner – one person, and two dogs in the room with cages – without the owners). There are two vets working in the veterinary practice on a daily basis. All studied rooms were naturally ventilated. Also, the gravity ventilation in the building was efficient.

Additionally, the air samples were collected at a point situated outside the building (as the "background"). The air samples were collected using a six-stage Andersen cascade sampler (model 10-710, Graseby-Andersen, Inc., Atlanta, GA). The sampler was placed at a height of 1.5 m above the floor or ground (outdoor measurements) to simulate the aspiration from the human breathing zone. A 5-minute sampling period and the flow rate of 28.3 $dm^3 \cdot min^{-1}$ were applied for the collection of air samples. Fungi were collected on malt extract agar (MEA LAB-AGAR™, BioMaxima, Poland). During sampling, the air temperature and relative humidity were measured using a hygrometer Kestrel 4000. The MEA plates were incubated for 4 days at 30°C, then 4 days at 22°C. The prolonged incubation of samples for culturing of fungi enables the growth of slowly growing strains at a lower temperature range. After incubation, the fungal colonies were counted. The concentration of fungal aerosol was calculated as the number of colony forming units per cubic meter of air ($cfu \cdot m^{-3}$).

Due to the specificity of the studied environment, isolated fungal strains were identified on the basis of macroscopic and microscopic features using diagnostic keys and, finally, by the mass spectroscopy (MALDI TOF MS), using laser desorption/ionization, with matrix-assisted and time-of-flight analyzer, by using MALDI Biotyper analyzer (Bruker).

The results were statistically analysed using Statistica 13.1 (StatSoft, Inc., Tulsa, OK, USA). The collected data was characterized by non-parametric distribution (Shapiro-Wilk test). The significance of differences between means was verified by the Kruskal-Wallis test. The results showing the effect of microclimatic parameters (temperature and relative humidity) on the prevalence of airborne microorganisms were evaluated using the R coefficient of the Spearman's correlation.

3. Results

The concentrations of fungal aerosol are presented in Table 1 and Table 2. Concentrations of fungi in the studied premises ranged from 1052 to 2739 $cfu \cdot m^{-3}$. The results showed that the average highest concentration of fungal aerosol was observed in the treatment room and the lowest concentration was observed in the room with cages. The statistical analysis showed a significant differences in the concentrations of fungal aerosol between the treatment room and room with cages (Kruskal-Wallis test). Also, the statistical analysis showed a significant differences in the concentrations of fungal aerosol between the treatment room and outdoor air. The concentrations of fungal aerosol in room with cages were higher than in the outdoor air, but the differences between them were not statistically significant. There were no statistical significant differences in the concentration of fungi between treatment room and waiting room. Concentration of fungal aerosol was significantly higher in the waiting room than in the room with cages.

Table 1. Fungal aerosol concentrations (cfu·m^{-3}) at animal veterinary practice and outdoor air

Environment		Fungi concentration	
		Range	Median
Indoor air	Treatment room	1052-2739	2306
	Room with cages	1203-1944	1463
	Waiting room	1626-2500	2055
Outdoor air		1184-1370	1277

Table 2. Average fungal aerosol concentration (cfu·m^{-3}, ±SD) in indoor air at animal veterinary practice including the time of measurement

Measuring time	Measuring point	Fungi concentration
Before opening	Treatment room	1264 ±299
	Room with cages	1296 ±131
	Waiting room	2160 ±481
Five hours after opening	Treatment room	2576 ±231
	Room with cages	1428 ±156
	Waiting room	2055 ±107
After work	Treatment room	2439 ±337
	Room with cages	1812 ±187
	Waiting room	1980 ±500

Results of microclimate parameters measurments are presented in Table 3.

By using a 6-stage Andersen's air sampler, it was possibile to get information about the size distribution of air fungal biota in the investigated measuring points at the animal veterinary practice (Figure 1). Based on the analysis of fungal aerosol particle size distribution it was found that in all investigated rooms the fungi concentration had a maximum value mainly in a range of diameters 3.3-7.0 μm.

Table 3. Temperature and relative humidity of indoor and outdoor air at animal veterinary practice

Environment		Temperature [°C]		Relative humidity [%]	
		Range	Median	Range	Median
Indoor air	Treatment room	22.5-24.1	23.6	52.5-64.5	60.7
	Room with cages	22.7-22.9	22.7	54.5-62.3	60.9
	Waiting room	22.5-25.7	23.2	49.2-59.1	57.0
Outdoor air		20.2-21.8	20.7	50.3-62.6	58.2

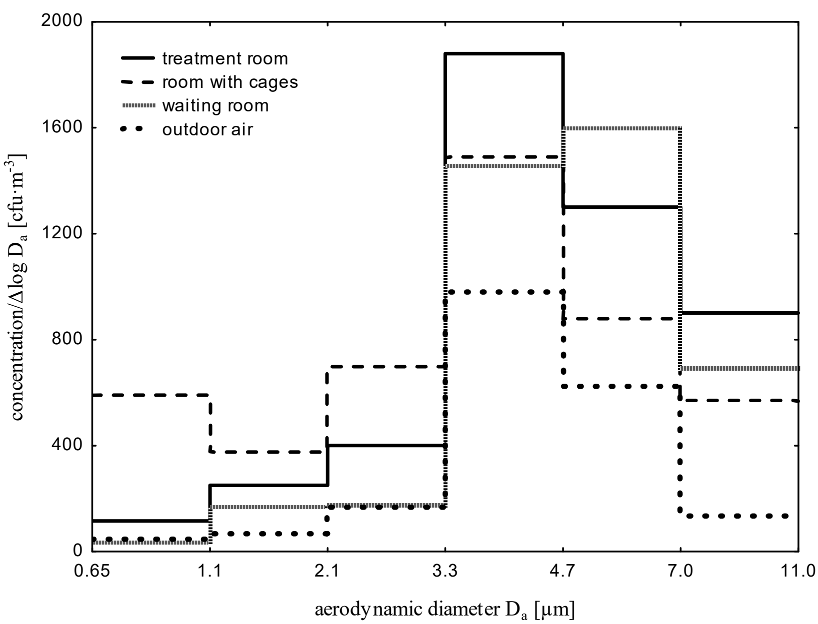

Fig. 1. The size distribution of fungal aerosol inside and outside the animal veterinary practice

The percentage shares of identified fungi in the examined veterinary practice and outdoor air are presented in Table 4.

Table 4. Species of fungi (%) isolated from the air at the studied animal veterinary practice: indoor and outdoor air

Environment	Species of fungi	Fraction [%]
Indoor air	*Penicillium* spp.	44.85
	Penicillium pinophilum	1.21
	Penicillium chrysogenum	3.75
	Cladosporium cladosporoides	14.21
	Alternaria alternata	2.53
	Alternaria spp.	1.21
	Fusarium spp.	2.05
	Scopulariopsis brevicaulis	4.05
	Aspergillus sydowii	4.80
	Aspergillus clavatus	0.05
	Aspergillus niger	0.05
	Aspergillus fumigatus	0.19
	Microsporum canis	9.05
	Rhizopus spp.	2.05
	Acremonium strictum	4.70
	Trichophyton verrucosum	4.85
	Ulocladium spp.	0.40
Outdoor air	*Penicillium* spp.	26.15
	Penicillium digitatum	4.60
	Penicillium chrysogenum	4.80
	Cladosporium cladosporoides	19.85
	Aspergillus spp.	13.95
	Scopulariopsis brevicaulis	7.55
	Alternaria alternata	9.10
	Fusarium spp.	9.55
	Rhizopus spp.	4.45

4. Discussion

Due to the specificity of work, veterinary staff come in contact with microorganisms present on the skin, mucous membrane or animal hair. Veterinarians and veterinary technicians can also be exposed to other infectious factors (e.g. animal excreta and body fluids). Occupational exposure to zoonotic diseases is a risk in veterinary medicine (Weese et al. 2002, Sitkowska et al. 2015). In these studies an assessment of the mycological quality of air in animal veterinary practice was made. Concentrations of fungi in the studied premises ranged from 1052 to 2739 cfu·m^{-3}. The obtained results of indoor measurements of fungal aerosol concentrations were compared with the Polish proposals for threshold limit values, which are $5 \cdot 10^3$ cfu·m^{-3} for fungi in indoor and outdoor environments. It was found that the average concentrations of fungi obtained in this study (Figure 2) were lower than reference values for fungi concentrations in residential and public buildings recommended by the Polish Panel of Experts of Biological Factors (Górny 2010). There are a few available works describing the problem of microbiological contamination of air at small animal veterinary clinics, veterinary hospitals and pet stores, where similar values of fungal aerosol concentration have been observed – the mean concentration of fungal aerosol in that types of facilities was 700 to 8068 cfu·m^{-3} (Jo & Kang 2006, Bulski 2017, Bulski & Korta-Pepłowska 2017, Chen et al. 2017).

In indoor air, total of 17 species of fungi have been identified. The predominant fungi was *Penicillium* spp. and *Cladosporium cladosporoides.* Fungi that can cause dermatophytoses have also been isolated from indoor air: *Microsporum canis* and *Trichophyton verrucosum.* From the outdoor air, 9 fungal species were isolated. The predominant fungi in outdoor air was *Penicillium* spp., *Cladosporium cladosporoides* and *Aspergillus* spp. The fungal genera and species identified in this research mostly are associated with allergic respiratory diseases (especially in people with impaired immune systems); some of them can be a source of polysaccharides such as the β(1→3)-glucans (e.g. *Cladosporium* spp., *Alternaria* spp.). Some of fungi species, isolated from indoor air at veterinary practice, are important producers of mycotoxins, secondary metabolites, with neurotoxic and carcinogenic properties (e.g. *A. niger*, *A. clavatus*) (Pitt 2000). In tested air, the presence of *Microsporum canis* and *Trichophyton verrucosum* was found. *M. canis*, a species widespread throughout the world, it is characterized by a significant degree of adaptation to various animal species and a wide range of pathogenicity. It causes a dermatophytoses, especially in cats or dogs and can be dangerous for people by causing mycosis of skin of head (Wawrzkiewicz et al. 1994). *T. verrucosum* is a dermatophyte largely responsible for fungal skin disease in dogs. Infection to humans is largely zoonotic and can cause the scalp ringworm. The majority of infections are occupational, and this includes veterinarians and veterinary technicians (Kane et al. 1997). According to other authors, the fungi that occurred most frequently in the veterinary hospitals or other veterinary facilities were *Coriolopsis* spp. and *Microporus* spp. (Chen et al. 2017). People working in this type of environment are most often exposed to dermatologic diseases caused by *Microsporum* spp., *Trichophyton* spp., and *Blastomyces dermatitidis* (Weese et al. 2002). The species of microscopic fungi isolated from the air in this study (*Aspergillus fumigatus*, *Microsporum canis,* and *Trichophyton verrucosum*) belong to the second risk group according to the list of harmful biological agents in the work environment (may cause disease in humans, can be dangerous to employees, but their spread in the human population is unlikely; usually, there are effective methods of prevention or treatment) (Regulation of the Polish Minister of Health, 2005).

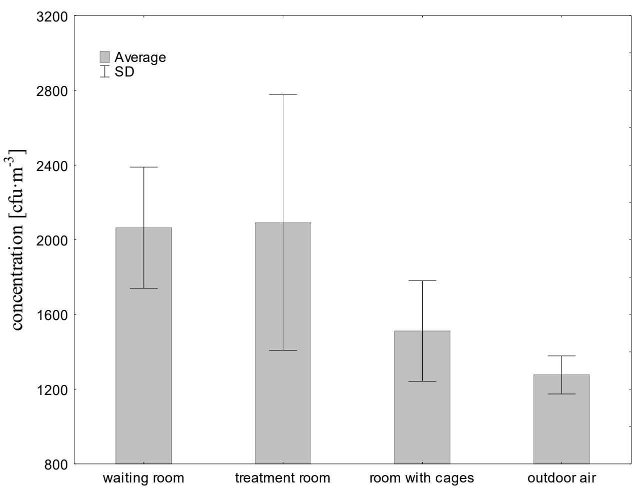

Fig. 2. Average concentration of fungi (cfu·m^{-3}, ±SD) in outdoor and indoor air at animal veterinary practice

The results showed various fungal contamination in different measuring points at different measuring times of the day, what could have been caused by the changes in the number of clients, animals or activities performed at veterinary practice. Based on the results of this study it was found that the largest "load" of fungi, isolated from the air, can reach (in the human respiratory tract) to the region of the throat, trachei and primary bronchi (Owen & Ensor 1992). This is necessary and important information for the assessment of the effects of biological aerosols on the human body – the place of deposition of a harmful biological factors determines the type of adverse health effect. Microclimate conditions may affect the number of microorganisms and their spread in the air

(Li & Kendrick 1995, Katial et al. 1997). Analysis of the impact of the temperature and relative humidity on the observed fungal aerosol showed a significant correlation between the concentration of fungi and temperature ($R = -0.73$, $p < 0.05$) and relative humidity ($R = 0.77$, $p < 0.05$).

The analysis showed that the higher concentration of fungi in the studied rooms was observed in the treatment room five hours after opening and the lowest concentration was observed in the treatment room before opening. The analysis showed that there were significant differences in the concentration of fungi in treatment room taking into account the measuring time – before opening and five hours after opening/after work, but there were no significant differences in concentration of fungi in treatment room five hours after opening and after work. There were no significant differences in concentration of fungal aerosol in other measuring points taking into account the measuring time.

5. Conclusions

Concentrations of fungal aerosol between the internal studied rooms at the veterinary practice were significantly different and were always lower than 2740 $cfu \cdot m^{-3}$. The highest concentrations of fungi in the studied rooms were observed in the treatment room five hours after opening the veterinary practice. However, the results of this study showed the possible biological risks for the veterinary workers or clients of animal veterinary practice. Although the concentrations of fungi did not exceed the Polish limit values for fungal aerosol, it was found that among the detected fungi pathogenic species as: *Microsporum canis* and *Trichophyton verrucosum* were present. The presence of pathogenic microorganisms and prolonged exposure can create a health risk for allergic symptoms or dermatophytoses in veterinary staff. To protect people from occupational injuries, causes by biological factors, it is recommended to maintenance proper disinfection and sterilization procedures in workplaces where animals need adequate medical care. Also, there should be introduced a high-performance mechanical ventilation or air conditioning system, providing the appropriate microbiological quality of air. Monitoring the quality of air is also very important for assessment of the exposure to potentially pathogenic microorganisms.

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References

Ajoudanifar, H., Hedayati, M., Mayahi, S., Khosravi, A., Mousavi, B. (2011). Volumetric assessment of air borne indoor and outdoor fungi at poultry and cattle houses in the Mazandaran province, Iran. *Archives of Industrial Hygiene and Toxicology 62*, 243-248. DOI: 10.2478/10004-1254-62-2011-2099

Bowers, R.M., McCubbin, I.B., Hallar, A.G., Fierer, N. (2012). Seasonal variability in airborne bacterial communities at a high-elevation site. *Atmospheric Environment 50*, 41-49. DOI: https://doi.org/10.1016/j.atmosenv.2012.01.005

Breza-Boruta, B. (2015). Microbiological air pollution of production room of the meat processing plant as a potential threat to the workers. *Environmental Medicine 18*(4), 37-42 (in Polish).

Bulski, K. (2017). Biological safety at selected pet stores in Cracow. *Woda-Środowisko-Obszary Wiejskie, 17,1*(57), 19-30 (in Polish).

Bulski, K., Korta-Pepłowska, M. (2017). Microbiological quality of indoor air at reptile store. *Woda-Środowisko-Obszary Wiejskie, 17,2,* 27-35 (in Polish).

Chmiel, M.J., Frączek, K., Grzyb, J. (2015). The problems of microbiological air contamination monitoring. *Woda-Środowisko-Obszary Wiejskie, 1(49),* 17-27 (in Polish).

Chen, Ch.T., Liu, B.H., Hsu, Ch.H., Liu, Ch.Ch., Liao, A.T.C. (2017). Bioaerosol investigation in three veterinary teaching hospitals in Taiwan. *Taiwan Veterinary Journal, 43*, 39-45. DOI: https://doi.org/10.1142/S1682648515500353

Frączek, K., Chmiel, M.J., Bulski, K. (2018). Bacterial Aerosol at Selected Rooms of School Buildings of Malopolska Province. *Rocznik Ochrona Środowiska, 20,* 1583-1596 (in Polish).

Galperin, M.Y., Yutin, N. (2013). A genomic update on clostridial phylogeny: Gram-negative spore formers and other misplaced clostridia. *Environmental Microbiology, 15(10),* 2631-2641. DOI: 10.1111/1462-2920.12173

Gatchalian, N.G., Wood, J., Lemieux, P.M., Betancourt, D., Kariher, P. (2010). Dry Thermal Resistance Of Bacillus Anthracis (Sterne) Spores And Spores Of Other Bacillus Species: Implications For Biological Agent Destruction Via Waste Incineration. *Journal of Applied Microbiology, 109(1*), 99-106. DOI: 10.1111/j.1365-2672.2009.04632.x

Górny, R.L. (2010). Biological aerosols – a role of hygienic standards in the protection of environment and health. *Environmental Medicine, 13(1)*, 41-51 (in Polish).

Grzyb, J., Pawlak, K. (2021). Impact of bacterial aerosol, particulate matter, and microclimatic parameters on animal welfare in Chorzów (Poland) zoological garden. *Environmental Science and Pollution Research, 2*8, 3318-3330. DOI: https://doi.org/10.1007/s11356-020-10680-9

Harper, T.A.M., Bridgewater, S., Brown, L., Pow-Brown, P., Stewart-Johnson, A., Adesiyun, A.A. (2013). Bioaerosol sampling for airborne bacteria in a small animal veterinary teaching hospital. *Infection Ecology and Epidemiology, 3*, 1-7. DOI: 10.3402/iee.v3i0.20376

Jo, W-K., Kang, J-H. (2006). Workplace exposure to bioaerosols in pet shops, pet clinics, and flower garden. *Chemosphere, 65*(10), 1755-1761. DOI: 10.1016/j.chemosphere.2006.04.068

Kalogerakis, N., Paschali, D., Lekaditis, V., Pantidou, A., Eleftheriadis, K., Lazaridis, M. (2005). Indoor air quality – bioaerosol measurements in domestic and office premises. *Journal of Aerosol Science, 36*, 751-761. DOI: https://doi.org/10.1016/j.jaerosci.2005.02.004

Kane, J., Summerbell, R., Sigler, L., Krajden, S., Land. G. (1997). *Laboratory Handbook of Dermatophytes*. California: Star. ISBN 0-89863-157-2.

Katial, R.K., Zhang, Y., Jones, R.H., Dyer, P.D. (1997). Atmospheric mold spore counts in relation to meteorological parameters. *International Journal Biometeorology, 41*, 17-22. DOI: 10.1007 / s004840050048

Li, D.W., Kendrick, B. (1995). A year-round study on functional relationships of airborne fungi with meteorological factors. *International Journal of Biometeorology, 39*(2), 74-80. DOI: https://doi.org/10.1007/BF01212584

Małecka-Adamowicz, M., Kubera, Ł., Jankowiak, E., Dembowska, E. (2019). Microbial diversity of bioaerosol inside sports facilities and antibiotic resistance of isolated Staphylococcus spp. *Aerobiologia, 35*, 731-742. DOI: https://doi.org/10.1007/s10453-019-09613-y

Menetrez, M.Y., Foarde, K.K., Dean, T.R., Betancourt, D.A. (2010). The effectiveness of UV irradiation on vegetative bacteria and fungi surface contamination. *Chemical Engineering Journal, 157*, 443-450. DOI: https://doi.org/10.1016/j.cej.2009.12.004

Owen, M.K., Ensor, D.S. (1992). Airborne particles size and sources fund in indoor air. *Atmospheric Environment, 12(26A)*, 2149-2162.

Pitt, J.I. (2000). Toxigenic fungi and mycotoxins. *British Medical Bulletin, 56*, 184-192.

Polymenakou, P.N. (2012). Atmosphere: A Source of Pathogenic or Beneficial Microbes? *Atmosphere, 3*(1), 87-102. DOI: https://doi.org/10.3390/atmos3010087

Puspita, I.D., Kamagata, Y., Tanaka, M., Asano, K., Nakatsu, C.H. (2012). Are uncultivated bacteria really uncultivable? *Microbes and Environments, 27*(4), 356-366. DOI: 10.1264/jsme2.me12092

Regulation of the Polish Minister of Health. (2005). https://www.pip.gov.pl/pl/f/v/19909/05%20ppb.pdf (in Polish).

Rim, K.T., Lim, C.H. (2014). Biologically Hazardous Agents at Work and Efforts to Protect Workers' Health: A Review of Recent Reports. *Safety and Health at Work, 5(2)*, 43-52. DOI: 10.1016/j.shaw.2014.03.006

Sitkowska, J., Sitkowski, W., Sitkowski, Ł., Lutnicki, K., Adamek, Ł., Wilkołek, P. (2015). Seasonal microbiological quality of air in veterinary practices in Poland. *Annals of Agricultural and Environmental Medicine, 22(4)*, 614-624. DOI: https://doi.org/10.5604/12321966.1185763

Thorne, P.S., Kiekhaefer, M.S., Whitten, P., Donham, K.J. (1992). Comparison of bioaerosol sampling methods in barns housing swine. *Applied and Environmental Microbiology, 58(8)*, 2543-2551. DOI: 10.1128/AEM.58.8.2543-2551.1992

Wawrzkiewicz, K., Ziółkowska, G., Czajkowska, A., Wawrzkiewicz, J. (1994). Microsporum canis: the major etiological agent of ringworm in cats and dogs. *Medycyna Weterynaryjna, 50*(7), 320-322 (in Polish).

Weese, J.S., Peregrine, A.S., Armstrong, J. (2002). Occupational health and safety in small animal veterinary practice: Part I – Nonparasitic zoonotic diseases. *The Canadian Veterinary Journal, 43*, 631-636.

Wlazło, A., Górny, R.L., Złotkowska, R., Ławniczek, A., Łudzeń-Izbińska, B., Harkawy, A.S., Anczyk, E. (2008). Worker's exposure to selected biological agents in libraries of Upper Silesia. *Medycyna Pracy, 59*(2), 159-170 (in Polish).

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A New Approach to the Maximum Quarterly Water Consumption Modeling on the Example of Individual Water Consumers in a Small Water Supply System

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Abstract: Quarterly water consumption data collected in a small water supply system were used for elaboration of a new water consumption modeling approach. In this paper, multi-distribution statistical analysis was performed. As the Anderson-Darling test proved, at least a half out of the ten tested theoretical probability distributions can be used for description of the water consumption. The application of the PWRMSE criterion made it possible to determine, which of the tested theoretical distributions is the best-fitted to the empirical data set. In the case of total daily water consumption for the group of the households, it was Johnson distribution, whereas for the average daily water consumption per capita, it was GEV distribution. Based on the best-fitted probability distribution, a 25-year water consumption simulation with the Monte Carlo method was conducted. Because methodology of this study is based on the probability distributions, even if the type of theoretical distribution of the water consumption will change, it will be still possible to use this simulation method by assuming the other distribution.

Keywords: water supply system, water consumption, modeling, probability distribution

1. Introduction

Rational water resources management and at the same time, providing the required drinking water quantity, is not easy task for the water supply service entities. It must be stressed that during water supply systems planning and designing, the first steps tending towards the rational water management should be taken; otherwise, this can result in the future in some operation and maintenance problems. In the case of the undersized water pipelines, high water velocity causes increased water flow resistances. This contributes to decrease the water pressure at the point of use below the required level; sometimes, it can result in a lack of the water in some water network areas. On the other hand, water pipes oversizing causes decrease in water flow velocity and thus, water retention time in the network is extend. Because under such conditions deposits are accumulated, besides the hydraulic resistances growth, there is a risk of a secondary water contamination. In order to avoid these problems, water network operators must provide their proper maintenance by regular pipelines' flushing and disinfection.

Currently, it is observed that many water supply systems are oversized. This is the result of some past activities, while the water pipelines were designed for the greater water demand than the required now. Although the water consumption in households depends on many factors and therefore, some differences between them may be observed (Pasela & Gorączko 2013, Sikora et al. 2006), in general, both in Poland (Gorączko & Pasela 2015, Pawełek 2015; 2016) and in many other countries (Baldino & Sauri 2018, Barraqué et al. 2011, Cahill & Lund 2013, Donnelly & Cooley 2015, Sauri 2019, Schleich & Hillenbrand 2009), decrease in water consumption is noted. This results in maladjustment of some technical parameters of the existing pipelines to the amount of the transported water. Decrease in water consumption is mainly due to the growth of the price for water supply and sewage disposal. In addition, common access to the water-saving devices and obligatory water meters installation make it easy to control the amount of the water used; this encourages tap water users for water saving. In order to avoid some operational and maintenance problems, water supply facilities should be planned and designed carefully. However as Bartkowska (2014), Bergel (2017) and Bergel et al. (2016a; b) suggest, current methods for the water demand prediction need to be modified and updated. This is because many methods are based on the water consumption indicators elaborated in the past; in many cases, these indicators not reflect an actual water demand properly. This is one of the main reasons of some designing faults, resulting in operational problems and high costs of the water supply systems maintenance. In order to verify these problems and identify their reasons, numerous studies of water consumption have been conducted for years (Bartkowska 2014, Bergel 2017, Bergel et al. 2016a; b, Bergel et al. 2017).

Because this paper is based on the quarterly water consumption, we intended to pay attention to the other literature studies related to the quarterly water demand. For example, Batóg and Foryś (2009) proved that only some of the tested water consumption variables in residential buildings were characterized by seasonal (quarterly) fluctuations. The results presented by Bergel et al. (2016a) show some disproportions between the quarterly water consumption in the households noted in a four-year period, but these were especially related to the water consumption for additional purposes. Finally, Reynaud et al. (2018) observed a strong quarterly seasonality of the water consumption in the case of single-family water users, in contrast to the multi-family water users.

Water systems' modeling in terms of the water consumption is still current issue. This is because the use of some statistical tools makes planning the new investments easier and provides many technical and financial benefits for the operated water supply facilities. For example, the report of the John Research Centre (the European Commission's in-house science service), contains very comprehensive analysis of the water consumption modeling issue in the 28 countries of the European Union (Reynaud 2015). As some literature studies show (Boryczko 2017, Cieżak & Cieżak 2015, Froelich 2015, Huang et al. 2017, Mombeni et al. 2013, Rathnayaka et al. 2017, Romano & Kapelan 2014, Tiwari & Adamowski 2015, Vijai & Sivakumar 2018), different methods are studied by many researchers in order to find some mathematical tools that can be the best for a reliable water consumption prediction. In the group of known methods we can find short-term-, intermediate-term- and long-term prediction methods. When it comes to the models, we can consider e.g. temporal extrapolation models, models based on 'unit water demand', multivariate statistical models, micro-component modeling or estimation based on projections for urbanization and land use (House-Peters & Chang 2011, Rinuado 2015).

As it turns out, there are no literature reports regarding to the water consumption modeling using probability distributions. Although this method should be considered as a reliable statistical tool for prediction, it must be noted that the assumption of a unique form of the water consumption probability distribution can be inappropriate; stationary mechanisms for process shaping are suggested then. Because the empirical distributions can be described by many theoretical functions, in order to avoid the prediction errors, it is important to select the best-fitted one. Considering the above, as part of this paper, elaboration of a new approach to the water consumption modeling based on the multi-distribution analysis was performed. An additional novelty of this paper is application of the Peak-Weighted Root Mean Square Error (PWRMSE) for selection of the best-fitted theoretical distribution.

2. Case study

In this paper, households' water consumption taken from a small rural water supply system located in the Southern Poland (Wołowice village) was tested; as part of this study, 34 selected households were analyzed. Because the households located in the study area are connected to the collective water system and they are equipped with toilet, bathroom and local source of hot water, they are classified into the fourth group of the standard of water and sewage devices equipping. In this case, as the Polish Regulation of the Minister of Infrastructure (2002) determines, average standard for water consumption per capita is between 80 dm^3/d (non-sewered areas) and 100 dm^3/d (sewered areas). Over the research period, each of the tested households was inhabited by one to seven persons. Most of the households (68%) were inhabited by two, four and five persons, whereas only 17% households were inhabited by one, six and seven persons. It must be stressed, although the rural water system was tested, water taken from the network was not used for agricultural purposes, but only for household purposes; if any additional purposes appeared (e.g. home gardens irrigation), own water sources were used.

3. Materials and methods

Statistical analysis and modeling was performed based on the water consumption data collected in the 34 selected households between the January 2011 and December 2015. Data for analysis refers to the quarterly water consumption and were elaborated both for total daily water consumption for the whole group of the tested households and for the average daily water consumption per capita.

At the beginning, preliminary statistical analysis of the water consumption was performed. The values of some descriptive statistics, such as minimum (Min), maximum (Max), average (Avg), standard deviation (S), coefficient of variation (CV), skewness (Sk) and kurtosis (Kurt) were determined.

Statistical homogeneity of the water consumption data was examined using a non-parametric Kruskal-Wallis test. Investigation of the quarterly data series homogeneity consisted in assigning the ranks to the ordered elements in all tested samples (quarters); then, the sum of the ranks for each sample was determined. If differences between the calculated sums of the ranks were small, null hypothesis H_0 assuming origination all the samples from the same general population was considered as true (samples are homogeneous). A critical region of the test was defined by Pearson's statistic χ^2 with k-1 degrees-of-freedom, where k is number of the compared samples (Wałęga et al. 2016). For k-1 = 3 degrees-of-freedom, critical statistic χ^2 was 7.518. In this paper, both for total daily water consumption for the group of the tested households and for the average daily water consumption per capita, the Kruskal-Wallis test was also used for investigation of the significance of water consumption differences between the quarters. Hypothesis H_0 was verified for the significance level α = 0.05. The Kruskal-Wallis statistic is described as follow:

$$H = \frac{12}{n(n+1)} \sum \frac{R_i^2}{n_i} - 3(n+1) \quad (1)$$

where:
H – Kruskal-Wallis statistic,
n – total number of components for all samples,
R_i – sum of the ranks in a given sample,
n_i – number of components in a given sample.

Based on the quarterly water consumption observational data series, determination of theoretical distributions that can be used for modeling was made. In this paper, Gaussian Mixture Model (GMM), Generalized Extreme Value (GEV), Johnson, Weibull, Normal, Log-normal, Half-normal, Triangular, Rayleigh and Pareto distribution were tested; these are described as follow:

Gaussian Mixture Model distribution (GMM) (Jaini & Poupart 2016):

$$f(x) = \sum_{i=1}^{n} \omega_i N(\mu_i, \Sigma_i) \quad (2)$$

Generalized Extreme Value distribution (GEV) (Provost et al. 2018):

$$f(x) = \frac{1}{\alpha}\left(1 + \kappa\left(\frac{x-\xi}{\alpha}\right)\right)^{-\frac{1}{\kappa}-1} exp\left(-\left(1 + \kappa\left(\frac{x-\xi}{\alpha}\right)\right)^{-\frac{1}{\kappa}}\right), \ \kappa \neq 0 \quad (3)$$

Johnson distribution (Parresol 2003):

$$f(x) = \frac{\delta}{\sqrt{2\pi}} \frac{\lambda}{(x-\xi)(\xi+\lambda-x)} exp\left(-\frac{1}{2}\left(\gamma + \delta ln\left(\frac{x-\xi}{\xi+\lambda-x}\right)\right)^2\right) \quad (4)$$

Weibull distribution (Lai 2014):

$$f(x) = \left(\frac{\kappa}{\alpha}\right)\left(\frac{x}{\alpha}\right)^{\kappa-1} exp\left(-\left(\frac{x}{\alpha}\right)^{\kappa}\right) \quad (5)$$

Normal distribution (Papoulis & Pillai 2001):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{1}{2\sigma^2}(x-\mu)^2\right) \quad (6)$$

Log-normal distribution (Papoulis & Pillai 2001):

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} exp\left(-\frac{1}{2\sigma^2}(ln(x)-\mu)^2\right) \quad (7)$$

Half-normal distribution (Bosch-Badia et al. 2020):

$$f(x) = \sqrt{\frac{2}{\pi\sigma^2}} exp\left(-\frac{x^2}{2\sigma^2}\right) \tag{8}$$

Triangular distribution (Forbes et al. 2011):

$$f(x) = \begin{cases} \frac{2(x-a)}{(b-a)(m-a)} & for\ a \le x \le m \\ \frac{2(b-x)}{(b-a)(m-a)} & for\ m \le x \le b \end{cases} \tag{9}$$

Rayleigh distribution (Papoulis & Pillai 2001):

$$f(x) = \frac{x}{\sigma^2} exp\left(-\frac{x^2}{2\sigma^2}\right) \tag{10}$$

Pareto distribution (Forbes et al. 2011):

$$f(x) = \frac{\kappa\alpha^\kappa}{x^{\kappa+1}} \tag{11}$$

where:
a – lower limit,
b – upper limit,
i – number of ordered data,
m – mode,
N – Gaussian distribution,
n – number of components,
α – scale parameter,
γ, δ, κ – shape parameters,
λ – range parameter,
μ – mean,
ξ – location parameter,
Σ – covariance matrix,
σ – standard deviation,
ω – mixture weight such that $\Sigma_{i=1}^{n}\omega_i = 1$.

The assessment of theoretical and empirical water consumption distributions compatibility was performed using Anderson-Darling test (A-D); for this purpose, Equation (12) (Kvam & Vidakovic 2007) was used. Compared with other, Anderson-Darling test is considered as better one for assessment of the measured and predicted values compatibility (Engmann & Cousineau 2011, Islam 2011). Anderson-Darling test statistic is sensitive in the whole distribution range; thus, this is more likely to identify some differences between distributions. Verification of the *A-D* test was performed for the significance level of $\alpha = 0.05$ and based on the probability *p*. This is because critical values of *A-D* test depend on the type of the tested probability distribution. For the Anderson-Darling statistic, null hypothesis H_0 (data follow a specified distribution) and alternative hypothesis H_1 (data not follow a specified distribution) must be defined. If the *p*-value is less than α = 0.05, hypothesis H_0 about the data's compatibility with the tested distribution is rejected. Otherwise, i.e. if the *p*-value is greater than α = 0.05, it can be assumed that variables follow a specified distribution and there is no reason to reject a hypothesis H_0.

$$A - D = -n - \sum_{i=1}^{n} \frac{(2i-1)\, ln(F(x_i)) + ln\,(1 - F(x_{n+1-i}))}{n} \tag{12}$$

where:
A-D – Anderson-Darling statistic,
i – number of ordered data,
n – number of components,
F – cumulative distribution function.

As part of this paper, the assessment of the best-fitted theoretical and empirical distributions was conducted. Although the results of the Anderson-Darling test (i.e. *p*-value), also gives a such possibility (the higher *p*-value, the better theoretical distribution fitting), however, Peak-Weighted Root Mean Square Error (PWRMSE) method is considered as more precisely one for theoretical and empirical distributions fitting. The values of PWRMSE were calculated based on the Equation (13). The same formula was also used for hydrological modeling (Koch & Bene 2013, Młyński et al. 2019, Wałęga 2016). The best-fitted theoretical distribution is this one with the lowest PWRMSE value.

$$PWRMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2 \left(\frac{x_i + \mu}{2\mu}\right)}{n}} \tag{13}$$

where:
PWRMSE – Peak-Weighted Root Mean Square Error,
i – number of ordered data,
n – number of components,
x – measured value,
y – predicted value,
μ – mean of measured values.

Water consumption simulation was conducted based on the best-fitted theoretical distribution by using a Monte Carlo method. This method is used for mathematical modeling of complex processes. Obtained results are presented as parameters of a hypothetical population. Based on the created population sample, it is possible to make a statistical estimation of the tested parameter (Halton

1970). Simulation was performed for sample consisted of 100 random variables, both in relation to the total daily water consumption for the group of the tested households and in relation to the average daily water consumption per capita. Assuming that one variable is equivalent to the one quarter of the year, water consumption prediction was performed for a 25-year period. As it can be observed, Monte Carlo method has already been used e.g. for the wastewater treatment plant reliability modeling (Taheriyoun & Moradinejad 2015) or for studies on sewer systems (Ribeiro et al. 2009) and for water demand modeling in an office building (Wu et al. 2017).

4. Results and discussion

4.1. Preliminary statistical data analysis

The results of the preliminary statistical data analysis showed that in the each quarter of the 2011-2015, for the whole group of the 34 tested households, daily water consumption ranged from about 7 500 dm^3/d to 11 180 dm^3/d, with the average value of 10 100 dm^3/d. Coefficient of variation (CV = 0.082) indicates on small variation of the tested parameter in a five-year period. Calculated skewness (Sk = –1.65) indicates on asymmetry of the tested variables around the average. In turn, kurtosis greater than zero (Kurt = 3.55), is the result of the concentration of the measured values close to the mean value (Fig. 1a, Table 1).

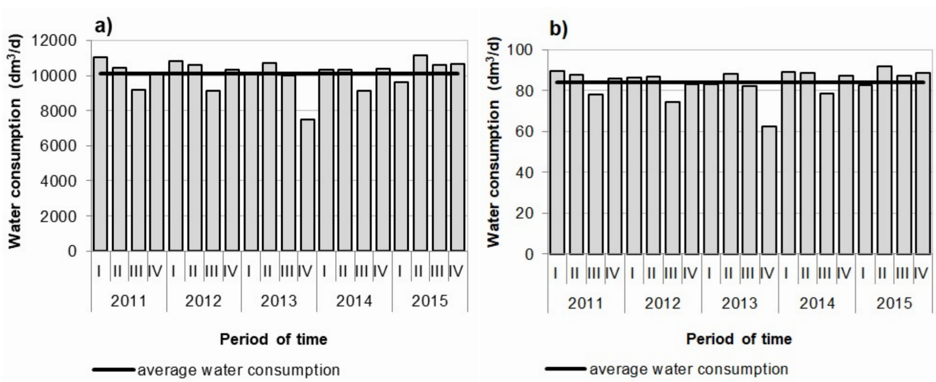

Fig. 1. Average daily water consumption for the each quarter of the 2011-2015:
(a) for the group of the tested households; (**b**) per capita

Based on the calculated coefficient of variation (CV = 0.078) (Table 1), it can be stated that the average water consumption per capita was not subjected a significant variability. Average daily water consumption per capita for a 2011-2015 period was 84.1 dm^3/d (Fig. 1b), which means that this value was in the range of the average water consumption for dwellings from the fourth category (80-100 dm^3/d), as the Polish Regulation (2002) determines. Kurtosis for the asymmetric water consumption distribution (Kurt = 4.90) indicates clearly on the concentration of the variables close to the mean value (Table 1).

Table 1. Descriptive statistics for the quarterly water consumption (2011-2015)

Descriptive statistic	Unit	Total daily water consumption for the group of the tested households	Average daily water consumption per capita
Min	(dm^3/d)	7 493.5	62.3
Max		11 178.0	91.9
Avg		10 111.8	84.1
S		832.6	6.6
CV	(–)	0.082	0.078
Sk		–1.65	–1.99
Kurt		3.55	4.90

where: Min – minimum, Max – maximum, Avg – average, S – standard deviation, CV – coefficient of variation, Sk – skewness, Kurt – kurtosis.

4.2. Testing of the quarterly water consumption homogeneity

The results of the homogeneity testing basis on the Kruskal-Wallis test (Table 2) proved that there is no reason to reject null hypothesis H_0 assuming a homogeneity of the tested quarterly data series. Both for total daily water consumption for the group of the tested households and for the average daily water consumption per capita, the values of statistics H were lower than the Pearson's statistic adopted during the determination of the critical region of the test; for four compared time series, χ^2 statistic was 7.518. Based on the obtained results it can be stated that there are no significant differences between the quarterly water consumption. Therefore, it was concluded that in the analyzed multi-year period, any significant factors not affected the water consumption.

Table 2. The results of the Kruskal-Wallis homogeneity testing for the quarterly water consumption in the period of 2011-2015

Kruskal-Wallis test parameter	Total daily water consumption for the group of the tested households	Average daily water consumption per capita
H	4.66	6.09
χ^2	7.518	7.518
p	0.20	0.11

where: H – Kruskal-Wallis statistic, χ^2 – Pearson's critical statistic, p – probability.

4.3. Analysis of theoretical and empirical distributions fitting

The results of theoretical and empirical distributions fitting obtained by using the Anderson-Darling test showed that as many as six out of the ten tested probability distributions can be used for description of the total daily water consumption for the group of the 34 tested households (Table 3). Both in the case of GMM, GEV, Johnson, Weibull, Normal and Log-normal distribution, *p*-values for A-D test statistic were greater than the assumed significance level of $\alpha = 0.05$. Null hypothesis H_0 about theoretical and empirical distributions compatibility was rejected in the case of the other four distributions (Half-normal, Triangular, Rayleigh and Pareto). In turn, observational data series for the average daily water consumption per capita can be described by using five probability distributions; these include GMM, GEV, Weibull, Normal and Log-normal distribution (Table 3). Lack of the possibility of using Half-normal, Triangular, Rayleigh, Pareto and also Johnson distribution may be due to their characteristics. Namely, these functions are homogenous; in turn, water consumption is a dynamic process and many time-variable factors may affect this.

Table 3. The results of theoretical and empirical water consumption distributions fitting

Statistical distribution	Total daily water consumption for the group of the tested households		Average daily water consumption per capita	
	Statistical parameter			
	A-D	p	A-D	p
GMM	0.187	0.993	0.226	0.982
GEV	0.355	0.891	0.451	0.795
Johnson	0.470	0.776	–	–
Weibull	0.416	0.831	0.588	0.657
Normal	0.951	0.383	1.228	0.257

Table 3. cont.

Statistical distribution	Total daily water consumption for the group of the tested households		Average daily water consumption per capita	
	Statistical parameter			
	A-D	p	A-D	p
Log-normal	1.187	0.272	1.485	0.180
Half-normal	8.786	0.000	8.936	0.000
Triangular	4.966	0.003	6.248	0.001
Rayleigh	6.752	0.000	6.952	0.000
Pareto	26.582	0.000	29.163	0.000

where: A-D – Anderson-Darling statistic, p – probability.

Figures 2a-f and Figures 3a-e show the quantile-quantile graphs of the probability distributions that can be used for description of the water consumption.

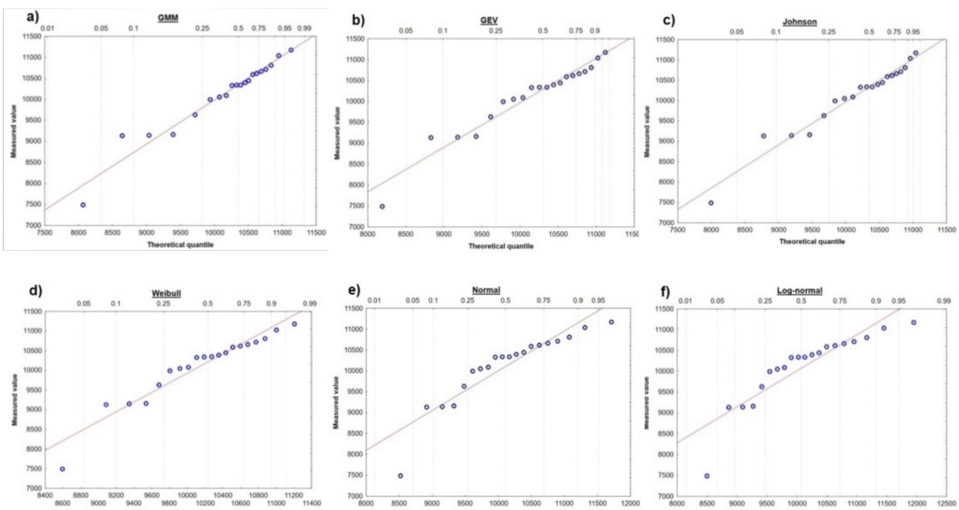

Fig. 2. Quantile-quantile graphs of theoretical and empirical distributions fitting for total daily water consumption in the group of the tested households: (**a**) GMM; (**b**) GEV; (**c**) Johnson; (**d**) Weibull; (**e**) Normal; (**f**) Log-normal

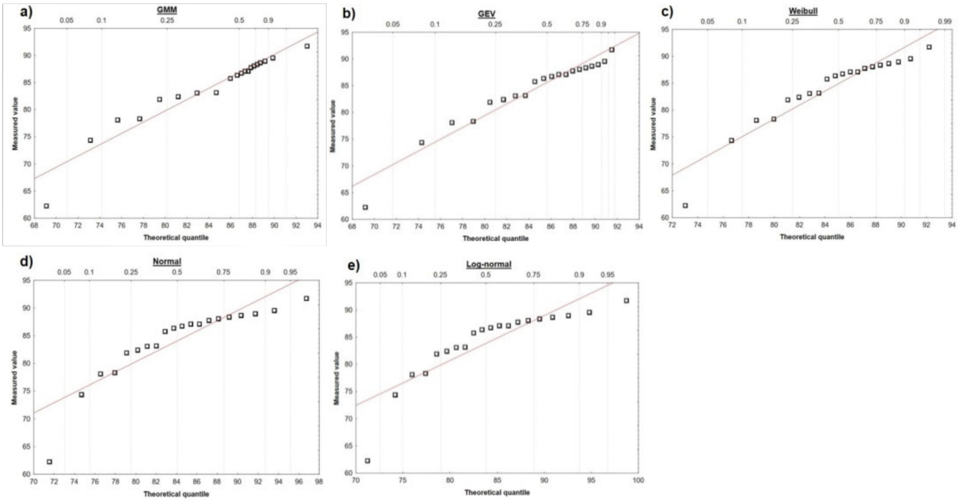

Fig. 3. Quantile-quantile graphs of theoretical and empirical distributions fitting for the average daily water consumption per capita: (**a**) GMM; (**b**) GEV; (**c**) Weibull; (**d**) Normal; (**e**) Log-normal

4.4. Selection of the best-fitted theoretical distribution

As it was presented in chapter 4.3., water consumption variables can be described by using several different theoretical distributions. However, it must be determined, which of the tested theoretical distributions is the best-fitted to the empirical data. Although the *p*-values coming from the Anderson-Darling test can be used for this purpose, however, in this paper, PWRMSE criterion was used. In the case of total water consumption in the group of the tested households, the best-fitted theoretical distribution turned out to be Johnson distribution (PWRMSE = 164.73 dm^3/d). In turn, performed analysis showed that for the average daily water consumption per capita, the best-fitted theoretical distribution was GEV distribution (PWRMSE = 1.64 dm^3/d) (Table 4). For comparison, if for the selection of the best-fitted theoretical distribution we would use *p*-value instead the PWRMSE criterion, in both cases, it would be GMM distribution (Table 3).

Table 4. PWRMSE values for the best-fitted theoretical distribution selection

Statistical distribution	Total daily water consumption for the group of the tested households	Average daily water consumption per capita
	PWRMSE (dm^3/d)	
GMM	176.08	1.74
GEV	193.42	1.64
Johnson	164.73	–
Weibull	262.95	2.44
Normal	324.30	2.95
Log-normal	376.14	3.40

4.5. Simulation of the water consumption

Simulation of the water consumption was conducted using a Monte Carlo method (Fig. 4a, b).

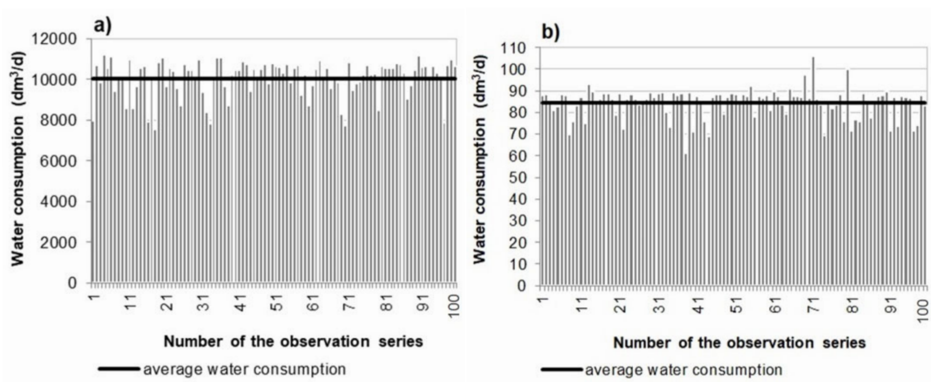

Fig. 4. The results of the water consumption simulation based on the Monte Carlo method: (**a**) for the group of the tested households; (**b**) per capita

The best-fitted theoretical distributions coming from the PWRMSE testing were used. Just for the record, in the case of total daily water consumption in the group of the tested households it was a Johnson distribution, whereas for the average daily water consumption per capita, it was GEV distribution. Performed simulation showed that for the assumed a 25-year prediction period, the average value of total water consumption in the whole group of the households (10 066.9 dm^3/d) (Fig. 4a) is close to the average water consumption (10 111.8 dm^3/d) (Fig. 1a) noted in the period of 2011-2015. Similarly, in the case of the average water consumption per capita, a predicted average water consumption

(84.3 dm^3/d) (Fig. 4b) is compatible with the average daily water consumption per capita (84.1 dm^3/d) noted in the period of 2011-2015 (Fig. 1b). It can be stated that the presented in this paper simulation's method gives a real possibility for a long-term water consumption prediction, even if the type of theoretical distribution of the water consumption will change over time. In this case, it will be still possible to use this simulation method as a reliable forecasting tool by assuming the other best-fitted distribution.

5. Summary and conclusions

For sure, mathematical models development for a long-term water consumption prediction will let to avoid some water system's design mistakes, resulting in many operational and maintenance problems. These are often caused by incorrect universality of using the out-of-date water demand indicators elaborated in the past; in many cases, they don't reflect an actual water demand properly and contribute to the water pipelines' oversizing or undersizing.

In this paper, a new approach to the maximum quarterly water consumption modeling based on the probability distributions was developed. Because the random variables are indeterminate and they can support hypothesis with different distributions, a multi-distribution analysis was performed. The essential part of this paper was preceded by the preliminary statistical data analysis. Based on the coefficient of variation, a small variability of the water consumption in a five-year period was stated. The obtained results of the Kruskal-Wallis test have proved no significant differences between the quarterly water consumption; homogeneity of the water consumption time series was found. In turn, when it comes to the main findings of this study, the results of the Anderson-Darling test showed that at least a half out of the ten tested theoretical probability distributions can be used for the description of the water consumption variables. Both in the case of total daily water consumption in the group of the tested households and the average daily water consumption per capita, it was GMM, GEV, Weibull, Normal and Log-normal distribution; for the first case, there was additionally Johnson distribution. The using of the PWRMSE criterion has proved that Johnson distribution was the best one for the description of total water consumption in the group of the tested households, whereas for the average daily water consumption per capita, it was GEV distribution. The obtained in this paper modeling's results carried out with the Monte Carlo method can be used for designing the other water systems supplying a similar group of the individual water users as the subjected one. But what's important, because the methodology presented in this paper is based on the probability distributions, the proposed simulation method can be used, even if the type of the best-fitted theoretical distribution of the water consumption will change over time; this is because the possibility of assuming the other theoretical distribution.

Thank to this, it is believed that the statistical tools and methodology presented in this paper can be used for a reliable water systems planning and designing.

References

Baldino, N., Sauri, D. (2018). Characterizing the recent decline of water consumption in Italian cities. *Investigaciones Geográficas, 69*, 9-21. DOI: https://doi.org/10.14198/INGEO2018.69.01

Barraqué, B., Isnard, L., Montginoul, M., Rinaudo, J. D., Souriau, J. (2011). Baisse des consommations d'eau potable et d´eveloppement durable. *Annales des Mines – Responsabilité et environnement, 63*(3), 102-108. DOI: 10.3917/re.063.0102

Bartkowska, I. (2014). Dynamics of water consumption changes in a tourist resort. *Journal of Ecological Engineering, 15*(4), 46-54. DOI: https://doi.org/10.12911/22998993.1125457

Batóg, B., Foryś, I. (2009). Forecasting of hot and cold water consumption in building societies. *Studies and Research of the FEM of the SU*, *15*, 21-31 (in Polish).

Bergel, T. (2017). Practical implication of tap water consumption structure in rural households. *Journal of Ecological Engineering, 18*(1), 231-237. DOI: https://doi.org/10.12911/22998993/67102

Bergel, T., Kaczor, G., Bugajski, P. (2016a). Analysis of the structure of water consumption in rural households in terms of design guidelines water and sewage systems. *Infrastructure and Ecology of Rural Areas*, *IV/4*, 1899-1910. DOI: http://dx.medra.org/10.14597/infraeco.2016.4.4.143

Bergel, T., Kotowski, T., Woyciechowska, O. (2016b). Daily water consumption for household purposes and its variability in a rural household. *Journal of Ecological Engineering, 17*(3), 47-52. DOI: https://doi.org/10.12911/22998993/63312

Bergel, T., Szeląg, B., Woyciechowska, O. (2017). Influence of a season on hourly and daily variations in water demand patterns in a rural water supply line – case study. *Journal of Water and Land Development, 34*(1), 59-64. DOI: https://doi.org/10.1515/jwld-2017-0038

Boryczko, K. (2017). Forecasting water use in selected water supply system. *Proceedings of the 9th Conference on Interdisciplinary Problems in Environmental Protection and Engineering (EKO-DOK 2017), Boguszow-Gorce, Poland, 23-25 April 2017. E3S Web of Conferences, 17*. DOI: 10.1051/e3sconf/20171700010

Bosch-Badia, M.-T., Montllor-Serrats, J., Tarrazon-Rodon, M.-A. (2020). Risk analysis through the half-normal distribution. *Mathematics*, *8*(11), 1-27. DOI: https://doi.org/10.3390/math8112080.

Cahill, R., Lund, J. (2013). Residential water conservation in Australia and California. *Journal of Water Resources Planning and Management, 139*(1), 117-121. DOI: https://doi.org/10.1061/(ASCE)WR.1943-5452.0000225

Cieżak, W., Cieżak, J. (2015). Routine forecasting of the daily profiles of hourly water distribution in cities. An effectiveness analysis. *Environment Protection Engineering, 41*(2), 179-186. DOI: 10.5277/epe150215

Donnelly, K., Cooley, H. (2015). *Water use trends in the United States*. Report. California: Pacific Institute. Available online: http://pacinst.org/publication/water-use-trends-in-the-united-states.

Engmann, S., Cousineau, D. (2011). Comparing distributions: The two-sample Anderson-Darling test as an alternative to the Kolmogorov–Smirnov test. *Journal of Applied Quantitative Methods, 6*(3), 1-17.

Forbes, C., Evans, M., Hastings, N., Peacock, B. (2011). *Statistical distributions*, 4th ed. New Jersey, USA: John Wiley & Sons.

Froelich, W. (2015). *Forecasting daily urban water demand using Dynamic Gaussian Bayesian Network*. Proceedings of the 11th International Conference on Beyond Databases, Architectures and Structures, Ustroń, Poland, 26-29 May 2015, 333-342.

Gorączko, M., Pasela, R. (2015). Causes and effects of the water consumption drop by the population of cities in Poland – selected aspects. *Bulletin of Geography. Socio-economic Series*, *27*, 67-79. DOI: https://doi.org/10.1515/bog-2015-0005

Halton, J. H. (1970). A retrospective and prospective survey of the Monte Carlo method. *SIAM Review, 12*(1), 1-63.

House-Peters, L. A., Chang, H. (2011). Urban water demand modeling: Review of concepts, methods, and organizing principles. *Water Resources Research, 47*(5), 1-15. DOI: https://doi.org/10.1029/2010WR009624

Huang, A. C., Lee, T. Y., Lin, Y. C., Huang, C. F., Shu, C. N. (2017). Factor analysis and estimation model of water consumption of government institutions in Taiwan. *Water*, *9*(7), 1-10. DOI: 10.3390/w9070492

Islam, T. U. (2011). Normality testing – A new direction. *International Journal of Business and Social Science, 2*(3), 115-118.

Jaini, P., Poupart, P. (2016). Online and distributed learning of Gaussian mixture models by Bayesian moment matching. *Preprint*. *ArXiv:1609.05881.* Available online: https://arxiv.org/abs/1609.05881.

Koch, R., Bene, K. (2013). Continuous hydrologic modeling with HMS in the Aggtelek Karst region. *Hydrology*, *1*(1), 1-7. DOI: 10.11648/j.hyd.20130101.11

Kvam, P. H., Vidakovic, B. (2007). *Nonparametric statistics with applications to science and engineering*. New Jersey, USA: John Wiley & Sons.

Lai, C. D. (2014). *Generalized Weibull distributions*. Berlin, Germany: Springer.

Młyński, D., Wałęga, A., Petroselli, A., Tauro, R., Cebulska, M. (2019). Estimating maximum daily precipitation in the upper Vistula basin, Poland. *Atmosphere*, *10*(2), 1-17. DOI: 10.3390/atmos10020043

Mombeni, H. A., Rezaei, S., Nadarajah, S., Emami, M. (2013). Estimation of water demand in Iran based on SARIMA models. *Environmental Modeling & Assessment*, *18*(5), 559-565. DOI: 10.1007/s10666-013-9364-4

Papoulis, A., Pillai, U. (2001). *Probability, random variables and stochastic processes*, 4th ed. New York, USA: McGraw-Hill.

Parresol, B. (2003). *Recovering parameters of Johnson's SB Distribution*. Research Paper SRS-31. Asheville, USA: Southern Research Station. Available online: https://www.fs.usda.gov/treesearch/pubs/5455.

Pasela, R., Gorączko, M. (2013). Analysis of selected factors characterizing water consumption in multi-family buildings. *Rocznik Ochrona Srodowiska*, *15*, 1658-1672 (in Polish).

Pawełek, J. (2015). Water management in Poland in view of water supply and sewage disposal infrastructure development. *Infrastructure and Ecology of Rural Areas*, *II/2*, 367-376. DOI: 10.14597/INFRAECO.2015.2.2.029

Pawełek, J. (2016). Degree of development and functionality of the water supply and sewage systems in rural Poland. *Barometr Regionalny. Analizy i prognozy*, *14*(1), 141-149.

Provost, S. B., Saboor, A., Cordeiro, G. M., Mansoor, M. (2018). On the q-generalized extreme value distribution. *REVSTAT – Statistical Journal, 16*(1), 45-70.

Rathnayaka, K., Malano, H., Arora, M., George, B., Maheepala, S., Nawarathna, B. (2017). Prediction of urban residential end-use water demands by integrating known and unknown water demand drivers at multiple scales II: Model application and validation. *Resources, Conservation and Recycling, 118*, 1-12, DOI: 10.1016/j.resconrec.2016.11.015

Regulation of the Minister of Infrastructure of 14 January 2002 on the determination of the average water consumption standards (in Polish).

Reynaud, A. (2015). *Modelling household water demand in Europe - Insights from a cross-country econometric analysis of EU-28 countries*. Technical Report for the Joint Research Centre of the European Commision, Publications Office of the European Union, Luxemburg. Available online: https://ec.europa.eu/jrc/en/ publication/modelling-household-water-demand-europe-insights-cross-country-econometric-analysis-eu-28-countries.

Reynaud, A., Pons, M., Pesado, C. (2018). Household water demand in Andorra: Impact of individual metering and seasonality. *Water, 10*(3), 1-18. DOI: https://doi.org/10.3390/w10030321

Ribeiro, A. S., Almeida, M. C., Palma, J. (2009). Uncertainty evaluation of multi-sensor flow measurement in a sewer system using Monte Carlo method. *Proceedings of the XIX IMEKO World Congress: Fundamental and Applied Metrology, Lisbon, Portugal, 6-11 September 2009*, 1287-1292.

Rinaudo, J. D. (2015). *Long-term water demand forecasting*. Understanding and managing urban water in transition. Dordrecht, Netherlands: Springer, 239-268. DOI: 10.1007/978-94-017-9801-3_11

Romano, M., Kapelan, Z. (2014). Adaptive water demand forecasting for near real-time management of smart water distribution systems. *Environmental Modelling & Software, 60*, 265-276. DOI: 10.1016/j.envsoft.2014.06.016

Sauri, D. (2019). The decline of water consumption in Spanish cities: structural and contingent factors. *International Journal of Water Resources Development, 36*(6), 909-925. DOI: https://doi.org/10.1080/07900627.2019.1634999

Schleich, J., Hillenbrand, T. (2009). Determinants of residential water demand in Germany. *Ecological Economics, 68*(6), 1756-1769. DOI: 10.1016/j.ecolecon.2008.11.012

Sikora, J., Woźniak, A., Zemanek, J. (2006). Water consumption by Bystra village dwellers in the light of survey research. *Infrastructure and Ecology of Rural Areas, 3*(2), 53-65 (in Polish).

Taheriyoun, M., Moradinejad, S. (2015). Reliability analysis of a wastewater treatment plant using fault tree analysis and Monte Carlo simulation. *Environmental Monitoring and Assessment, 187*(1), 1-13. DOI: 10.1007/s10661-014-4186-7

Tiwari, M. K., Adamowski, J. F. (2015). Medium-term urban water demand forecasting with limited data using an ensemble wavelet-bootstrap machine-learning approach. *Journal of Water Resources Planning and Management, 141*(2). DOI: 10.1061/(ASCE)WR.1943-5452.0000454

Vijai, P., Sivakumar, B. (2018). Performance comparison of techniques for water demand forecasting. *Procedia Computer Science*, *143*, 258-266. DOI: https://doi.org/10.1016/j.procs.2018.10.394

Wałęga, A. (2016). The importance of calibration parameters on the accuracy of the floods description in the Snyder's model. *Journal of Water and Land Development, 28*, 19-25. DOI: 10.1515/jwld-2016-0002

Wałęga, A., Młyński, D., Bogdał, A., Kowalik, T. (2016). Analysis of the course and frequency of high water stages in selected catchments of the Upper Vistula Basin in the South of Poland. *Water*, *8*(9), 1-15. DOI: 10.3390/w8090394

Wu, G. Z., Sakaue, K., Murakawa, S. (2017). Verification of calculation method using Monte Carlo method for water supply demands of office building. *Water*, *9*(6), 1-21. DOI:10.3390/w9060376

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Evaluation of Zinc Accumulation in Moss (*Pylaisia polyantha*) Growing Near Intensive Traffic Street Based on Modelling and Experimental Data

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Abstract: *Pylaisia polyantha* moss growing near intensive traffic in Geležinis Vilkas street at Vingis Park (Vilnius) was selected as an indicator of environmental pollution. Two models were applied for the study: the Gaussian plume model – for zinc emission from automobiles calculation and mathematical model – for recalculating the zinc emission from transport to zinc concentration in moss. Moss samples were collected during spring, summer and autumn. There were no significant changes in Zn concentrations between these periods. Zn emission dispersion from pollution source was calculated only for one vehicle, in order to reach relationships between environmental conditions and dispersion of Zn emission from vehicle exhaust fumes pipe. It was detected that the concentration of Zn tends to decrease with the distance from the pollution source. It was observed that there was a strong relationship between wind speed and Zn concentration – the slower the wind speed, the higher concentration of zinc in moss.

Keywords: zinc, moss, atomic absorption spectroscopy, Gaussian plume model

1. Introduction

Pollution of environment is increasing now. Transportation is one of main polluters of the environment, which emits various pollutants to the environment. Transportation emits various heavy metals (HM). Zinc is not the most dangerous among other heavy metals, but its emission from transportation is one of the highest. Heavy metals and other pollutants in moss are currently the focus of attention in various countries, as moss is an excellent indicator of environmental pollution (Koz et al. 2014, Oishi 2019, Oishi 2018, Parmar et al. 2016, Pīrāga et al. 2017, Salo 2014, Sujetovienė & Galinytė 2016, Špirić et al. 2014, Urošević et al. 2018, Vuković et al. 2015, Zhu et al. 2018). HM are potentially toxic substances that enter foodstuffs from the environment, enter the human body through food, and are readily integrated into the biological cycle. Each region has its own pollution specific, which means that the total amount of HM in the moss is highly dependent on the area. Research needs to have as much comprehensive data as possible on the migration and accumulation of heavy metals in the environment and their effects on ecosystems and humans. Studies have shown that the quantity of heavy metals in moss depends on their location and distance to sites that emit heavy metals. From the air, heavy metals settle on the various surfaces. The main sources of anthropogenic pollution in the atmosphere are transportation; industry and energetics. Car emissions account for 60-70% of total emissions. The atmosphere, as a source of metals, is unique in that it has a very short life span, from day to week (I don't understand what you are trying to say, please check). However, even in such a short time, metal particles can travel long distances. Also, metal compounds released into the atmosphere are deposited on the plants at a distance of 10 to 40 km from the source of pollution. The sources of Zinc emissions are many: metalworking industry, transport, energy, fertilizers, and pesticides. It belongs to the intensive accumulation of technogenic dust (Radzevičius et al. 2004). According to Blok (2005) the emissions of zinc along roads originate from: wearing of brake lining; losses of oil and cooling liquid; wearing of road paved surface; wearing of tyres; corrosion of galvanized steel safety fence and other road furniture. The aim of the research was to use moss as an indicator for the assessment of environmental pollution by zinc near intense traffic street, to calculate emission of zinc from cars and to compare experimental results with modelling results.

2. Materials and methods

2.1. Study site

Vingis Park, the largest park in Vilnius, is located at the bend of the Neris River in Vilnius and covers an area of 160 hectares (Vingis park).

The area of investigations (54º40'28" N; 25º14'32" E) is situated between the park of Vingis and Geležinis Vilkas street (Fig. 1). All samples of moss (*Pylaisia polyantha)* were taken in this order: 5, 10, 15, 20, 25 meters from the Geležinis Vilkas street (Fig. 1).

Control samples of moss, in order to evaluate background level of zinc concentration in moss were taken around 500 meters from Geležinis Vilkas street at Vingis park. Samples of moss were taken on 7th of March, on 21st of August, on 14th of November. According to the methodology of moss sampling for EU surveys, samples should be taken in all seasons, except winter, because in winter mosses are covered with snow. During all three samplings of moss there was no rain or snow.

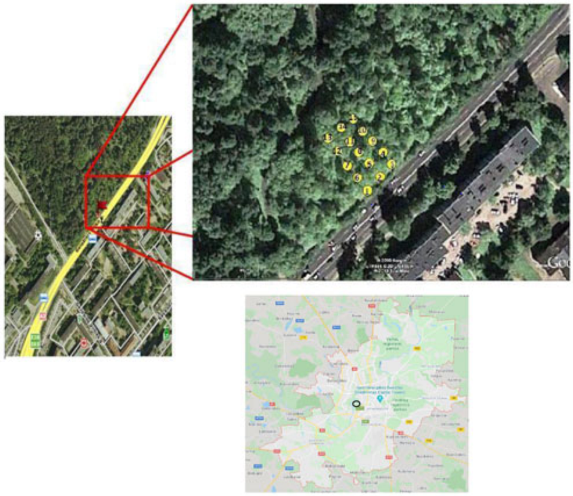

Fig. 1. Sampling places in Vingis park (Vilnius), near Geležinis Vilkas street

2.2. Climate conditions of study site

The pollutant emissions are transported to different distances, depending on the geographic area, its geology and the local meteorological factors: fog, wind, rains, thermal inversions (Dobra et al. 2006). The climate of Vilnius region is considered as humid continental or hemiboreal by Köppen climate classification. The average annual temperature is + 6.1°C, in January the average temperature is − 5.8°C, in July it is +17.4°C (Climate-data). The average precipitation in Vilnius is about 655 millimetres per year (Climate-data). Dominant wind direction – southwest, speed 2.5-4 m/s (Lithuanian Hydrometereological Service).

2.3. Morphological identification of moss

Closely related moss species are often difficult to distinguish from each other than other plants, but it is easy to sample and collect (Banienė 2001, Rowantree et al. 2010). In Lithuania there are 350 species of moss, they all belong to 33 families (Banienė 2001). Each moss species, though much alike in terms of stems and leaves, tends to have different types of capsules (Tiny Shag Moss).

2.4. Sampling of moss

Most methods in heavy metal monitoring employ moss as bioaccumulators (Stihi et al. 2006). Sampling and sample handling was carried out using plastic gloves and bags. All forest debris from moss must be removed (Aboal et al. 2008). Moss samples were stored at room temperature until preparation for analysis.

2.5. Calculation of moisture content

Moisture content was calculated in moss:

$$M_n = \frac{(W_W - W_D)}{W_D} \cdot 100 \quad (1)$$

where: M_n – moisture content of sample, %, W_w – wet weight of the sample, g, W_d – weight of the sample after drying, g (moisture content).

2.6. Reagents and equipment

All chemicals and reagents were of analytical grade or higher purity and they were obtained from Sigma Aldrich (Germany) and used in the experiments as received without further purification. The solutions were prepared by mixing appropriate standards in deionized water from the water purification system (Demiwa 3 ROI). Metal standards made in VWR Chemicals (England) were used for GFAAS and FAAS calibration. The concentration of Zn (II) in used standard solution was equal to 1000 mg/L in 2% of HNO_3. All volumetric flasks used in the experiments were soaked for 24 h with 5M HNO_3 and then rinsed 3-4 times carefully with deionized water. All the volumetric flasks used were of the highest accuracy class. High accuracy analytical balance AS 60/220.R2 (Radwag, Poland) was used to weigh moss samples.

2.7. Sample preparation for metal analysis

The moss samples collected were prepared by a high-temperature dry oxidation method. Each moss sample (about 20 g) was dried in a muffle furnace until constant weight at 100 ±5°C. After that the temperature was gradually raised from (100°C/1h) to 500 ±20.0°C in a muffle furnace for 2 hours. The resulting ash was cooled to room temperature. The aqua regia (3:1, v/v, HCl to HNO_3) digestion procedure was used for analysing total-recoverable heavy metal (Zn) content in ashes. Concentrations of acid used for digestion of moss samples were the following: 36.5% (HCl) and 63% (HNO_3). The digestion of the moss samples (about 0.5 g) was performed by using microwave digestion system Milestone Ethos Touch Control (Milestone SRL, Italy) for about 50 min in Teflon containers. After cooling to room temperature, the solution was filtered through a 0.45 μm PTFE membrane filter, transferred quantitatively to a 50 mL volumetric flask and supplemented with deionized water to the mark. Deionized water used in experiments meets requirements of ISO 3696:1987 (Water for analytical laboratory use – Specification and test methods) standard. After, its concentration of Zn was analysed with an atomic absorption spectrophotometer, model 210 VGP, Buck Scientific (USA), equipped with a Buck Scientific model 220-GF graphite furnace atomizer and acetylene-air flame. 0.7 nm slit was selected for measurement of zinc concentrations in solutions. 213.9 nm wavelength was used during measurements. The content of Zn in moss ash (mg/kg) was calculated by formula (2):

$$C = \frac{Ce \cdot V \cdot k \cdot 1000}{m} \tag{2}$$

where: C – the concentration of analyte in sample, mg/kg, C_e – the concentration of the analyte in solution, mg/mL, V – the volume of the sample, mL, k – the dilution factor, m – the amount of moss ash taken for the test, g.

Zn analysis method used for the moss was validated by using a recovery analysis. The percentage recoveries were calculated by using the following equation (Sarker et al. 2015):

$$\text{Percentage recovery} = \frac{C_E}{C_M} \cdot 100 \tag{3}$$

where: C_E – the experimental concentration that was determined from the calibration curve, C_M – the spiked concentration.

According to the European Commission (2003), a method can be considered accurate and precise when the accuracy of the data is between 70 and 110%. Experimental result meets these requirements.

2.8. Quality control and statistical evaluation

The concentration of Zn in used standard solution was equal to 1000 mg/L in 2% of HNO_3. Working aqueous standard solutions containing Zn was prepared by serial dilution of the certified reference metal standard solution for atomic absorption spectroscopy with deionized water. Three samples of moss were taken from each place. All experiments were conducted in triplicate. Two blanks (without Zn ions) were used for each zinc concentration determination. Statistical analysis of data was carried out using Excel and Statistica software. Arithmetic average, standard deviation, confidence intervals and Pearson coefficients were estimated at $p < 0.05$.

2.9. Theoretical calculation

60 km/h – allowable speed at Geležinis Vilkas street in Vilnius near Vingis park. It was assumed that for 100 km, vehicle uses 10 l of petrol in the city, e.g. 1 automobile consumed 6 l of petrol per hour. Traffic intensity at Geležinis Vilkas street is 1200 vehicles per hour. Total fuel consumption per hour in investigated area will be 7200 l. The density of fuel (in this model only petrol fuel was evaluated) is 770 g/L (What are the types of fuel). Zinc emission factor for vehicles in mg/kg is equal to 1 for passenger car (Road transport). Total emissions of zinc per 1 hour in investigated area is equal to 0.00154 g/s.

2.10. Mathematical modelling

In a Gaussian plume, the spatial distribution of concentration along a transverse axis is Gaussian in shape. The following steady state 3-dimensional model describes the concentration at any point in a coordinate system where the wind is moving parallel to the x-axis (Gaussian plume model):

$$C(x,y,z) = \frac{Q}{2\pi \cdot u \cdot \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2} \right) \right] \exp\left[-\frac{1}{2}\left(\frac{H^2}{\sigma_z^2} \right) \right] \tag{4}$$

where: C – concentration of contaminant, g/m^3, x, y, z – distance from origin in x, y, z coordinates, m, H – effective stack height, m, Q – rate of emission of gas, g/s, σ_y, σ_z – horizontal and vertical plume standard deviations (m), each a function of x, u – wind speed at effective stack height, m/s.

The input data of the model are presented in the Table 1.

Table 1. Input data for mathematical modelling of Zn dispersion in atmosphere

Input data	Value
Stack height, m	0.3
Stack diameter, m	0.1
Emission	
Zn emission rate, g/s	0.00154
Gas velocity in the pipe of car, m/s	1.0
Gas temperature in the pipe of car, °C	200
Atmospheric condition	3 – slightly unstable
Ambient average temperature, °C	
Spring	6.2
Summer	16.8
Autumn	7.1

The emission of zinc downwind from the vehicle (in this case vehicle is a stack) was simulated. Input parameters needed for simulating, are as follows: the height of the stack above the ground (in meters); the diameter of the opening of the stack (in meters); the velocity of the gas emitted from the stack (in meters per second); the temperature of the gas as it exits the stack (in degrees Celsius); the rate at which pollution is emitted from the stack (in grams per second); the atmospheric stability; the number of wind velocities that you wish to investigate; the wind velocities; the number of distances downwind to calculate; the actual distances downwind. The atmospheric stability categories accounts for the fact that a parcel of air changes temperature as it changes in altitude. With this input data, it is possible to calculate the concentration of the pollutant at various locations downwind from the stack, usually measuring from 0 kilometers (the base of the stack) down to 100 km from the stack (Gaussian plume model).

3. Results and discussion

3.1. Moisture content in moss

18 samples were taken from Vilnius Vingis park, near Geležinis Vilkas street. The average results from three seasons of moisture content in samples of moss are presented in Fig. 2.

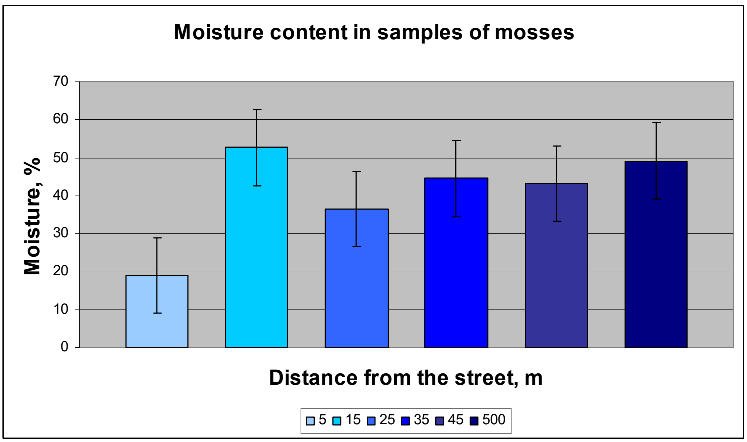

Fig. 2. An average results from three seasons of moisture content in moss

In moss which were located 5 meters from the street, the moisture content was determined as 18.96%. In collected *Pylaisia polyantha* moss which were located at the distance of 15 meters from the street - the average moisture content was 52.65%. In moss which were collected 25 meters from the street the moisture content was 36.44%. In moss located at a distance of 35 meters from the street the moisture content was 44.55%. In samples of moss which were collected at 45 meters from the street the moisture content was 43.22%. In the control samples 49.07% of moisture content was detected.

3.2. Zn concentration in sample of moss

Zn concentration was determined in samples of *Pylaisia polyantha* moss, along the high intensive traffic Geležinis Vilkas street in Vilnius. Zinc concentrations in moss (*Pylaisia polyantha*) growing near Geležinis Vilkas street are presented in Fig. 3. (in spring, in summer and in autumn).

There is a direct relationship between the Zn content found in moss and the distance from the Geležinis Vilkas street. It was observed that Zn content in all samples of moss tends to decrease with the distance from the Geležinis Vilkas street.

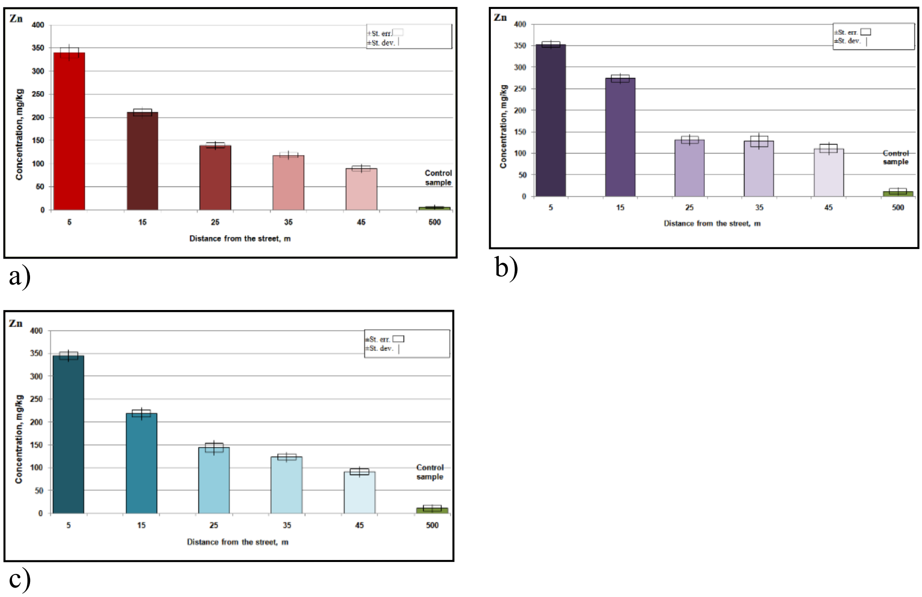

Fig. 3. Zinc concentrations in moss near Geležinis Vilkas street: a) in spring, b) in summer, c) in autumn

At the distance 5 and 15 meters from the Geležinis Vilkas street Zn concentrations were considerably high and it reveals that the moss near intensive traffic were heavily polluted (Fig. 3). At a distance of 5 meters from the street, the highest concentration of zinc – 339.96 ±10.72 mg/kg in dried moss (Fig. 3) was observed. In samples of moss at 15 meters distance from the street, the concentration of zinc was lower – 210.47 ±7.24 mg/kg. In 25 meters from the street zinc concentration decreased till 139.47 ±5.24 mg/kg. In 35 meters from the street, zinc concentration decreased till 118.44 ±5.37 mg/kg. The lowest concentration of zinc in samples of moss was observed at the 45 meters from the intensive traffic – 89.52 ±5.34 mg/kg. In control sample quite low concentration of Zn was determined – 6.03 ±2.15 mg/kg. Control sample was 41 times lower in concentration of zinc than the sample located at 5 meters from the street. It can be stated that Zn emission source could be high around intensive traffic flow in Geležinis Vilkas street (Fig. 3a).

At a distance of 5 meters from the street it was observed that the highest concentration of zinc – 352.14 ±6.52 mg/kg in dried moss (Fig. 3b) was in summer. In samples of moss at a distance of 15 meters from the street, the concentration of zinc was lower – 273.75 ±8.40 mg/kg. In 25 meters from the street, the concentration of zinc was equal to 128.01 ±11.98 mg/kg. The lowest concentration of Zn was observed at 45 meters from the Geležinis Vilkas street – 110.74 ±10.15 mg/kg. In control sample of moss small concentration of Zn was determined – 7.49 ±7.133 mg/kg, it was 47 times lower than closer to the (in 5 meters) pollution source (Fig. 3b).

At a distance of 5 meters from the street, it was observed that the highest concentration of zinc – 344.65 ±7.84 mg/kg in dried moss (Fig. 3c) was in autumn. In samples of moss at a distance of 15 meters from the street, the concentration of zinc was lower – 217.82 ±7.81 mg/kg. At a distance of 25 meters from the street, zinc concentration decreased till 143.71 ±9.52 mg/kg. In 35 meters from the street, zinc concentration decreased till 123.19 ±6.38 mg/kg. The lowest concentration was observed at 45 meters from the Geležinis Vilkas street – 90.88 ±6.86 mg/kg. In the control sample small concentration of Zn was determined – 6.17 ±6.13 mg/kg – 56 times lower concentration than in distance of 5 meters (Fig. 3c).

3.3. Zinc emissions from transport into atmosphere

Emission of zinc from transport in Geležinis Vilkas street is presented in Fig. 4. (in spring, in summer and in autumn).

The highest emission of zinc was calculated at 5 meters from the pollution source, this congruous (I don't understand what you are trying to say, please check) with the results from collected samples of moss, moreover, concentration tends to decrease from the source in both (real and modelled) cases in spring. According to the Lithuanian Hydrometeorological Service under Ministry of Environment, an average of annual wind speed in Vilnius is 4 m/s. Accumulation of Zn has a strong relationship with the speed of wind. The highest concentrations of Zn near emission pollution source in the atmosphere were detected when wind speed was low (Fig. 4 a).

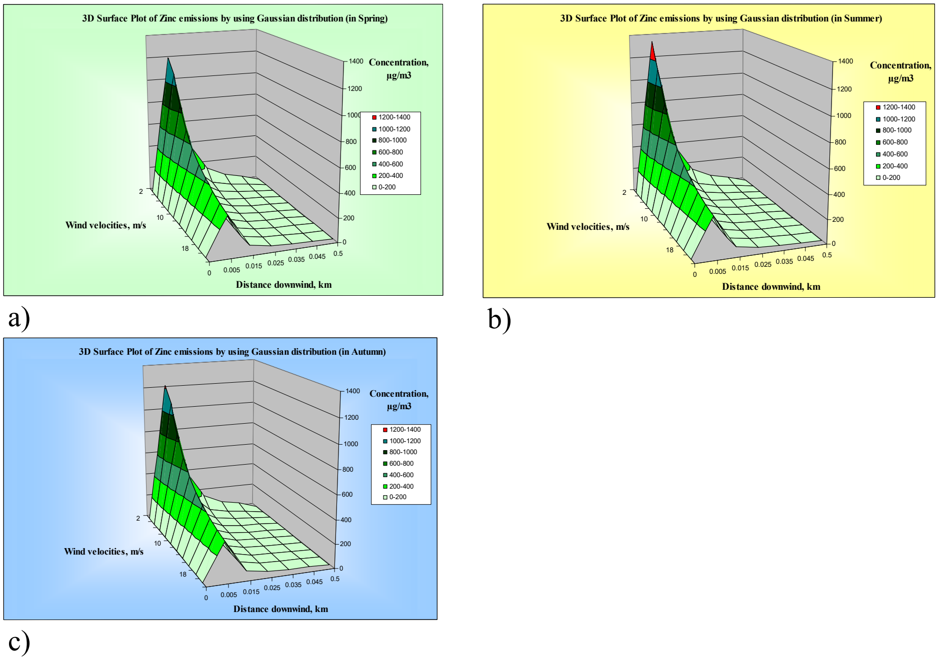

Fig. 4. 3D surface plot of Zn emission based on Gaussian distribution: a) in spring, b) in summer, c) in autumn

In summer, the situation is almost the same like during the spring period. Zn emission had the tendency to decrease with the distance from pollution source. The relationship of wind and zinc concentration is also the same. During summer modelling, one more relationship was observed. The concentration tends to increase with higher temperature, comparing with spring and autumn. This relationship is presented in Fig. 4b, where concentration of zinc at 5 meters reaches more than 1200 $\mu g/m^3$ (in red colour) when the wind speed was 2 m/s. This tendency is similar to results of analysed samples, where Zn concentration was slightly higher in summer period than in spring. Moreover, the highest concentrations of Zn were found during the summer period.

The situation in autumn was almost the same like in spring (Fig. 4c). This was due to the similarity of average ambient temperature (spring 6.2°C and autumn 7.1°C). Strong relationship between wind speed and Zn concentrations near pollution source was observed. Lowest concentrations of zinc were simulated when the speed of wind is higher. Concentration of Zn had the tendency to decrease with the distance from the pollution source – Geležinis Vilkas street.

3.4. Correlation of experimental and modelling data

Correlations between experimental and modelling data were performed by the Excel and software STATISTICA (Fig. 5).

For determination of correlation, Pearson coefficient was used. Correlation between experimental data and modelling results was determined. The calculated Pearson correlation coefficient for zinc was high – r = 0.8738.

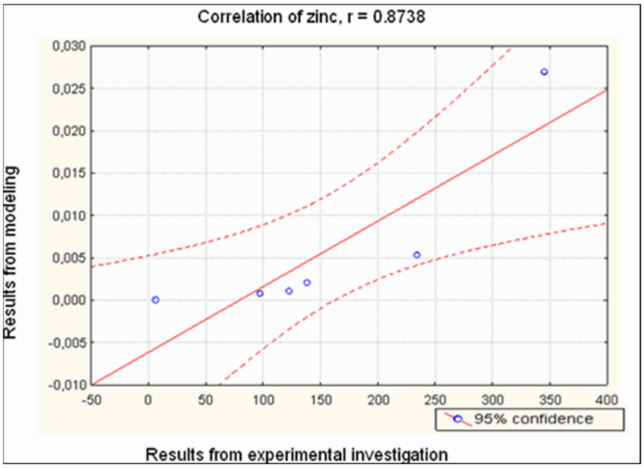

Fig. 5. Correlation between experimental and simulated results for zinc

This shows, that real results and modelling results have strong relationships, moreover, this helps to prove, that high concentrations of zinc were determined due to pollution from intensive traffic (Fig. 5).

3.5. Comparing of modelling and experimental data

After modelling, experimental data and simulated results were compared. The hypothesis of this calculation was such that traffic influences Zn concentration in moss, therefore in order to get clear result of transport impact, from all concentrations at different distances it is necessary to make a subtraction of background pollution, for this case:

Concentration in moss - concentration of control sample = Concentration of HM caused by transport. This mathematical equation was suggested:

$$C_{\text{in moss}} = K \cdot (C_{\text{modelled results}})^{n} \tag{5}$$

where: $C_{\text{in moss}}$ – concentration of Zn in moss from modelling results, K – empirical coefficient, which converts results from mg/m^3 to mg/kg, n – empirical coefficient.

The empirical coefficients K and n (K = 300 and n = 0.346) was calculated. All results and formulas for calculations are presented in Table 2.

From Table 2 it can be seen, that simulated results are quite similar to investigation results, differences vary from 0.01 to 25%. In order to evaluate investigation results, a mathematical model based on Gaussian plume was performed. All data analysis were made in three main steps: mathematical modelling, calculation of correlation and, finally, in order to make sure that results from mathematical modelling and experimental results can be compared, error of calculation for Zn was calculated.

Table. 2. Comparison of experimental and modelled results of zinc concentrations

Distance	(t, v)	Real results from experiment	Modelled results, mg/m^3	Error	Converted results from modelling
m	°C; m/s	mg/kg	mg/m^3	%	mg/kg
				f = (d-g-m) ·100 /(d-m)	$C_{\text{in moss}} = K \cdot (C_{\text{modelled results}})^n$
Spring period					
5	6.2; 4	339.96	1.08857	-1.85908	339.83347
15		210.47	0.22379	3.70181	196.59083
25		139.47	0.08475	-5.51755	140.49345
35		118.44	0.04389	0.20111	111.89152
45		89.52	0.02674	-13.3082	94.26109
500		6.33	0.00023	–	–
Summer period					
5	16.8; 4	352.14	1.13358	-1.11259	344.63114
15		273.75	0.22480	24.97441	196.89790
25		131.55	0.08489	-16.9061	140.57256
35		128.01	0.04393	4.10017	111.92373
45		110.74	0.02675	5.19154	94.27753
500		5.08	0.00023	–	–
Autumn period					
5	7.1; 4	344.652	1.09489	-2.15008	340.51526
15		217.816	0.22394	4.78291	196.63470
25		143.71	0.08477	-6.11661	140.50475
35		123.188	0.04390	-0.01084	111.89612
45		90.877	0.02675	-18.4616	94.263436
500		6.17	0.00023	–	–

Simulation model showed few strong important relationships with conditions of the atmosphere. First is wind speed – the slower the speed – the higher the concentration of Zn near the emission source. Second is – the higher the temperature – the higher the concentration of Zn, especially near pollution source. That is why the model from summer period had the highest concentration of Zn. On the other hand, model does not include rain and snow precipitation. Emission factor simulated for Zn was calculated and other input data was chosen according to an average for one passenger automobile, which is the main reason why it was difficult to expect accurate results.

It is important to note that the mathematical model was prepared for one passenger car, in order to get main relationships between Zn dispersion and atmospheric conditions. The results would be very inaccurate results if they were simulated for all 1200 vehicles, because all vehicles have different technical characteristics – age, type of vehicle (passenger, bus, etc.) engine and fuel type, different speed, different situations in traffic (peak hours, etc.).

4. Conclusions

For monitoring of zinc atmospheric deposition, it is popular to apply terrestrial moss, because moss do not have any roots, their surface is large, they grow in wide-spread population in groups, they have long life cycle, they survive in the high-polluted environment, they are able to obtain nutrients from wet and dry deposition and clearly reflect the atmospheric deposition. All these environmental characteristics prove that moss is a good indicator in airborne pollution monitoring, especially in HM monitoring.

Samples of moss accumulate high amounts of precipitation, according to the calculations, moisture in *Pylaisia polyantha* moss were in the range of 13.82-60.07%. Results of moisture content show that it is important to take large amount of samples during sampling process, because after the drying of moss, the sample can be lost due to underweight. According to the measurement, the ratio of mass - loss in samples of moss was 73.28-83.18%.

Investigation results of this work clearly present a strong traffic-related gradient - zinc concentrations in samples of moss tends to decrease with distance from the source of pollution – Geležinis Vilkas street. At the distance 5 and 15 meters from the Geležinis Vilkas street Zn concentrations were considerably high and it reveals that the moss *Pylaisia polyantha* near intensive traffic are heavily polluted.

Sample of moss were collected three times in different sessions (spring, summer, autumn). There were no significant changes in Zn concentrations between these periods. Results of different seasons vary in range of 3-10 mg/kg for Zn. This insignificant variation could be due to short period of investigation.

The highest concentration of zinc accumulated in samples of *Pylaisia polyantha* was recorded at 5-meter distance from the street. The highest concentration of zinc was found during summer season – 352.14 ±6.52 mg/kg. At the distance of 15 meters from the street the highest concentration of zinc was also found in summer season – 273.75 ±8.40 mg/kg. At 25 meters from intensive traffic Zn concentration in autumn season was 143.71 ±9.52 mg/kg. The highest concentration of Zn at the 35 meters from intensive traffic flow was 128.01 ±11.98 mg/kg. At 45 meters from the street moss contain 110.74 ±10.15 mg/kg of zinc and this was the highest concentration, which was determined in summer season. In sample of control at 500 meters was found 6.325 ±2.13 mg/kg of Zn.

Mathematical modelling results based on Gaussian plume is presented. Zn emission dispersion from pollution source was calculated only for one vehicle, in order to reach as clear as possible relationships between environmental conditions and dispersion of Zn emission from vehicle exhaust fumes pipe. It was not possible to calculate total pollution, caused by highly intensive traffic, because there are no accurate data about different types of vehicles, for example: engine type, fuel type, age and other factors, which could have an influence on the modelling results. It was observed during modelling, that the concentration of Zn tends to decrease with the distance from pollution source. The same trend was observed in the experimental research. Moreover, a strong relationship between wind speed and Zn concentration was observed – the slower the wind speed, the higher the concentration of zinc in moss near pollution source.

References

Aboal, J. R., Fernández, J. A., Couto, J. A., Carballeira, A. (2008). Testing Differences in Methods of Preparing Moss Samples. *Environmental Monitoring and Assessment*, *137,* 371-378. DOI: 10.1007/S10661-007-9772-5.

Banienė, J. (2001). *Lihuanian Moss*. Kaunas: Lututė (in Lithuanian).

Blok, J. (2005). Environmental Exposure of Road Borders to Zinc. Science *of the* Total Environment*, 348(1-3),* 173-190. DOI: 10.1016/J.Scitotenv.2004.12.073.

Climate-Data.Org. Retrieved From: Https://En.Climate-Data.Org/Europe/Lithuania/ Vilnius-County/Vilnius-431/#Temperature-Graph (Accessed 1 April 2020).

Dobra, M., Viman, V., Vatca, Gh. (2006). Contributions to the Study of Heavy Metals Concentration Variation in Sedimentable Dusts According to the Distance from the Pollution Source. *American Journal of Environmental Sciences, 2(3),* 92-94.

Gaussian Plume Model. Retrieved From: http://Www.Envi.Hufs.Ac.Kr/Gwlee/ Session9/Gaussian.Html (Accessed 11 April 2020).

Koz, B., Cevik, U. Ğ. U. R. (2014). Lead Adsorption Capacity of Some Moss Species Used for Heavy Metal Analysis. *Ecological Indicators*, *36*, 491-494. DOI: 10.1016/J.Ecolind.2013.08.018.

Lithuanian Hydrometereological Service. Retrieved From: Http://Www.Meteo.Lt (Accessed 1 March 2020)

Moisture Content. Science & Engineering. Retrieved From: http://Compost.Css.Cornell.Edu/Calc/Moisture_Content.Html (Accessed 15 April 2020).

Rowantree, J. K., Cowan, R. S., Leggett, M., Ramsay, M. M., Fay, M. F. (2010). Which Moss is Which? Identification of the Threatened Moss Orthodontium Gracile Using Molecular and Morphological Techniques. *Conservation Genetics, 11*, 1033-1042. DOI: 10.1007/S10592-009-9948-3.

Oishi, Y. (2019). Moss as an Indicator of Transboundary Atmospheric Nitrogen Pollution in an Alpine Ecosystem. *Atmospheric Environment*, *208,* 158-166. DOI: 10.1016/J.Atmosenv.2019.04.005.

Oishi, Y. (2018). Comparison of Moss and Pine Needles as Bioindicators of Transboundary Polycyclic Aromatic Hydrocarbon Pollution in Central Japan. *Environmental Pollution*, *234*, 330-338. DOI: 10.1016/J.Envpol.2017.11.035.

Parmar, T. K., Rawtani, D., Agrawal, Y. K. (2016). Bioindicators: The Natural Indicator of Environmental Pollution. *Frontiers In Life Science*, *9(2)*, 110-118. DOI: 10.1080/21553769.2016.1162753.

Pīrāga, D., Tabors, G., Nikodemus, O., Žīgure, Z., Brūmelis, G. (2017). Current Content of Selected Pollutants in Moss, Humus, Soil and Bark and Long-Term Radial Growth of Pine Trees in the Mezaparks Forest in Riga. *Environmental Science and Pollution Research*, *24(13)*, 11964-11977. DOI: 10.1007/S11356-015-5540-1.

Radzevičius, A., Gregorauskienė, V., Kadūnas, V., Putys, P. (2004). Geochemical Atlas of Panevezys County. Panevėžys.

Road Transport. Retrieved From: http://Www.Eea.Europa.Eu/Publications/EMEPCORINAIR5/B710vs6.0.Pdf (Accessed 29 April 2020).

Salo, H. H. (2014). Preliminary Enviromagnetic Comparison of The Moss, Lichen, and Filter Fabric Bags to Air Pollution Monitoring. *Fennia-International Journal of Geography*, *192*(2), 154-163. DOI: 10.11143/41354.

Sarker, N., Chowdhury, M. A. Z, Fakhruddin, A. N. M, Et Al. (2015). Heavy Metal Contents and Physical Parameters of Aegiceras Corniculatum, Brassica Juncea, and Litchi Chinensis Honeys from Bangladesh. Biomed Research International, 1-9. DOI: 10.1155/2015/720341.

Sujetovienė, G., Galinytė, V. (2016). Effects Of The Urban Environmental Conditions on the Physiology of Lichen and Moss. *Atmospheric Pollution Research*, *7*(4), 611-618. DOI: 10.1016/J.Apr.2016.02.009.

Stihi, C., Bancuta, A., Popescu, I., Virgolici, M., Cimpoca, V., Gugiu, M., Vlaicu, Gh. (2006). Air Pollution Studies Using PIXE and ICP Methods. *Journal of Physics: Conference Series, 41*, 565-568. DOI: 10.1088/1742-6596/41/1/070.

Špirić, Z., Vučković, I., Stafilov, T., Kušan, V., Bačeva, K. (2014). Biomonitoring of Air Pollution with Mercury in Croatia by Using Moss Species and CV-AAS. *Environmental Monitoring and Assessment*, *186*(7), 4357-4366. DOI: 10.1007/S10661-014-3704-Y.

Tiny Shag Moss. Retrieved From: Http://Www.Sherrysknowledgequest.Com/Moss.Htm (Accessed 15 April 2020).

Urošević, M. A., Vuković, G., Vasić, P., Jakšić, T., Nikolić, D., Škrivanj, S., Popović, A. (2018). Environmental Implication Indices from Elemental Characterisations of Collocated Topsoil and Moss Samples. *Ecological Indicators*, *90*, 529-539. DOI: 10.1016/J.Ecolind.2018.03.048.

Vingis Park. Retrieved From: Https://Www.Govilnius.Lt/Visit-Vilnius/Places/Vingis-Park (Accessed 30 April 2020).

Vuković, G., Urošević, M. A., Goryainova, Z., Pergal, M., Škrivanj, S., Samson, R., Popović, A. (2015). Active Moss Biomonitoring for Extensive Screening of Urban Air Pollution: Magnetic and Chemical Analyses. *Science of the Total Environment*, *521*, 200-210. DOI: 10.1016/J.Scitotenv.2015.03.085.

What are the Types of Fuel? Retrieved From: http://Proin.Ktu.Lt/ ~Tomablaz/Azina/ Index.Php?Akcija=Klatsas&Tema=12&KLKODAS=46 (Accessed 18 March 2020) (in Lithuanian).

Zhu, R. G., Xiao, H. Y., Zhang, Z., Lai, Y. (2018). Compound-Specific Δ 15 N Composition of Free Amino Acids in Moss as Indicators of Atmospheric Nitrogen Sources. *Scientific Reports*, *8*(1), 1-11. DOI: 10.1038/S41598-018-32531-X.

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An Improved Method of Serial Balancing of Hybrid Boiler Station Systems

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Abstract: This paper presents a prototype of a thermo-hydraulic distributor for a hybrid boiler station supplying a small hotel in Koszalin. The task of the device was to balance the hybrid system with four circuits with different operating parameters, also changing in an extremely irregular manner. A prototype of a thermo-hydraulic distributor with improved internal structure was developed, ensuring the operation of the device in accordance with the temperature logic. Dimensions of the device have been calculated in accordance with the existing design principles of hydraulic distributors.

Keywords: thermo-hydraulic distributor, hybrid boiler station, system balancing, temperature logic

1. Introduction

Hybrid boiler stations with heating and supply circuits with different operating parameters are very effective and at the same time complex heating systems that need innovative technological solutions for their correct balancing both hydraulically and thermodynamically in order to achieve high operating efficiency (Szkarowski et al. 2007). In line with the policy of the European Union countries, it is of key importance, inter alia, for increasing the improvement of energy efficiency in the residential sector (Żelazna 2012). One of such devices influencing the correctness and efficiency of operation may be an innovative thermo-hydraulic distributor, the feature of which is a serial connection of boiler and heating circuits (Szkarowski et al. 2007).

In recent years, many heating systems have been developed based on the economization of the process of preparing and supplying heat to consumers, minimizing both losses and energy consumption costs. The essences of the planned energy – efficient economy in modern heating systems are the appropriate, precise design criteria and quality assumptions (Orłowska 2020). The design criteria include: type and number of heat sources, method of heat distribution, type of heating devices and regulation system. The qualitative assumptions take into account: the specificity of systems that require a lowered or increased temperature of the heating medium, periodic overheating in the hot water system, associating heat from primary and alternative sources, and using the heat of the flow returning from the system in the absence of consumption. In such a defined thermal energy management system, newer solutions can be noticed in technological systems such as: layered heat buffers, vertical hydraulic distributors (PRH), ZORT – System hydraulic distributors and mini – hot water nodes. Despite numerous examples of their effective application, especially in housing construction, paradoxically new problems may arise related to their comprehensive operation (Szkarowski & Naskręt 2008). The most common problems during the operation of new systems include:

- overheating or underheating of buildings, while overheating increases energy costs,
- too long heating time of rooms after the morning start – up of the system,
- failure to ensure the required thermal comfort, despite the use of devices with the required thermal power,
- too large fluctuations in air temperature in rooms caused by improper operation of control valves or improper difference between the supply and return water temperatures,
- too low temperature of hot water during its distribution,
- reduction of the efficiency of the heat source or sources by insufficient use of thermal energy in receiving circuits (Szkarowski & Naskręt 2008, Dopieralska et al. 2015).

The technology of heat supply in multi – family buildings, offices, public buildings, etc., is more and more often characterized by diversified operating parameters of heating, hot water, ventilation and air conditioning circuits. Moreover, they can be powered from several sources and cooperate with renewable energy sources (RES). The main condition for the proper functioning of these systems in terms of hydraulics is the elimination of the mutual influence of water flows, e.g. caused during pump switching on, and from the thermodynamic point of view – the supply of a heating medium with an appropriate supply and return temperature for each circuit, consistent with the adopted calculation parameters. Economical selection of the number and parameters of devices, mainly such as boilers, pumps, control valves, etc., is possible when the technological system is separated into a boiler circuit (primary) and a heating circuit (secondary) (Szkarowski 2019).

The commonly used PRH or ZORT – System distributors use the principle of parallel coupling of hydraulic circuits. In the case of PRH, the circuits remain thermodynamically independent, while the ZORT – System devices are the zero point in terms of hydraulics and thermodynamics. Where heat loads differ and change unevenly over time, the common principle of parallel coupling of hydraulic circuits into one system may not be entirely effective.

Vertical hydraulic distributors (PRH and others) only provide hydraulic balancing at the same flow temperature of the circuits equal to the temperature of the heat source. ZORT distributors equalize the temperature of all flows returning to the coupling and this temperature is the same for supplying these circuits. The multi – section ZORT – Multi devices allow you to combine thermally diverse circuits. However, when the heat demand of these circuits varies, additional devices are needed.

Serial coupling of heat consumption circuits with a gradually decreasing supply temperature of the circuits (according to the so – called temperature logic) is particularly advantageous when efficient condensing heat sources are used (Janta-Lipińska 2020). Compared to parallel systems, the series circuit enables the guaranteed return water parameters from the heat source to be obtained for a longer time during sudden and unpredictable fluctuations in the heat load. Serial connection of circuits allows to avoid mutual hydraulic and thermodynamic contradictions or at least to alleviate these contradictions (Shkarovskiy & Zelenov 2012).

2. Object, goals and methodology of research

The object of the research is the hotel "Services & Bistro" in Koszalin. The facility has a multi – circuit heating system, which is characterized by the demand for a heating medium with very varied parameters, which also change in an extremely irregular manner. It was the unpredictable nature of these changes that initiated the idea of balancing them with an improved serial hydraulic – distributor and the need for this solution.

The facility has 4 heating circuits:

1. Hot water with the parameters of the heating medium 70/50°C and the power of demand $\boldsymbol{Q}$ = 25 kW,
2. Mechanical ventilation with the parameters of the heating medium 50/40°C and the power of demand $\boldsymbol{Q}$ = 35 kW,

3. Radiator heating with the parameters of the heating medium 45/35°C and the power of demand $\boldsymbol{Q}$ = 17 kW,
4. Floor heating with the parameters of the heating medium 42/30°C and the power of demand $\boldsymbol{Q}$ = 4 kW.

The diagram of the existing hybrid boiler station is shown in Figure 1. The system includes: heat generation circuit, internal systems circuits consuming heat, and indirect systems of heat exchangers, heat storage and distribution systems. An additional element is the cooling system of the mechanical ventilation circuit.

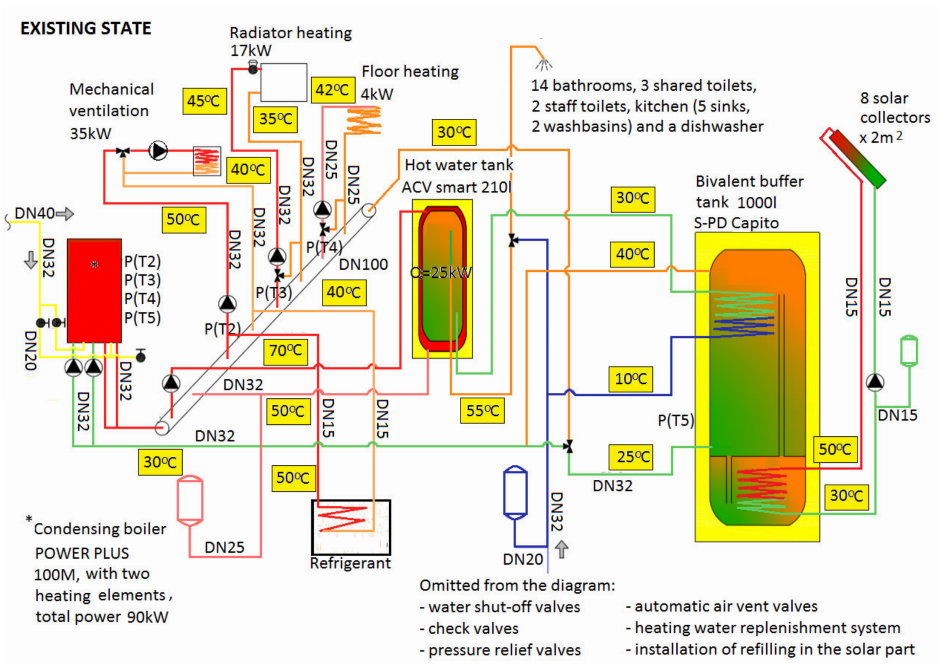

Fig. 1. Technological scheme of a hybrid boiler station in Hotel Services & Bistro

The diagram omits a number of typical devices that are not significant in terms of system operation.

In terms of technology, the scheme of the boiler station can be divided into four units:

1. Main heat source – gas condensing boiler PLUS 100M from POWER with two heating elements with a total power of 90 kW.
2. Auxiliary heat source – 8 solar collectors with an area of 2 m^2 each as the main heat source in the summer period.

3. Heat storage system – bivalent buffer tank with a capacity of 1000 dm^3 S – PD Capito.
4. Domestic hot water heating system – ACV smart 210 shell heat exchanger with a capacity of $\boldsymbol{Q}$ = 25 kW, supplying batteries in 14 bathrooms, 3 shared toilets, 2 toilets for staff. The kitchen has 5 sinks, 2 washbasins and a dishwasher.

Currently, the role of a serial distributor is a stainless steel pipe with a diameter of DN100 with pipe stubs of DN32 and DN25. The distributor was tilted assuming that the change in density would act by gravity in the direction of the fluid's movement. During the tests, it was found that it is of little importance in the case of the pump cycle. However, the tilt of the device has proven useful in bleeding and desludging. The pipe stubs in the distributor are immersed to the half of the pipe diameter, and besides, the device has no additional internal elements. The heating circuits are connected in serial to each other, from the highest parameters to the smallest, as shown in the diagram (Fig. 1).

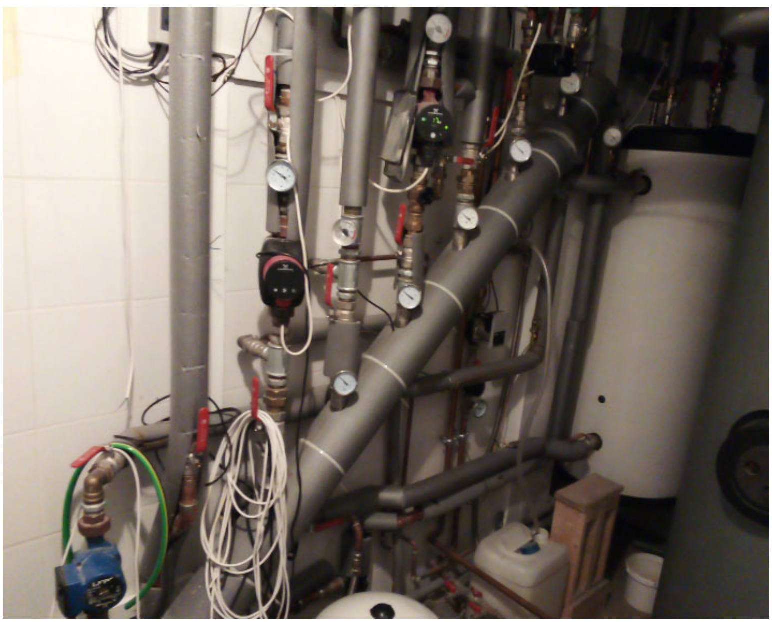

Fig. 2. Photo of the device prototype during operation

The research problem of this boiler station is the temperature fluctuation of the supply heating medium, especially in subsequent circuits, at the moment of peak power demand. The authors concluded that the existing distributor, despite its simplicity, performs its task well, but requires improvement.

The aim of this research was to develop a concept of a thermo-hydraulic distributor, the task of which is the optimal hydraulic and thermodynamic balancing of hybrid boiler station systems with heating and supply circuits with different operating parameters. The research method was mainly theoretical calculations based on the initially obtained technological information and partially on the performed measurements.

3. Working on a conception

3.1. Principles of operation of the device

As mentioned above, the basic idea behind serial connection of circuits needed to be improved. The concept of an improved serial thermo-hydraulic distributor was developed. The method of its operation is based on appropriate separation of the flow in each segment of the distributor supplying the receiving circuit. The part that feeds this circuit is separated from the common flow with a predetermined flow rate and temperature. The remainder of the flow moves freely, mixing with the recycle flow.

After the temperature has stabilized, the combined flow feeds the next distributor segment. The establishing mixture temperature is the design temperature for supplying another recipient circuit. This means that the device works by the so – called temperature logic.

3.2. Design of a thermo-hydraulic distributor

The shape of the device is in the form of a cuboid with a total length $\boldsymbol{L}$ = 1170 mm, height $\boldsymbol{H}$ = 200 mm and width $\boldsymbol{W}$ = 200 mm (Fig. 3).

The device consists of 5 segments of various lengths resulting from technological or design requirements. The division into segments was made with the use of $\mathbf{PP_{1\text{-}4}}$ perforated plates. Their function is to even out and calm the flows after they have been combined and mixed.

Moreover, each segment is equipped with a dividing plate $\mathbf{DP_{1\text{-}4}}$. Structurally, the partition divides the segment into a division zone $\mathbf{DZ_{1\text{-}4}}$ and a mixing zone $\mathbf{M_{1\text{-}4}}$. The hydraulic operation of the partition is complex. First, it promotes the separation of part of the inlet flow for the next cycle from the part of the flow moving on. Second, the partition disturbs the flow and ensures effective mixing with the return flow. This helps to obtain a homogeneous mixing temperature in the entire volume of the zone.

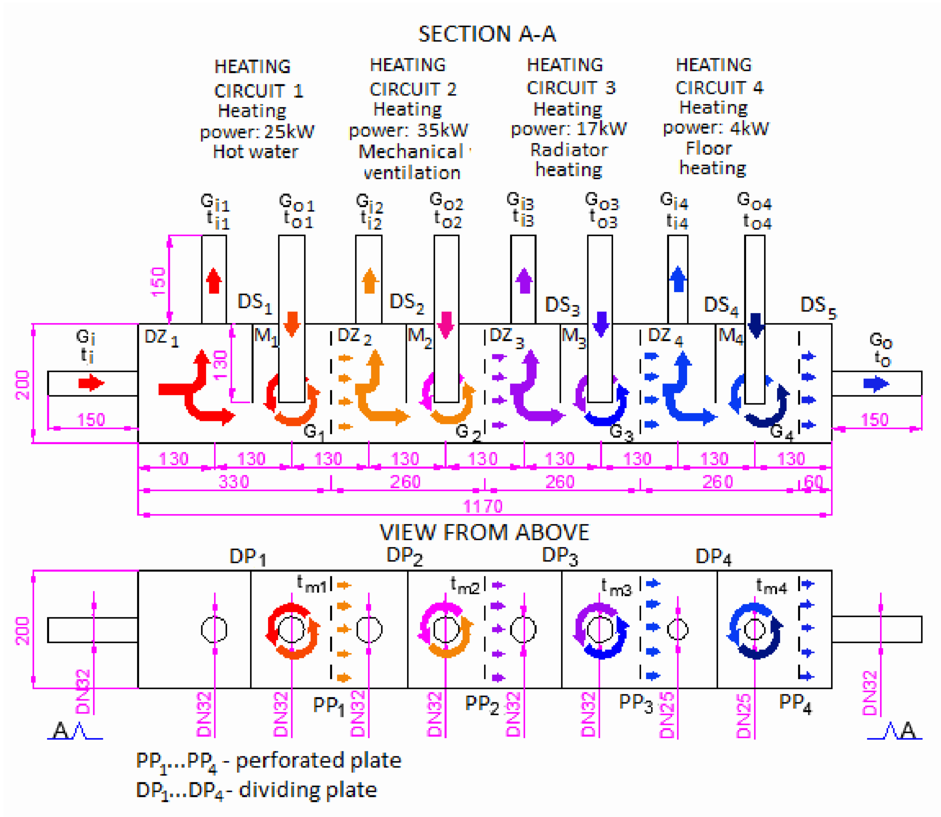

Fig. 3. Construction of an improved thermo-hydraulic distributor

DN32 pipe stubs are used for the 1st, 2nd and 3rd circuit and boiler connections. Circuit 4 pipe stub are DN25 (according to the existing technological state). For an efficient mixing process, the length of the return pipes stubs are the same as that of the dividing plates.

3.3. Theoretical basics

Along with the changes in the design of the device, the previously developed theoretical foundations of its operation (Szkarowski et al. 2007) have been clarified.

First divider segment **DS**$_\mathbf{I}$ is supplied from the boiler with the heating medium flow $\boldsymbol{G_i}$ about the inlet temperature $\boldsymbol{t_i}$ (Fig. 3). Then the inlet flow is divided. Thanks to the design of the distributor, a heating flow is generated in the division zone **DZ**$_\mathbf{I}$ with the temperature $\boldsymbol{t_{iI}} = \boldsymbol{t_i}$ and the flow rate $\boldsymbol{G_{i1}}$, proportional to the design power of the heating circuit "1". This flow feeds the first circuit.

The remainder of the flow, with a flow rate $\boldsymbol{G_i}$ **-** $\boldsymbol{G_{i1}}$ and a temperature $\boldsymbol{t_{I1}}$, flows around the dividing plate **DP₁** and is mixed with the recycle flow of circuit "1" with a flow rate $\boldsymbol{G_{o1}} = \boldsymbol{G_{i1}}$ and a temperature outlet $\boldsymbol{t_{o1}}$. A mix flow $\boldsymbol{G_1}$ at temperature $\boldsymbol{t_{m1}}$ is formed.

This flow leaves the first distibutor segment and feeds the second segment through the perforated plate $\mathbf{PP_1}$. The principle of operation in subsequent segments is the same as for the first.

Summarizing for the operation of the entire device can be saved:

$$G_i = G_1 = G_2 = G_3 = G_4 = G_O \tag{1}$$

$$t_i = t_{i1}\ ;\ t_{m1} = t_{i2}\ ;\ t_{m2} = t_{i3}\ ;\ t_{m3} = t_{i4}\ ;\ t_{m4} = t_o \tag{2}$$

$$G_{i1} = G_{o1}\ ;\ G_{i2} = G_{o2}\ ;\ G_{i3} = G_{o3}\ ;\ G_{i4} = G_{o4} \tag{3}$$

where:

$$t_{m1} = t_i - \frac{G_{i1}}{G_1\left(t_i - t_{o1}\right)} \tag{4}$$

$$t_{m2} = t_{m1} - \frac{G_{i2}}{G_2\left(t_{m1} - t_{o2}\right)} \tag{5}$$

$$t_{m3} = t_{m2} - \frac{G_{i3}}{G_3\left(t_{m2} - t_{o3}\right)} \tag{6}$$

$$t_{m4} = t_{m3} - \frac{G_{i4}}{G_4\left(t_{m3} - t_{o4}\right)} = t_o \tag{7}$$

3.4. Design calculations

The common principle of dimensioning vertical hydraulic distributors is used in the distributor design. It consists in determining the size of the distributor diameter ***D*** as a function of the diameter of the inlet conduit ***d***.

It is assumed that the water velocity in the inlet stub pipe is 0.7-0.9 m/s, while the average water velocity in the device itself should not exceed 0.10-0.15(0.20) m/s (Mizielińska & Olszak 2005). With this assumption, the condition for optimal dimensioning is $\boldsymbol{D \geq 3d}$ (Szkarowski et al. 2007).

However, the case under consideration differs significantly from vertical distributors. First, the distributor works in series. The device is not vertical but slightly inclined. In addition, the device has the shape of a cuboid. These differences caused the ***D/d*** ratio to be quadrupled. Size ***D*** was assumed to be the lateral side of the cross – section.

The distance between the connection pipe stub in vertical distributors is ***(3-4)d***. This ensures proper mixing of the flows and stratification of the temperature field (Mizielińska & Olszak 2005). In the case at hand, the stratifying principle is not applied. However, due to the good mixing, this ratio is correct. The same distance of 130 mm has been assumed for the DN32 and DN25 pipe stubs.

The next step in the design was the dimensioning of the perforations of the perforated plates. The general rule is that the cross – section of the perforation in the light should be approximately three times larger than the inlet stub (Szkarowski et al. 2007). As the cross – sectional area of the DN32 pipe stub is approx. 1000 mm^2, the required area of perforation is approx. 3000 mm^2. In order to reduce the hydraulic resistance, this ratio was increased by 1/3, i.e. to approx. 4000 mm^2.

The final symmetry design decided to use 81 perforation holes with a diameter of 10 mm (Fig. 4. a). The dimensions of the dividing plate (Fig. 4. b) were determined by the issues of effective division of flows in front of it and effective mixing of flows in the mixing chamber.

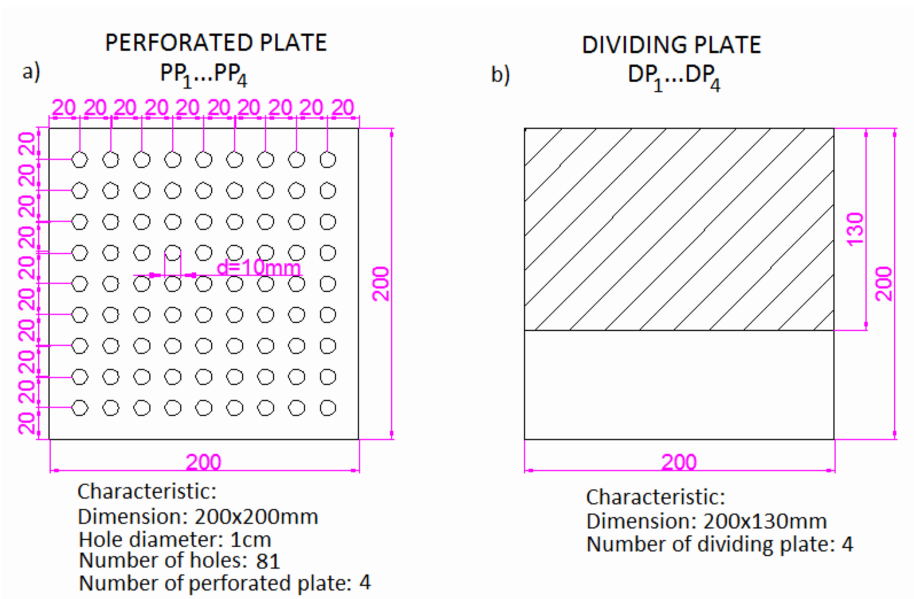

Fig. 4. Perforated plate a) and dividing plate b)

4. Summary

An improved design and operating principles of the thermo-hydraulic distributor were developed, the purpose of which is to balance the hybrid boiler station system with heating and supply circuits with different operating parameters in a hotel located in Koszalin.

A characteristic feature of the device is its internal structure, which allows the flows to be divided and mixed in order to adapt to the calculated temperature of the heating medium for the given circuits according to the temperature logic.

There is no such type of distributors on the market. However, the length of the device may be a problem, as the more heating circuits, the longer the manifold becomes. This would require more space in the boiler station or in the district heating substation. For a given object, this length was not a problem for the placement and assembly of the device.

References

Dopieralska, K., Siuta-Olcha, A., Cholewa, T., Tatara, G. (2015). Technical and Economic Analysis of Hydronic Balancing for Central Heating System. *Rocznik Ochrona Środowiska*, *17*, 1609-1621 (in Polish).

Janta-Lipińska, S. (2020). The Method of Nitrogen Oxide Emission Reduction During the Combustion of Gaseous Fuel in Municipal Thermal Power Boilers. *Rocznik Ochrona Środowiska*, *22*(1), 376-390.

Mizielińska, K., Olszak, J. (2005). *Low – power gas and oil heat sources*, Warszawa: Publishing House of the Warsaw University of Technology (in Polish).

Orłowska, M. (2020). Experimental Research of Temperature Distribution on the Surface of the Front Plate, of a Flat Plate Heat Exchanger. *Rocznik Ochrona Środowiska*, *22*(1), 256-264.

Shkarovskiy, A., Zelenov, G. (2012). Solution of hydraulic and thermodynamic problems of heat supply of various loads by the method of serial connection. *Bulletin of Civil Engineers*, *4*(33), 208-213 (in Russian).

Szkarowski, A. (2019) *Heat supply*. 3rd edition, updated. Warszawa: PWN (in Polish).

Szkarowski, A., Nakręt, L., Szokalski, W. (2007). Differential thermal system based on a series hydraulic clutch. Savings pooled. *Magazyn Instalatora*, *10*, 52-53 (in Polish).

Szkarowski, A., Naskręt, L. (2008). Theoretical Issues of Use of Hydraulic Dividers and Buffer Tanks in Heating Systems. *Rocznik Ochrona Środowiska*, *10*, 319-334 (in Polish).

Żelazna, A. (2012). Assessment of Environmental Effects of Thermomodernization on the Example of a Detached House. *Rocznik Ochrona Środowiska*, *14*, 729-740 (in Polish).

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Problems of Environmental Law: Possibilities for Legislative Changes

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Abstract: Kazakhstan is a country experiencing tangible environmental problems. Currently, it faces numerous environmental problems such as air pollution, water pollution, exploitation of natural resources, negative consequences of mining, etc. In order to cope with environmental problems, a number of legislative acts have been enacted: the Environmental Code, the Water Code, the Forestry Code, a number of laws and government decrees that provide a legal basis for sustainable development. But, unfortunately, these laws and policies were not properly implemented due to issues such as inconsistency, weak enforcement, the presence of internal contradictions, gaps, and discrepancies, etc. As a result, the current legislation in the field of environmental protection does not meet the development objectives of our country, its lack of transparency hinders the development of the economy, and indistinctness reduces the competitiveness of domestic producers in the world market and the volume of investments attracted to the economy. Many aspects of the state's environmental activities remain unregulated from a legal point of view, which, on the one hand, leads to a deterioration in the quality of the environment and the plunder of natural resources, and on the other hand, creates conditions for the development of corruption. This study proposes individual solutions to problems in the environmental sphere by creating new legal norms, as well as eliminating contradictions between existing regulatory legal acts, systematizing legislation and establishing a unified practice of applying norms. It is concluded that the implementation of environmental human rights depends on the quality of regulatory legal acts and their effective application.

Keywords: sustainable development, environmental law, environmental impact, environmental protection

1. Introduction

The Environmental Code of the Republic of Kazakhstan does not directly indicate the purpose of environmental legislation. It should be noted that until now, the state policy of Kazakhstan in the field of environmental protection has been focused on ensuring environmental safety, that is, the protection of natural systems, the vital interests of society, and the rights of the individual from threats arising from anthropogenic and natural impacts on the environment (which was, in particular, reflected in the Concept of Environmental Safety of Kazakhstan for 2004-2015, which has lost its force today). «Environmental safety, as a component of national security, is an indispensable condition for sustainable development and is the basis for the preservation of natural systems and the maintenance of appropriate environmental quality. The Kazakhstan political and legal mechanism for ensuring environmental security against the background of multilateral and dynamically evolving international institutions has not achieved any significant efficiency yet» (Buribayev et al. 2020).

Meanwhile, global trends pose new challenges for Kazakhstan and more strategic, long-term goals that go beyond ensuring only environmental safety and require creating conditions for the sustainable development of the country and society. In this regard, the main goal of Kazakhstan's environmental legislation should be to promote sustainable development of the country, including in the field of environmental protection, the transition to a "green" economy to ensure a healthy and favorable environment for today's living and future generations.

As for the sphere of regulation, then, in the broadest sense, environmental law is aimed at regulating social relations arising from the interaction of society and nature, first of all, the influence of human activity on the natural environment. Therefore, it includes as a direct "environmental" aspect - environmental protection ("environmental law"), the core of which is the prevention and control of pollution, and relations in the field of natural resources management ("natural resource" law). The fact that in most countries of the world environmental legislation is not codified, but is represented by a large number of separate laws in various areas of environmental and natural resource law determines the complex nature of this industry. Among European countries, the exceptions are countries such as France, Sweden, and Luxembourg (Percival et al. 2017), which have independent environmental codes, the coverage of regulated relations in which, at the same time, varies significantly. «With the proposed concept of sustainable development, being popularized in the late 1980s, environmental legislation in developed countries began to shift and has changed from focusing on pollution and treatment to prevention and a holistic approach to the whole process of management of natural resources development and utilization. Moreover, an accompanying shift has also been to focus on national legislation to address deals with the international common environmental issues through legislation. Today, legislation has become sophisticated and comprehensive, even with acknowledged limitations in applying it effectively. At the same time, environmental legislation in developing countries has also been improving step by step» (Mu et al. 2014).

Environmental legislation of the Republic of Kazakhstan is a complex branch of legislation. Based on the Constitution of the country, it is at the junction of public and private law and includes norms of various branches of law (civil, administrative, business, criminal, and others). Following the Constitution (paragraph 1 of Article 31), the state aims to protect the environment favorable to human life and health. Besides, according to paragraph 3 of Article 6 of the Constitution of Kazakhstan, the land and its subsoil, waters, flora, and fauna, and other natural resources are in state ownership. Thus, the state, on the one hand, ensures environmental protection, and, on the other hand, exercises the powers of the owner of natural resources (possession, use, and disposal under the law).

In Kazakhstan, with the adoption of the Environmental Code in 2007, the formal separation of the branches of environmental legislation (Environmental Code of the Republic of Kazakhstan; partially - the Law "On Specially Protected Natural Areas") and natural resources (Land Code, Water Code, Code "On Subsoil and Subsoil Use", Forest Code, Law "On the Protection, Reproduction and Use of Wildlife") legislation. At the same time, relations in the field of natural resource management are significantly influenced by environmental standards. At the same time, it should be noted that the Environmental Code of the Republic of Kazakhstan, going beyond the environmental function, regulates certain issues of natural resource management (concepts and types of natural resource use, the grounds for the emergence of the right of special nature use, and others), which is the subject of regulation of special, natural resource legislation, and existing the natural resource laws of Kazakhstan in some cases contain environmental requirements (that is, requirements for environmental protection), which can cause contradictions and inconsistencies between the natural resource and environmental legislation.

Legal analysis of the legislation also revealed the presence in the Environmental Code of reference norms that do not have any legal significance, there is a duplication of norms. Such and other shortcomings of the environmental legislation of Kazakhstan should be subjected to critical analysis and, if necessary, should be harmonized with each other, and individual norms should be removed (in case of duplication or loss of relevance) or transferred to the relevant law, while a clearer distinction should be made between the norms of environmental and natural resource law, provided that they are interconnected and interact.

There is a need to revise the terminology used in the system of environmental legislation, introduce new terms, for example, "polluter", "operator" or "person having an impact on the environment", as is customary in the legislation of developed foreign countries (EU, USA, other developed countries).

The system of regulation by subject composition requires a radical revision: the number of regulated entities should be optimized to improve the quality of control of those entities that make or may make the greatest contribution to the deterioration of the environmental situation in the country, and regulatory requirements for entities that have a minimal or insignificant impact on the environment should be reduced.

The authors proceed from the fact that legislative regulation of environmental protection and nature management is the most important (but not the only) lever for solving environmental problems. The manuscript includes an analysis of the adopted and upcoming laws, the development of recommendations for their improvement. The main goal of this work was the development of a system of environmental legislation. This can be achieved by improving existing laws, identifying and filling gaps in existing environmental legislation, development of recommendations for the further development of environmental legislation.

2. Principles of legal regulation in the field of environmental protection

The principles of legal regulation in the field of environmental protection are listed in Article 5 of the Environmental Code of the Republic of Kazakhstan, while:

a) the content of such principles is not disclosed, which complicates the application and interpretation of environmental legislation;
b) the principles are very extensive and do not always fully comply with the principles of international environmental law;
c) some principles are not always observed in the norms of environmental legislation, which calls into question their fundamental nature (the principle of "harmonization of environmental legislation of the Republic of Kazakhstan with the principles and norms of international law" is rather a principle of state legislative policy in the field of environmental protection than a principle of legislation. The wording of this principle can be finalized by developing the meaning of Article 8 of the Constitution of the Republic of Kazakhstan, according to which the Republic of Kazakhstan respects the principles and norms of international law, in particular, by proclaiming the undeniable influence of

the generally recognized principles of international environmental law on the national environmental legislation of Kazakhstan and the need to take them into account in law enforcement);

d) certain principles, in their essence, are not legal principles (for example, "state regulation in the field of environmental protection and state management in the field of use of natural resources", "interaction, coordination of activities of state bodies for environmental protection").

The principles of law should contain the fundamental ideas that determine the very essence and purpose of the rules of law and fill in the gaps in regulation. In this regard, the principles of environmental legislation should be critically revised, optimized, and filled with a more capacious, fundamental content, which will be deciphered in detail and will determine the further content and directions of legal regulation.

We believe that the fundamental principles should include, among other provisions:

- the precautionary principle, according to which the lack of certainty should not be a reason for refusing or delaying the adoption of effective and proportionate measures aimed at preventing the risk of causing significant and irreversible damage to the environment;
- the principle of prevention and control, under which it is required to prevent the formation of contaminants, primarily at the source and control and to the extent possible, eliminate the resulting pollution of the environment, for which is necessary to take all necessary measures, including the use of best available technologies, methods, and techniques, taking into account technical, technological and socio-economic aspects, with the overall aim of achieving a high level of environmental protection as a whole;
- the "polluter pays" principle;
- the principle of integration, according to which, to achieve sustainable development of the state, environmental protection should be an integral part of such development and cannot be considered in isolation from it. "Environmental legislation requires a socio-ecological focus, bringing together all the pillars of sustainable development in a unified manner. There is real potential for resilience to become integrated into environmental law though with the assistance of additional policy" (Wright 2014);
- the principle of participation and involvement of society, which requires that everyone has access to environmental information, including information on environmentally hazardous substances and activities, and according to which the public should be involved in decision-making processes related to the implementation of projects that have a significant impact on the environment, including in the planning of settlements, industrial facilities, roads, etc.);

- the principle of the inevitability of responsibility for causing environmental damage, the completeness of compensation for environmental damage, according to which the person responsible for the caused environmental damage must eliminate or compensate it in full.

The consolidation of clear, concise, and understandable principles will contribute to the maximum harmonization of legal norms, clarity in law enforcement, and, most importantly, the achievement of long-term goals to ensure a favorable environment and sustainable development of the country and society.

3. The quality of the environment

In developed foreign countries, environmental norms, regulations, and standards are included in the system of environmental legislation and are supported by serious legal guarantees. These norms clearly define the natural objects and resources to be protected, permissible levels of impact and indicators of permissible technogenic oppression, list sanctions for violation of norms and regulations, methods of monitoring the implementation of environmental requirements. Such a regulatory framework is becoming an important tool of public administration in the field of environmental protection.

Despite the important reforms carried out within the framework of the Environmental Code of the Republic of Kazakhstan in 2007, the use of modern approaches in regulating the quality of the environment is extremely limited. In Kazakhstan, there is no system of proper environmental standards for environmental quality, so a set of sanitary and hygienic standards is mainly used.

Kazakhstan has not approved and officially does not have its own (national) and independent environmental standards regulating the levels of anthropogenic impact on nature and habitat, which form the basis of environmental regulation. The entire field of environmental regulation related to man-made environmental pollution is based on hygienic standards established for compliance with sanitary and hygienic requirements. However, sanitary and hygienic standards are focused exclusively on human health and do not take into account the conditions of preservation and stability of natural ecosystems. Permissible pollution for humans can lead to a violation of the physiological state of many species of plants, animals, and the entire ecosystem as a whole.

The existing approach to the legislative and regulatory framework in Kazakhstan causes the presence of an inadequately wide list of pollutants subject to environmental regulation and requires extremely low concentrations in the environment. In Kazakhstan, the number of regulated parameters (more than 1,000) significantly exceeds the number of equivalent parameters used in the EU countries. At the same time, a large number of regulated parameters and more stringent requirements for maximum concentrations in Kazakhstan do not guarantee the achievement of a higher environmental quality.

According to OECD experts, the excessive vastness and rigor of Kazakhstan's regulations is based on deliberately unrealistic assumptions and imposes requirements that, in many cases, cannot be achieved even with the use of the most advanced available techniques that ensure the lowest possible levels of emissions, or requires financial investments that are unaffordable for most industrial enterprises in the country. Also, in practice, the number of parameters that can be controlled remains small. Toxic pollutants are not fully covered in Kazakhstan's current monitoring programs, and laboratories are not always equipped to analyze controlled substances. At the same time, substances subject to priority control for water resources in the EU countries in Kazakhstan are covered only by about one-third of the parameters (SC MNE RoK 2019).

Taking into account the current environmental situation in Kazakhstan in many cities, the maximum permissible concentration of harmful substances, in fact, is, at best, the target indicators of environmental quality, to which it is necessary to strive.

Recognizing the importance of the existing system of maximum permissible concentrations of harmful substances as a necessary but important measure to curb the further growth of pollution, it should be recognized that there is a practical need to develop new approaches to environmental regulation and rationing.

Approaches to environmental quality standards should be reviewed in the light of international experience and set at reasonable and realistic levels, that is, striking a balance between what is desirable from an environmental point of view and what is feasible from a technical and economic point of view. A clearer distinction should be made between environmental quality standards and standards for permissible environmental impact (including the cumulative impact within specific territories, zones).

It is necessary to lay down rules on the gradual transition from sanitary and hygienic standards to environmental standards adopted and used in the EU and OECD countries (for example, the EU Directive 2013/39/EU on priority substances in the field of water policy, the EU Directive 2008/59/EU "On atmospheric air quality and Cleaner air for Europe", the Protocol on Heavy Metals, the Gothenburg Protocol to the Convention on Long-range Transboundary Air Pollution, etc.). At the same time, taking into account the need to gradually improve the quality of the environment (by achieving the target parameters) and the development of green technologies, the possibility of gradually introducing new standards with more stringent requirements in the future should not be excluded, to the extent that this is justified from a technical, technological, environmental and economic point of view. This approach will make it possible to set specific medium- and long-term tasks for enterprises to reduce emissions and improve environmental efficiency and purposefully manage these processes.

4. Environmental control and enforcement

Enforcement measures should be based on a strong regulatory framework and achieve several goals, the main of which is to return the violator to environmental compliance. In general, an effective enforcement regime should provide for the flexible application of a wide range of proportionate penalties, allowing the authorities to respond according to the specific case and nature of the violation.

The hierarchy of enforcement measures is often depicted as a so-called "enforcement pyramid", which implies that regulatory authorities are willing to toughen penalties when soft measures to eliminate violations do not lead to environmental compliance and that the penalties at the top of the enforcement pyramid are sufficiently serious and effective to prevent possible violations.

To translate this theory into practice, Kazakhstan at the top of the enforcement pyramid provides sufficient punishment as a harsh deterrent to repeat violations. For example, environmental crimes are punishable by various sanctions, including imprisonment for up to 8 years, and ecocide for up to 15 years. At the same time, the “enforcement pyramid” method requires further development since there is insufficient understanding of the need to take less stringent measures at the base of the pyramid.

In contrast to the OECD countries, where non-reprisal measures are usually taken first to eliminate an administrative offense, in Kazakhstan, administrative fines are a legal instrument at the bottom of the pyramid of administrative law enforcement. A negative factor is that the activities of regulatory authorities are assessed by the number of fines imposed, which creates false incentives for environmental inspectors to issue fines in the vast majority of cases (OECD 2017).

Many effective alternative legal instruments of influence used in the OECD countries are not used in Kazakhstan. As international practice shows, non-reprisal measures give the offender a sufficient opportunity to eliminate the violation without loss of tangible and intangible assets, while ensuring a more favorable state of the environment. Such measures are quite effective in countries such as Finland, Japan, the Netherlands, the United Kingdom, and others. For example, in Japan, the main purpose of administrative action is not to impose fines, but to direct the operator towards compliance with environmental requirements, about which they are given specific instructions for execution. Tougher enforcement measures (including fines) are only taken in cases of significant or repeated violations (OECD 2019).

The lack of preventive responses in the law enforcement system in Kazakhstan does not allow us to assess the effectiveness/sufficiency of the use of harsher penalties. Theoretically, the deterrent effect of the latter can be judged by the probability of correcting violations with the help of soft measures that form the base of the pyramid of law enforcement.

There is a demand for the introduction of provisions aimed at improving the environmental control system by introducing alternative measures of influence (as opposed to using only monetary penalties), including the use, where appropriate, of preventive enforcement measures (for example, a warning, including oral, etc.) in the event of violations.

The existence of strict penalties for violations of environmental legislation is in itself insignificant to ensure a high level of environmental protection if there is no mechanism for timely and effective detection of environmental non-compliance.

The legislation of Kazakhstan imposes several requirements and restrictions on the system of inspection inspections (a long period between scheduled inspections, the need for prior approval and registration, early notification of the subject of control about the inspection), which reduce the likelihood of detecting violations. “For environmental legislation to 'work', it must not only be well designed but also efficiently and effectively enforced. Strategies must be developed as to how inspectors should go about the task of intervening in the affairs of regulated organizations to ensure compliance and enforcement” (Gunningham 2011).

According to the recommendations of the OECD experts, in addition to inspections carried out by the state, the status of environmental compliance can be verified by monitoring the environment near the site, the results of the operator's industrial environmental control program, inspections of the production process chain, independent audit, and public monitoring. Inspections carried out by public authorities remain the basis of all environmental control systems. At the same time, a simple visit to the site, but without the application of administrative measures, in some cases can have a greater effect on the level of environmental compliance than penalties (OECD, 2017).

However, this form of control and supervision does not fully meet the goal of ensuring a high level of environmental protection. Preventive control and supervision with a visit to the subject (object) of control and supervision in the field of environmental protection can be initiated only by the results of an unscheduled inspection (in compliance with all relevant requirements and with the application of all relevant consequences, including administrative sanctions). Verification when individuals and legal entities address specific facts about causing harm, including the environment, refers to unscheduled inspections, and not to preventive control and supervision with a visit to the subject (object) of control and supervision.

The introduction of provisions on such a form of state monitoring of environmental compliance as "site visits" is in demand. It is necessary to allow environmental inspectors to visit Category I facilities suddenly (without a complex registration and warning mechanism) when receiving a message from public associations in the field of environmental protection (public environmental control), with the possibility of short-term finding and monitoring production processes in order to determine their environmental compliance or, in case of non-compliance, warning the enterprise about them and providing recommendations for their elimination.

Thus, the state inspector performs the function of an auditor who helps to identify nonconformities and is limited only to notifying the subject (orally or in writing) of an existing or potential nonconformity, without initiating administrative proceedings, issuing an order to eliminate violations and without applying rapid response measures, any administrative, law-limiting, or other coercive measures. In case of detection of an obvious fact of causing damage to the environment, an unscheduled inspection should be scheduled by the grounds and procedure established in the legislation. Such a system will increase the probability of detecting environmental inconsistencies and ensure transparency of enterprises' activities.

In Kazakhstan, participation of public and NGOs in detecting non-compliance with environmental requirements and in law enforcement is very episodic. Most often, NGOs use their right to signal to authorized state bodies about non-compliance by enterprises with environmental requirements. There is a demand for elaboration and consolidation of provisions on increasing the role of public organizations and the public in the field of environmental control and law enforcement, strengthening the norms on public control. "Deficits in the promulgation and implementation of environmental legislation and citizen participation have been and will continue to be a major impediment to environmental protection and natural resource conservation and management in most developing countries. What is actually required is the enactment of effective environmental legislation that encompasses environmental standards, management objectives, and priorities in a contextual domestic and global environment as well as a development framework, with domestic law development in respect of liability and compensation for environmental perturbations caused to individuals. Extensive measures coupled with a legal stance may be the option for the facilitation of effective citizen participation to equilibrate the prevailing elite domination of questions pertaining to technical policy making" (Chukwuma 1996). Moreover, as the studies have shown, corruption, poor enforcement, and the muzzling of civil society render the state incapable of resolving arguably its most significant environmental challenge: illegal and unregulated resource use (Newell & Henry, 2016).

5. Social impact tools and analytical framework for violations

For environmental enforcement to be effective and efficient, it must be based on a solid analytical framework. In addition, the principles of transparency, accountability, and public access to information must be applied in practice to ensure that penalties are fair.

In addition to the tools of state influence, in OECD countries, great importance is given to the social impact on the violator, which provides for mandatory publication of the results of inspections, which ensures better compliance with environmental requirements by control subjects, in order to avoid the risk of public pressure and loss of business reputation (Winter & May 2001, Short & Toffel 2008, Delmas & Toffel 2004).

A particularly good example of a system for making such information public is the Online Enforcement and Compliance History website in the United States (hereinafter referred to as "ECHO"). This website provides information on environmental compliance and regulatory activities for approximately 800,000 regulated entities across the country. It allows users to find information about authorizations, inspections, violations, enforcement actions, unofficial enforcement actions, and penalties over the past five years. Because of ECHO, the public can monitor environmental compliance at the local level, corporations can monitor compliance by their own enterprises, and it is easier for investors to take environmental activities into account in their decisions. Besides, it is important to note that public authorities in the United States may require companies to publish information on enforcement in the media at their own expense, which reduces the burden on public authorities (Bergeson 2003).

As recommended by the OECD experts, Kazakhstan should pay more attention to the problem of asymmetry of information available to users. The various bodies should strive to create a single, consistent set of indicators that are monitored with appropriate frequency and statistical reliability. They should prepare and submit periodic summary reports (including activity reviews) on inspection and supervisory activities. Reports should include data on ensuring compliance with the law by law enforcement agencies (courts, environmental prosecutor's office, and environmental police). Regular reviews of environmental enforcement should be carried out, in particular careful consideration of the deterrent effect of various penalties (OECD 2016).

Environmental control data are collected regularly in Kazakhstan, although the information collected is not sufficiently adapted to the needs of strategic planning and is not made public to the extent necessary to ensure that the public exerts pressure on violators. Also, the principle of confidentiality of information on inspection activities enshrined in the Environmental Code applies to all information on cases of law enforcement, and not only to information on forensic examinations and information on criminal cases.

It is reasonable to review the provisions on the confidentiality of information on inspection activities to ensure the availability of information necessary to increase public participation in accordance with the Aarhus Convention. In this connection, it is possible to introduce the possibility for the court to impose on the violator the obligation to publish at its own expense in the media information about the penalties imposed on it and the measures taken/planned to eliminate environmental violations. It is appropriate introduction of the practice of regular publication of the relevant state bodies of analytical reports on the level and changes in the level of environmental compliance.

6. Environmental responsibility

Despite the introduction of important legislative changes, environmental liability for environmental damage in Kazakhstan remains focused on calculating and collecting monetary compensation, rather than on preventing and repairing damage, reducing emissions over time, and encouraging the use of the best available technologies.

The Environmental Code does not provide for the priority of eliminating damage before its monetary compensation. Moreover, the law explicitly provides that compensation for harm in kind is allowed only with the "consent of the parties by a court decision". As a result, the financial compensation applied in Kazakhstan actually remains an ineffective tool from an environmental point of view, since it does not perform an environmental or nature-preserving function because in most cases the consequences of damage caused to the environment are not eliminated and the money is simply "dissolved" in the state budget. In such a situation, a more effective, from an environmental point of view, and a more cost-effective way would be to oblige the subjects of control to finance the restoration of the environment under the control of the state.

In the environmental legislation of Kazakhstan at present, there is the concept that binds the responsibility of the perpetrator for the sole fact of exceeding limits/standards, without requiring proof as the fact and amount of damage to the environment and causal relationships between actions and consequences.

Economic assessment of environmental damage can formally be carried out by direct or indirect methods, depending on whether it is possible to completely eliminate the damage caused by environmental restoration measures. The Environmental Code establishes the priority of the direct method of assessing environmental damage over the indirect method, based on the fact that the indirect method is used in cases where the direct method of economic assessment of damage cannot be applied. However, as law enforcement practice shows, the priority of the direct method is declarative. In the vast majority of cases, the authorized state body is forced to use an indirect method of assessing environmental damage (in particular, in the case of exceeding emissions and discharges). The correctness of such calculations is often challenged in court because the calculation methods are not reliable enough.

The liability for environmental damage provided for in most advanced countries (EU, USA) is compensatory (i.e. aimed at eliminating the damage caused), and not punitive in nature (Martin-Ortega et al. 2011, Zaredar & Zarkesh 2012). In this regard, losses are calculated based on actual damage to restore the state that existed before the violation; the effect of penalties is limited and subject to the principles of reasonableness and proportionality, and the amounts of compensation received can only be used for the restoration or replacement of a damaged natural resource. Methods for calculating environmental damage require taking into account the actual and expected consequences of restoration measures, the ability of the ecosystem to restore itself. The key characteristic of the calculation mechanism is its concrete, not abstract nature: the amount of damage to be compensated is calculated based on the plan for the restoration or replacement of this particular damaged natural resource. In EU countries, legislation prescribes that the pollutant must be identified, the damage must be specific and quantifiable, and a causal relationship between the damage and the pollutant must be found (Lindhout & Van den Broek 2014).

In this regard, the norms on environmental responsibility should be revised in strict accordance with the principles of" polluter pays " and the inevitability of liability for violation of environmental legislation. There should be a strict "polluter pays" model based on the proven fact and amount of damage to the environment, establishing a causal relationship between the actions of the polluter and the resulting negative consequences for the environment, as well as the use of only a direct method of assessing the damage in each case. The absence of an environmental permit should not be the basis for making claims for compensation for environmental damage, since instead only administrative liability should be provided. At the same time, the necessary provisions should be introduced to ensure the inevitability of environmental responsibility.

7. Environmental monitoring

World experience shows that the first step in solving environmental problems is to obtain objective information about the state of the environment. The only possible way to obtain such information is monitoring, that is, a system of observations, assessment, and forecast of the state of the natural environment. In the EU, the main purpose of environmental monitoring is to assess progress made as a result of set environmental goals, as well as to identify new environmental problems. The results are fundamental to environmental management in general, as the development and prioritization of environmental policies are based on the results of environmental monitoring (Lovett et al. 2007).

According to the Environmental Code of the Republic of Kazakhstan, state environmental monitoring (monitoring of the environment and natural resources) is a comprehensive system of monitoring the state of the environment and natural resources, including using remote sensing data from space, to assess, predict and control changes in their state under the influence of natural and anthropogenic factors. The objects of state environmental monitoring are atmospheric air, land, surface and underground waters, subsurface resources, flora, and fauna, as well as the climate and ozone layer of the Earth, ecological systems, and factors of environmental impact on public health.

The Environmental Code provides for the formation of a Unified State System for Monitoring the Environment and Natural Resources (USSMENR), which is defined as a "multi-purpose information system", which is an incorrect definition, since the USSMENR includes, in addition to a single information system, also relevant monitoring entities, infrastructure, and monitoring tools. Thus, a single information system USSMENR, conditions the creation of which are established by Article 139 of the Environmental Code of the Republic of Kazakhstan, shall constitute a separate component USSMENR, be it information and communication platform, used for collecting, storing, keeping, processing and storage of results of environmental monitoring on the common methodological basis.

Environmental and natural resource monitoring data is currently collected and processed by a large number of authorized bodies and organizations on their own information resources, which are often not integrated. To improve the efficiency of the organization of state environmental monitoring and analysis of the collected information, it is necessary to accumulate the necessary environmental data on a single information resource (a single national database (bank) of environmental monitoring data) that meets modern requirements in the field of information and telecommunications technologies, ensuring openness for information interaction, including integration with existing and created information systems, and security taking into account the requirements of information security.

In this regard, it is proposed to:

- correct and clarify the corresponding conceptual framework;
- adjust the list of monitoring objects taking into account the types of monitoring currently available in Kazakhstan;
- to provide a legal basis for the formation and to establish the necessary norms and mechanisms for the creation and effective functioning of a unified information system USSMENR and developing a national database for environmental monitoring and natural resources, including through the integration of information systems of the competent authorities for all existing types of state monitoring of the environment and natural resources into a single functional system, to update the list of data on the state of the environment and natural

resources, clearly define the necessary competence and mechanisms of interaction of all authorized state bodies and other interested persons to create and operate a single information system;

- to formulate the principles of information disclosure, information exchange by participants within the unified information system of the Unified State Educational Standard on a gratuitous basis;
- ensure the openness and accessibility of the obtained results of environmental monitoring.

8. Environmental information and public access to environmental information

It is necessary to continue work on improving the norms of environmental legislation related to the collection, storage, processing, systematization, analysis, scientific research, and provision of environmental information, as well as ensuring public access to it. Kazakhstan has ratified by Law No. 92-II of 23.10.2000 the Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters (Aarhus Convention). The Convention recognizes the rights of the public to access information, participation in decision-making processes, access to justice in environmental matters, and imposes obligations on States Parties to ensure them. The convention links environmental protection with human rights standards.

The Aarhus Convention on Access to Information, Public Participation and Access to Justice in Environmental Matters represents a major new departure in international environmental law. For the first time, the vital contribution of individual citizens and NGOs in environmental decision-making is given legal recognition. The Convention defines new rights in three areas. It creates specific and detailed rights of freedom of access to a wide range of environmental information held by national, regional, and local levels of government. Linked to this it requires States to take the initiative in publishing and disseminating information about the state of the environment. Secondly, it requires states to notify the public of proposals for environmental projects and programs, to allow sufficient time for meaningful consultation, and to take the views of the public into account in any decision-making process. Thirdly, these procedural rights are to be made legally enforceable - without excessive costs - through national courts or independent and impartial bodies (Morgera 2005).

According to the Environmental Code, the State Fund for Environmental Information (SFEI) is maintained to provide state bodies, individuals, and legal entities with reliable information about the state of the environment and its objects, environmental impact factors, measures taken to protect it, prevent and reduce environmental pollution, and the use of natural resources. The management of the SFEI is carried out by a subordinate organization of the authorized body in the field of environmental protection and includes measures for the collection, storage, processing, analysis, scientific research, provision, dissemination of environmental information, education of the population and nature users on environmental protection and the use of natural resources.

It is necessary to introduce into legislation norms and mechanisms for the formation and operation of a single database of environmental information (using modern digital technologies) in the following thematic areas: air pollution, air quality and ozone depletion, climate change, water resources, biological diversity, land resources and soil, energy, waste, including waste generation and hazardous waste management.

Besides, it is necessary, taking into account the best international practice of implementing the principles of "circular" economy in the field of waste management, to expand the list of the required information on collection (including separate), transportation, disposal, and recycling of waste. To implement the above approaches, you need to define the necessary expertise and clear mechanisms of interaction of the authorized state bodies and other stakeholders to promote and support a unified information system SFEI. Work is needed to harmonize the provisions on public access to environmental information with the requirements of the Aarhus Convention and other international obligations of Kazakhstan.

Over the years of independence, Kazakhstan has become a party to a significant number of international treaties in the field of environmental protection. There is a demand for updating and supplementing environmental standards to harmonize them with all the country's international obligations on environmental protection. Results suggest a positive relationship between domestic environmental legislation with both international environmental agreements and preferential trade agreements (PTAs) with environmental provisions. This link is more robust for PTAs, mostly present in developing countries, more pronounced before rather than after the treaties' entry into force, and shows significant variation depending on the issue area (Kaklauskas et al. 2019).

9. Conclusion

Summarizing the results of this review, the following main conclusions can be formulated.

The environmental legislation of Kazakhstan does not clearly define the purpose of regulating public relations in the field of environmental protection, and the principles of legal regulation are not disclosed. The principles listed in Article 5 of the Environmental Code do not fully comply with the principles of international environmental law.

Kazakhstan has not approved and officially does not have its own (national) and independent environmental standards regulating the levels of anthropogenic impact on nature and habitat, which form the basis of environmental regulation. Environmental legislation requires updating and improvement in order to harmonize it with all international obligations of the country on environmental issues.

The main objectives of improving the legislation should be to establish a clear, transparent, non-discriminatory, effective, and stable regulation of relations in the field of environmental protection in order to ensure a favorable environment for the population and create conditions for sustainable development of Kazakhstan, as well as to approach the standards of environmental regulation of the OECD countries. In particular, the introduction of new legal institutions that are successfully implemented in practice in the OECD countries (environmental assessment, strategic environmental assessment, integrated pollution prevention and control system and integrated environmental permits, waste management hierarchy, etc.), creation of an effective system of economic regulation and incentive mechanisms, improvement of the system of environmental monitoring, environmental control and law enforcement, resolution of problematic issues related to waste management, environmental responsibility, historical pollution, full implementation of the ecosystem approach, a higher level of ensuring the rights of the public to access environmental information and participate in decision-making on environmental issues, development of the system of environmental audit and environmental insurance, optimization and updating of legislative regulation of relations related to greenhouse gas emissions, ozone-depleting substances, defining the national legal framework for implementing the provisions of the Paris Agreement on Adaptation to Climate Change, as well as minimizing legislative contradictions and gaps, harmonizing norms with Kazakhstan's international obligations.

The conclusions, proposals and recommendations contained in the manuscript have both theoretical and applied significance: they can be used in the legislative activities of the legislative bodies of Kazakhstan. The results of the study will be useful to researchers in the further study of the legislative process in the field of environmental protection, to pedagogical workers in the course of teaching environmental, constitutional, and natural resource law.

References

Bergeson, L. L. (2003). Legal lookout. *Pollution Engineering, 35*(2), 41-41.

Buribayev, Y. A., Khamzina, Z. A., Suteeva, C., Apakhayev, N. Z., Kussainov, S. Z., & Baitekova, K. Z. (2020). Legislative regulation of criminal liability for environmental crimes. *Journal of Environmental Accounting and Management, 8*(4), 323-334. DOI:10.5890/JEAM.2020.012.002

Chukwuma, C. (1996). Undergirding environmental legislation and citizen participation in developing countries. *Environmental Education and Information, 15*, 319-330.

Delmas, M., & Toffel, M. W. (2004). Stakeholders and environmental management practices: an institutional framework. *Business strategy and the Environment, 13*(4), 209-222.

Gunningham, N. (2011). Enforcing environmental regulation. *Journal of Environmental Law, 23*(2), 169-201. DOI:10.1093/jel/eqr006.

Kaklauskas, A., Herrera-Viedma, E., Echenique, V., Zavadskas, E. K., Ubarte, I., Mostert, A. & Podviezko, A. (2018). Multiple criteria analysis of environmental sustainability and quality of life in post-Soviet states. *Ecological Indicators*, *89*, 781-807. DOI: 10.1016/j.ecolind.2017.12.070.

Lindhout, P. E., & Van den Broek, B. (2014). The polluter pays principle: Guidelines for cost recovery and burden sharing in the case law of the European court of justice. *Utrecht L. Rev., 10*, 46.

Lovett, G. M., Burns, D. A., Driscoll, C. T., Jenkins, J. C., Mitchell, M. J., Rustad, L., & Haeuber, R. (2007). Who needs environmental monitoring? *Frontiers in Ecology and the Environment, 5*(5), 253-260.

Martin-Ortega, J., Brouwer, R., & Aiking, H. (2011). Application of a value-based equivalency method to assess environmental damage compensation under the European Environmental Liability Directive. *Journal of environmental management*, *92*(6), 1461-1470.

Morgera, E. (2005). An update on the aarhus convention and its continued global relevance. *Review of European Community and International Environmental Law, 14*(2), 138-147. DOI:10.1111/j.1467-9388.2005.00434.x

Mu, Z., Bu, S., & Xue, B. (2014). Environmental Legislation in China: Achievements, Challenges and Trends. *Sustainability, 6*(12), 1-13.

Newell, J. P., & Henry, L. A. (2016). The state of environmental protection in the Russian Federation: A review of the post-soviet era. *Eurasian Geography and Economics, 57*(6), 779-801. DOI:10.1080/15387216.2017.1289851.

OECD (2016), Multi-dimensional Review of Kazakhstan: Volume 1. Initial Assessment, OECD Development Pathways, OECD Publishing, Paris. DOI:10.1787/9789264246768-en.

OECD (2017), Multi-dimensional Review of Kazakhstan: Volume 2. In-depth Analysis and Recommendations, OECD Development Pathways, OECD Publishing, Paris. DOI: 10.1787/9789264269200-en.

OECD (2019), *Addressing Industrial Air Pollution in Kazakhstan: Reforming Environmental Payments Policy Guidelines*, OECD Green Growth Studies, OECD Publishing, Paris. DOI: 10.1787/0e04ea86-en.

Percival, R. V., Schroeder, C. H., Miller, A. S., & Leape, J. P. (2017). *Environmental regulation: Law, science, and policy*. Wolters Kluwer Law & Business.

SC MNE RoK (2019), Introduction of green growth indicators in the Republic of Kazakhstan. N-27 National Report based on the OECD Green Growth Indicators – Nur-Sultan, 2019, 84.

Short, J. L., & Toffel, M. W. (2008). Coerced confessions: Self-policing in the shadow of the regulator. *The Journal of Law, Economics, & Organization, 24*(1), 45-71.

Winter, S. C., & May, P. J. (2001). Motivation for compliance with environmental regulations. Journal of Policy Analysis and Management: *The Journal of the Association for Public Policy Analysis and Management, 20*(4), 675-698.

Wright, H. J. (2014). Has sustainable development been integrated into environmental legislation? an assessment of the resilience approach. *Environmental Law and Management, 26*(1-2), 10-23.

Zaredar, N., & Zarkesh, M. M. K. (2012). Examination of compensatory model application in site selection. *Environmental monitoring and assessment*, *184*(1), 397-404.

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Processing and Performance of Blended Biodiesel Produced from Microalgae *Pediastrum Boryanum*

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Abstract: In this present study, biodiesel was synthesized as per ASTM method by using algae as a raw material, which in the environment is considered as being a harmful waste and of a nature that blooms in ponds, lakes and reservoirs. In order to improve fuel quality, the transesterification process was carried out in this study so as to remove fatty acids and thereafter, analyze several fuel parameters of the biodiesel were determined. The calorific value of the biodiesel and its specific gravity was 42660 kJ/kg and 0.803 g/cm^3 respectively. The viscosity of the sample was found to be 1.99. The cetane number of diesel fuel ranged from 40 to 55 and for the biodiesel it was found to be 47. The flashpoint and firepoint of the sample was recorded as 80°C and 94°C respectively. The conclusion is that it is worthy to mention that this process does not require high-end technology; hence, it could be used in the energy generation process in remote areas and as an alternative resource, as well.

Keywords: biodiesel, diesel, algae, esterification, transesterification, residue

1. Introduction

Responding to dire warnings of the consequences of global climate change, researchers worldwide have searched all over for renewable fuels that could be considered as being economically viable, technologically feasible, and environmentally sustainable (Adenle et al. 2013). Bearing that in mind, during the last few years, the scientific community has had as an aim the reduction of greenhouse gas emissions, through a combination of improved energy efficiency, technology change and the use of renewable energy sources that could come from several different sources, such as: the sun, waste, water, wind and wood.

Currently, renewable energy is achieving ever more popularity due to several causes amongst which we could include an increase in the crude prices, which are going up day by day, and the phenomenon known as global warming, caused (amongst other reasons) by the burning of fossil fuels (Amin et al. 2016). Therefore, crude fossil petroleum could be substituted by algae biomass with the intention of getting an eco-sustainable biodiesel production in the upcoming future. In view of the constant diminishing supply, crude oil will continue to have a rise in cost. Analyzing from such a perspective enables the production of fuels from alternate sources to be quite more feasible. Continued climatic changes are also being furthermore increased by the constant use of fossil fuels, due to the release of environmentally potential noxious gases such as CO_2. With the dwindling reserves of fossil fuels, it is now more important than ever to search for transportation fuels that could serve as alternatives to crude oil-based fuels such as gasoline and diesel fuel. Biodiesel is a transportation fuel that has grown immensely in popularity over the past decade. Furthermore, there are many sources for biodiesel feedstock, which include canola, castor, soy, palm and sunflower. Recently, scientists and academics from all over the globe speak frequently in relation to the ever-growing controversy about the use of potential food sources for the production of fuel. Looking from such a perspective, researchers have turned their attention from some of these popular feedstock and are currently investigating the use of alternative, non-food related feedstock such as the oil that comes from algae's (Grace et al. 2010).

Biodiesel is produced from microalgae that are the largest autotrophic microorganisms that could be produced in lesser amount of water than crops and besides that a better biofuel could be produced, because it does not require land, alongside it also converts more than 60% of its body weight in lipids (Christi 2007). Researchers have estimated that microalgae produce 15-300 times more oil than crops (Christi 2007). Fossil fuels while burning emits CO, NO_x, SO_x, hydrocarbon and particulates which creates a significant amount of air pollution, when compared with CNG and biodiesel fuels (Yun et al. 2016, Liu et al. 2015). Around the world presently 934 million tons of diesel is consumed per year as a source of energy in various sectors (Kulkarni & Dalai 2006).

Nowadays, biodiesel is also used in diesel engines and as a consequence the demand of biodiesel has increased considerably (Ramkumar & Kirubakaran 2016). Biodiesel is composed of mono alkyl esters of long chain fatty acids and it is derived from vegetable oil (Zareh et al. 2017) or algae. Biodiesel is more beneficial when compared to conventional diesel. It decreases the carbon dioxide and pollutants emission from diesel engines, at the same time without needing a significant modification of the same utilized engine. Also, biodiesel has a high cetane number, therefore its performance is better in a diesel engine while compared to a normal diesel fuel. Vegetable oil is produced from seeds and plants like palm, soybean, rapeseed, sunflower etc. (Fu et al. 2016, Focke et al. 2012, Berman et al. 2011, Ghosh et al. 2016). These raw materials are very costly (Jain & Sharma 2010) due to their demand in day to day consumption by human beings both for cooking and for running diesel engines. Also, large scale production of this edible oil would promote deforestation (Leung et al. 2010).

Although vegetable oil is used as a biodiesel (Arain et al. 2009, Evangelista et al. 2012, Silva et al. 2011), it has certain restrictions when introduced on the direct injection of engine types. It has a high viscosity, lower ignition point and also is less efficient while utilized in diesel engines. These types of problems could be solved, when biodiesel is produced from micro-algae. Microalgae could be described as being a readily available source of feedstock, coupled with the advantage of not competing with food or other oilseed crops used for arable lands. Furthermore, they thrive in contaminated water, freshwater, saltwater and sludge. As a matter or a fact, microalgae adapts well in different habitats not at all suitable for energy oil crops such as lakes, ponds, sea, and even on wastelands. Apart from that, micro-algal oil also contains quite high percentages of monounsaturated and saturated FAs that are very important from the standpoint of diesel fuel quality. This is because these problems with FAs could significantly reduce polymerization of fuel during combustion. Therefore, from the standpoint of all these considerations, *Nannochloropsis*, members of the marine green algae are considered as being remarkable candidates for biodiesel production and biomass productivity.

The last few years witnessed a weaker global growth rate which was below the average of 0.6 million barrels per day (b/d) from fossil fuels, reaching the lowest level since the mid-nineties of last century. Furthermore, energy derived from petroleum is expected to continue growing at a very slow pace. This will be due to the ever-increasing prices and gradual reduction of world governmental subsidies (B.P. statistical Review of World Energy 2012). On the other hand, the projected global supply of feedstock biofuels is expected to grow around 30% by 2030. Apparently, one major candidate representing the renewable feedstock that has the potential to replace petroleum diesel in large amounts of places without incurring in the problem of affecting food supply chain, as well as other crop products is certainly the micro algal oil (B.P. statistical Review of World Energy 2012, Demirbas & Demirbas 2011, Pienkos & Darzins 2009, Ehimen et al. 2010, Vicente et al. 2010, Shirvani et al. 2011). Most of the productive oil crops, such as canola oil, castor oil, palm oil and rapeseed do not reach the standards of microalgae in relation to being a potential provider of the global energy security so badly needed.

However, since emerging nation´s economy depends mainly on agricultural activities, the utilization of national resources for energy production is an extremely important issue. Diesel engines have been widely used as a power of engineering machinery, automobile and shipping equipment for its excellent drivability and thermal efficiency. Diesel fuels could be used in heavy trucks, city transport buses, locomotives, electric generators, farm equipments, underground mine equipments etc. (Sekhar et al. 2018).

One of the most attractive advantages is related to the fact that the cost associated with harvesting and transportation is quite low when compared to that of other oil crops. Residual biomass post extraction offers different methods for improving sources of economics by utilizing it as a type of fertilizer or for producing other types of high energy products (Ahmad et al. 2011). Microalgal biodiesel is considered a sustainably advantageous fuel due to the fact of being a carbon neutral fuel, in view of the photosynthetic fixation of atmospheric carbon dioxide. Microalgal growth actively utilizes 1.85 kg of CO_2 for every 1 kg of dry biomass produced and the obtained biodiesel has properties, such as density, viscosity, flashpoint, cold flow and heating value similar to those of petrodiesel. Very few, if not none of the other potential sources of biodiesel are a true candidate to replacing petrodiesel utilization as microalgae, in view of the fact due to the environmental impacts that occur as a result of use of those other feedstocks as mentioned in scientific literature (Ahmad et al. 2011).

The algae growth agitates the ecology of the water reservoir or local ponds and if removed then large amount of waste encroaches the land. This waste could be converted into significant resource. Moreover not much attention has been paid on solving the problem of algal proliferation and eutrophication occurring in lakes and ponds or other surface water bodies, which are very rich in nutrients. Researchers around the world are working on diverse types of proper waste management techniques but very few have emphasized on how to redeem such a valuable waste.

Alongside, there has been a postulation that oil content in microalgae contributed to the present day crude oil deposits that were formed some millions of years ago (Leung et al. 2010, Wang et al. 2011). Approximately, 650 billion barrels of crude oil energy equivalent is released by different types of microorganisms on a yearly basis (Wackett 2008). Analyzing from such a perspective, microalgae definitely is a promising sustainable source of energy for the nearby future.

In order to have an optimal yield, these algae need to have carbon dioxide (CO_2) in large quantities in the basins or bioreactors where they grow. Algae can grow practically anywhere where there is enough sunshine. Different types of algae contain carbohydrates, lipids, nucleic acids, and proteins in varying proportions. While the amount yield in relation to percentages significantly vary according to the type of algae, there are some that are comprised up to 40% of their overall mass by fatty acids (Sheehan at al. 1998). The yield of algal oil is a most significant distinguishing characteristic and hence its biodiesel yield. Scientific literature shows some estimates, where the yield (per acre) of oil from algae is above 200 times the yield from plant/vegetable oils of great performance (Campbell 2008, Sheehan at al. 1998). Therefore; considering the above mentioned facts in view a study has been carried out in order to utilize pond algae. It is a high lipid raw material which could be converted into biodiesel.

One could consider that a quite limiting path for the development of biodiesel production industry happens to be the lipid extraction process is based upon microalgae. As a matter or a fact, lipid extraction from microalgae is mainly performed by organic solventes. Therefore; not happening through conventional physical methods, due to several problems encountered, such as in breaking the cell wall, enabling that microalgae-based biodiesel production becomes unfeasible per example at industrial scale (Hidalgo et al. 2013).

A Simultaneous procedure of lipid extraction, as well as esterification/transesterification is a technique of great value for biodiesel production through microalgae, as it permits extracting and converting fatty acids into fatty acid methyl esters (FAME) in a single step bypassing the use of large quantities of organic solvents used in lipid extraction as described in some researches (Jin et al. 2014, Wahlen et al. 2011).

The obtained biodiesel could be tested for various parameters mentioned in the American Society of Testing Materials (ASTM) standards and further utilized in blend with diesel or directly in the vehicular purposes. Therefore, an attempt has been made to convert algae into biodiesel and performance of the diesel engine has been evaluated using biodiesel as a fuel.

2. Materials and methods

2.1. Biodiesel production

The algae samples of species (Pediastrum boryanum) were collected from the Salt Water Ponds of Extremoz, a city in the state of Rio Grande do Norte, Brazil, 21km from the state's capital, Natal. Furthermore, they were collected for bio-diesel processing and production. It is one of many species of tiny plants that are called "green algae". The thumb rule is that academics, researchers and scientists could cultivate microalgal strains that adapt to the reality of their local environmental surroundings.

The biomass obtained from Pediastrum boryanum could be considered as a suitable substrate for conversion into biofuels through a procedure known as algal recycling, enabling the process to be economically sustainable (Park & Craggs 2014). Apart from the fact that it happens to be a dominant species of the region where it was collected, in comparison for example with Botryococcus braunii, another potential species of algae with many scientific literature citations.

Therefore, the use of endemic indigenous microalgal strains is highly recommended since these strains are already adapted to the local environmental conditions (Mutanda et al. 2011, Xu et al. 2006). The overall laboratory conversion pathway, with sample photographs, is presented in Figure 1.

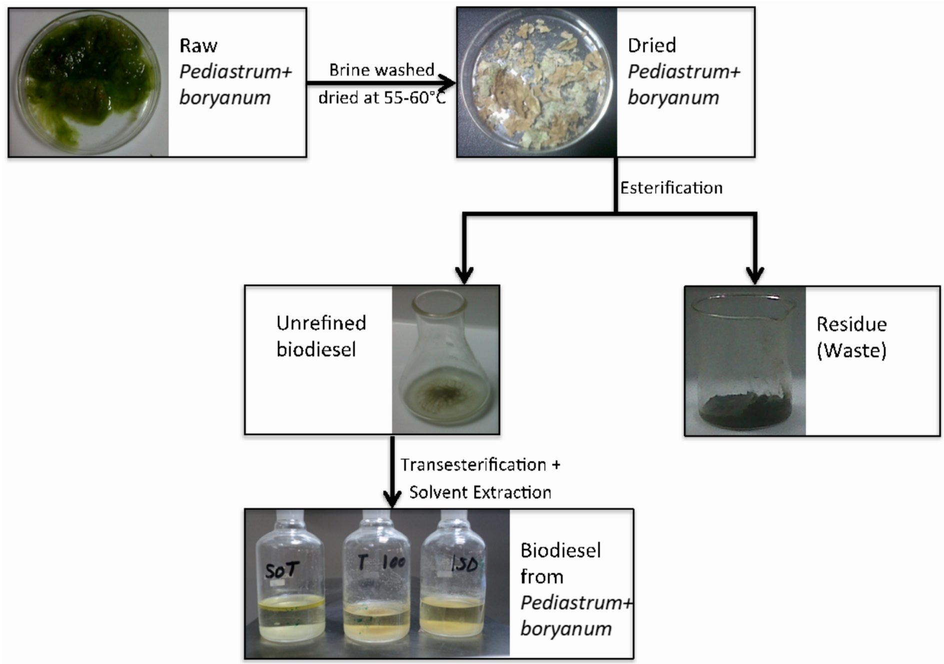


Fig. 1. Pathway of laboratory biodiesel production from *Pediastrum boryanum*

Conditions of the culturing process directly influences characteristics of growth, as well as the cellular composition of microalgae, which results in different biomass concentration and productivity, not to mention the possible variation in lipids content, carbohydrates, proteins and other components (Chojnacka & Marquez-Rocha 2004).

Prior to transesterification, the algae were washed with brine water to remove impurities and dried in an oven between 55 and 60°C. In relation to algae biodiesel, water content must be reduced to a bare minimum before the transesterification process. Common drying methods that are used include: drum drying, freeze drying, spray drying or sun drying.

Freeze drying becomes very expensive in large scale production but does produce the most pure results (Mutanda et al. 2011).

Algal hydrocarbon contents were measured using the following method. The wet slurry of Pediastrum boryanum was freeze-dried; 0.3 g NaOH was mixed with 28.8 ml methanol and stirred continuously for 24 minutes. The mixture of catalyst and methanol was poured to the algal oil in a conical flask and tranesterification process allowed to take place. The bio-oil was separated from the sedimentation by a flask separator. Bio-oil was washed with 5% sterile water until it became clean. Bio-oil was dried by using a dryer at temperature ranging between 55-60°C. and kept under air for 12 hrs. Harvesting contributes approximately 20-30 percent to the total cost of producing the biomass. The treated samples after washing and drying are shown in Figure 1(a) and 1(b) respectively. The dried samples were grinded in the mortar and pestle to produce a fine powdered form.

2.2. Process description of methodology used for biodiesel production

Removal of oils could be done through solvent extraction using hexane. Hexane-based solvent extraction is the standard method for lipid extraction from microalgae (Mutanda et al. 2011, Xu et al. 2006). Therefore, solvent extraction method was employed here being used for the extracting of biofuel, and the complete conversion of algae biomass to biodiesel. As per the ASTM method an equal volume of mixtures of hexane and diethyl ether were added to the powdered sample in a conical flask. Afterwards, the mixture was kept for 24 h settling and after settling, oil was separated from the residue by the filtering process.

The obtained biodiesel was of slightly below the average quality and characteristics. Therefore, in order to improve the quality and characteristics of the obtained biodiesel transesterfication process was carried out. Biodiesel could be extracted when a sample of algae reacts with methanol and NaOH is used as base catalyst. In this method methanol and NaOH have been used as a catalyst and the mixture was stirred at a speed of 1500 rpm for 3 h. Thereafter, the solution was transferred to a separator funnel and allowed to settle for 15 h till a fine layer of biodiesel was formed and the oil residue settled at the bottom of the funnel.

The biodiesel and residue were carefully separated and the weights of both were measured. The obtained biodiesel was washed with water to remove left out impurities and kept for drying for 12 h. The obtained biodiesel is pale yellow in colour, apart from having a strong alcoholic smell. The biodiesel yield was approximately 70% with the above mentioned process and described conditions.

2.3. Fuel Characterization and comparison

Biodiesel could be extracted from any type of biomass, however the extracted oil is to be verified by performing certain tests which determines the significant parameters of fuel. Initially pH value and weight of the biodiesel were measured. The calorific value of the obtained biodiesel was determined using a Bomb Calorimeter; Model Parr 6100. Thereafter, biodiesel was tested so as to verify the performance of the diesel engine. The smoke characteristics and various electrical parameters were also determined at 10% blend of biodiesel with diesel.

Biodiesel was characterized via: calorific value; density; viscosity; centane number; flash point; fire point; cloud point; pour point. To provide as basis of comparison, we obtained a series of edible oils from Blue Ville Santa Lúcia S/A and of non-edible oils from Sabão e Glicerina ltda, both located in São Paulo, Brazil. The instrument, and associated ASTM follows are given in Table 1.

Table 1. Instruments and ASTM methods used in biodiesel, diesel, and oil characterization

Fuel Quality	Instrument	Temperature (T) Range	Test Method
Density	Mettler Toledo Digital Density Meter DE 40	T < 90°C	ASTM D4052
Viscosity	ISL Viscometer Model TVB445	T < 200°C	ASTM D445
Centane Number	CID Fully automated Derived Cetane Number (DCN) Analyzer	10° < T < 35°C; recommended 15° < T < 25°C; 80% relative humidity at 35°C	ASTM D6751
Flash Point	Semi-automatic Pensky-Martens Herzog Model HFP 362	40°C < T < 360°C	ASTM D93
Fire Point	Fully-Automatic Cleveland Fire Point Analyzer	25°C < T < 400°C	ASTM D92
Cloud Point	HCP 852 Automated Pour and Cloud Point tester, 230V, 50/60 Hz	-80°C < T < 50°C	ASTM D2500
Pour Point	HCP 852 Automated Pour and Cloud Point tester, 230V, 50/60 Hz	-80°C < T < 50°C	ASTM D97
Calorific Value	Parr 6100 Bomb Calorimeter	DT > 1.5°C	ASTM D250-02

2.4. Engine tests

A single cylinder direct injection diesel engine, produced by MS Perry & Co. with specifications as detailed in Table 2, was used to compare the performance of conventional diesel with a blend of this diesel with 10 vol% biodiesel from Pediastrum boryanum. Such an engine is widely employed for agricultural purposes, as well as small and medium scale industrial applications.

Table 2. Specifications of I.C. engine used for study

Parameter	Specification
Cylinders	1
Bore x Stroke	95 x 110 mm
Cubic Capacity	0.78 liters
Compression Ratio	17.5:1
Rated output as per BS5514/ISO 3046/ISO 10001	5.9KW (8.0 HP) at 1500 rpm
Starting	Hand start with cranking angle
SFC at rated hp/1500 rpm	251 g/kWh (185 g/bhp-hr)
Lube oil consumption	0.8% of SFC max
Lube oil sump capacity	3.7 liters
Fuel tank capacity	11.5 liters
Fuel tank re-filling time period	Every 6.9 hours at rated output
Engine weight (dry) without flywheel	118 Kg
Weight of flywheel	GENSET -64 kg
Rotation while looking at flywheel	Clockwise
Power take-off	Flywheel end Optional-Gear and half speed drive or Full Speed drive

To ensure the engine was operating at steady state, it was allowed an initial warm-up period of 10 minutes at a load of 60% while running the diesel fuel. After 10 minutes, the voltage, current, exhaust temperature, RPM, fuel consumption and emissions were measured. When we obtained three sets of measurements within 1% of each other's values, each at least 2 minutes apart, we assumed that the engine was operating at steady state.

At this point, the load was increased to 100%, and the engine ran for 2 minutes. Three measurements were taken, each 60 seconds apart at this load. The load was varied as: 40%, 0%, 80%, 20%; after each load change the engine ran for 2 minutes, and three measurements were again taken 60 seconds apart. To ensure confidence in our data and methods, we then varied the load as 100%, 20%, 80%, 40%, 0%, and 60% of capacity, repeating the 2 minutes wait and three data points taken 60 seconds apart. Before beginning the bio-diesel blend run, we calculated an average and standard deviation for each data point at each load to make sure all data points were within 2 standard deviations of the mean.

Given the difficulty in producing large amounts of biodiesel in laboratory settings, we ran one set of varying loads, at 100%, 20%, 80%, 40%, 0%, and 60% of capacity, taking again 2 minutes to reach steady-state, and then three data points 60 seconds apart, for the 10% biodiesel blend.

3. Results & discussion

The goal of this work was to determine if *Pediastrum boryanum,* a locally available microalgae harvested in the state of Rio Grande do Norte, Brazil is a suitable candidate for biodiesel production, and to gauge its performance as a blended fuel in a single cylinder direct inject diesel engine. While there are many potential cultivable algal species that yield large quantities of lipids for biodiesel production, the ability to identify indigenous species that could both be cultivated and sourced from algal blooms – as a way to remediate such events – is critical to the sustainability of biodiesel production for algae.

After determining the fuel pararmeters, performance of the diesel engine was veryfied by using the algae biodiesel as a fuel. By performing such a test, the properties of the obtained biodiesel could be compared with that of conventional diesel and other edible and non-edible seed oils.

3.1. Fuel parameter tests

The generated biodiesel was tested for various fuel parameters, such as: (a) calorific value (b) density (c) viscosity (d) cetane number (e) flash point (f) fire point (g) cloud point (h) pour point.

In order to understand the characteristics of the obtained biodiesel as a fuel, the same was tested for various fuel parameters. Therefore 1.5 l of biodiesel was obtained from 2.5 kg of algae sample. The calorific value and specific gravity of the biodiesel was 42660 kJ/kg & 0.803 g/cm^3 respectively. While, the specific gravity of the normal diesel is 0.804 g/cm^3 therefore, blending of diesel and biodiesel could be easily made.

The viscosity of the sample as experimentally determined was 1.9985. High viscosity affects the flow characteristics of the oil causing improper atomization of the fuel and an incomplete combustion, therefore needing to be avoided (Bojan et al. 2011).

The cetane number of diesel fuel as reported in literature (Bojan et al. 2011, Nabi et al. 2008) ranges from 40-55, and the obtained value for the biodiesel was 47. Cetane number of biodiesel when above 40 could be justified in terms of fuel quality that the obtained biodiesel took less time in combustion while being compared to commercial diesel fuel.

The standard value of flash point of a diesel fuel is 80°C. It is the temperature at which the fuel will continue to burn for 5 seconds after ignition in open flame. The flashpoint of the generated biodiesel was 94°C which was slightly higher when compared with the standard value of diesel. However, flashpoint values of biodiesel obtained from various sources such as neem and jatropa as reported in literature lies between 120-214 (Bojan et al. 2011, Nabi et al. 2008).

Another important parameter is cloud point which could be described as the temperature at which a dissolved solid is no longer in soluble form. In crude or heavy oil cloud point is used as a synonym of wax appearance temperature or wax precipitation temperature. The standard value of a cloud point of diesel is -5°C.

The pour point of the liquid is the lowest temperature at which it loses its fuel properties and semi-solidifies. In crude oil it occurs due to the high paraffin content. The pour point of the generated bio-diesel comes out to be -7°C which is slightly lower when compared with standard values of commercial diesel.

3.2. Comparative study of the fuel parameters

The fuel parameters of biodiesel generated from algae, edible & non-edible oil has been studied, compared and summarized in Table 3. The values depicted in Table 3 indicated that:

a. The calorific value of the algal biodiesel as determined was 42857 KJ/kg which is the highest among the non-edible and edible oils, with the exception of palm oil. However, the calorific value of the diesel and other biodiesel as reported in the scientific literature lies between 35000-40000 KJ/kg (Karmakar et al. 2012, Bojan et al. 2011, Nabi et al. 2008). Therefore, the value of the obtained gross biodiesel was higher than that reported in literature and was a good indication of the fuel value in terms of energy.
b. The specific gravity of the algal biodiesel was lesser when compared to edible, non-edible oils & diesel. The specific gravity of a substance is the ratio of the density of the substance compared to the density of the reference substance. It is a dimensionless quantity and usually water is taken as a reference substance keeping the temperature and pressure constant.
c. The viscosity of the algae biodiesel was 1.998 which was lesser than diesel and other edible and non-edible oils. The lesser the viscosity better is the pour point and its functionality in the diesel engine. The process of upgrading is done because of the high viscosity of the bio-oils. This indicated that the quality of algal biodiesel is better than those of other fuels and oils.
d. Cetane number of the algal biodiesel was 50 which could be well compared with other fuels such as diesel which has a value of 49. Also most of the biofuels or oils lies within a similar range.
e. Flashpoint of the algal biodiesel as determined is 80 which are slightly higher than the 56 value of diesel. Flashpoint of the generated biodiesel was 94 which is also more than that of diesel which was 64, however lesser than that of other biodiesel and oils. This also indicated the better quality of algal biodiesel than other biofuels and oils.

The value of the cloud and pour point of the algal biodiesel was -5°C and -7°C respectively and cloud and pour point of the diesel was -8°C and -20°C respectively. The value of cloud point and pour point as compared to biodiesel is not much appreciable. Therefore, certain tests needs to be performed for improving these factors as the fuel may tend to freeze at low temperatures. It means diesel could work nicely at lower temperatures. These results are summarized and shown in Table 3.

Table 3. Properties of biodiesel produced from pediastrum boryanum as compared to diesel used in engine tests and selected edible and non-edible oils

Property	Diesel	Algal Biodiesel	Non-edible oils					Edible oils					
			TPSO	Jatropha	Pangumia	Mahua	Neem	Corn	Palm	Cotton	Mustard	Sunflower	Rice bran
Calorific value (kJ/kg)	43200	42660	4252	42250	42334	42062	41905	41905	42857	42150	42102	41260	42125
Specific Gravity	0.804	0.803	0.828	0.816	0.821	0.815	0.829	0.820	0.826	0.838	0.823	0.825	0.828
Viscosity @40°C (cSt)	3.90	2.00	6.50	4.84	6.40	4.80	6.80	4.50	5.30	5.87	5.60	5.20	5.80
Cetane number (°C)	49	50	51	48	50	47	50	51	48	50	47	48	47
Flashpoint (°C)	56	80	88	92	95	85	87	78	81	88	86	79	87
Firepoint (°C)	64	94	95	96	98	92	93	85	87	95	90	82	96
Cloud point (°C)	-8	-5	-6	-3	-5	-4	-6	5	8	-1	3	5	2
Pour point (°C)	-20	-7	-18	-16	-17	-14	-16	-2	-3	-7	-5	-3	-8

3.3. Mechanical & thermal parameters

After determination of the fuel characteristics, algal biodiesel was introduced in the diesel engine so as to obtain thermal and mechanical parameters. During the combustion, 10% of algal biodiesel was blended with 90% of diesel. During the experiment, the following parameters were determined:

a) Brake Specific Fuel Consumption**:** In engine test, brake specific fuel consumption is measured as mass of fuel consumed per unit time per brake horse power. If brake specific fuel consumption of one fuel is less than other fuel, it means one liter of oil produce more brake horse powers that other fuel. It is represented as BSFC.

   Brake Specific Fuel Consumption = Mass of Fuel Consumed per Unit Time / BHP

   The power developed by engine after varying load for diesel and biodiesel indicates that maximum power is higher in case of Diesel (3.982 KW) as compared to biodiesel (3.741 KW). This is due to the synergy of calorific value, oxygen content and viscosity.

b) Exhaust gas temperature: Exhaust gases are emitted as a result of the combustion of the fuel in an engine. According to the type of the fuel utilized during the combustion exhaust gas is discharged in the atmosphere. Exhaust gas temperature is a significant parameter of a catalytic converter of an internal combustion engine.
c) Carbon monoxide: Carbon monoxide is formed during the combustion process, when insufficient air (oxygen) is supplied to the fuel. Due to insufficient supply of the air, generation of heat decreases and fuel does not burn properly. Mechanical efficiency decreases and brake specific fuel increases.
d) Carbon content: Complete combustion of hydrocarbon fuel results into water and carbon dioxide. Release of carbon dioxide in the environment is quite noxious to the atmosphere. Therefore it is important to calculate the amount of carbon content in a fuel.
e) Unburnt hydrocarbon: The hydrocarbon content varies from methane to the heaviest solid hydrocarbons. It remains in the vapor phase at about 190°C. Hydrocarbons heavier than this therefore condenses and with the solid-phase soot, are filtered from the exhaust gas stream upstream of the detector. The composition of the unburned and partially oxidized hydrocarbons in the diesel exhaust is much more complex than any other fuel in spark ignition engine and extends over a larger molecular size range. Engine idling and light load operation produces significantly higher hydrocarbon emissions than full-load operation.
f) Nitrogen oxides: Nitric oxide and nitrogen dioxide are grouped together as NO_x emission. Nitric oxide is the predominant oxide of nitrogen produced in the engine cylinder. NO_x discharge of blank diesel and biodiesel B10 increase with the increase of torque. NO_x discharge increases with the increase of adding biodiesel at the same torque. When biodiesel is added into diesel, it means more of the oxygen element is added into the diesel, so NO_x discharge gradually increases. There are reports about the fact that NO_x emission increases from 1.5% to 9.5% when B100 is used instead of B20 (Bojan et al. 2011). Neat biodiesel contains about 9.5-11.5% oxygen in its molecule. This additional oxygen is responsible for higher NO_x emission. However, Nabi et al. (Nabi et al. 2008) had investigated the combustion and exhaust emissions with diesel fuel and diesel-NOME blends (5%, 10%, and 15%). He found that exhaust emissions including smoke and CO were reduced, while NO_x emission was increased with diesel blends for all the injection timing, compared with conventional diesel fuel. It was reported that NO_x emissions increases 10% in comparison to diesel when B50 blend of neem methyl ester was used (Mathiyazhagan et al. 2011).
g) Smoke number: It quantifies the emission of the smoke. It is a dimensionless quantity.

h) Oxygen content: Carbon dioxide, water vapor and heat energy are produced, when petroleum fuel burns in the presence of oxygen. Alternative fuels like biodiesel contain oxygen molecules as well as hydrogen and carbon. This promotes complete combustion. Therefore, less amount of soot, carbon monoxide and hydrocarbon are released enabling it to become a cleaner fuel.

Thermal and electrical parameters were determined and tabulated in Table 4. The tests were performed at a blend of 10% algal biodiesel with 90% diesel. The overall efficiency of the engine coupled electric generator at different load conditions were measured and summarized in Table 4.

Table 4. Thermal and electrical parameters of 10% blend of algal biodiesel with varying load condition

Load	Voltage (V)	Current (A)	Exhaust temperature (°C)	RPM	Time for fuel consumption (20 ml) in sec.
0	240	1	204	1580	138.86
20	246	44	233	1544	91.92
40	244	86	280	1495	73.37
60	234	125	343	1468	56.23
80	248	17.3	378	1440	40.20
100	232	20.8	445	1436	25.35

It was evident that the overall efficiency using biodiesel as a fuel was higher than the overall efficiency of the engine using diesel as fuel at all load conditions. This was mainly because of the oxygen content available in the biodiesel which improves the combustion process.

The obtained results indicated that biodiesel could be utilized in the place of diesel. Some experiments were essential to observe the performance of the vehicle at variable load starting from 0 to 100 Watts. At low load conditions, an engine works well, but as soon as the load increases, smoke capacity and exhaust temperature increases and rotation per minute (rpm) decreases.

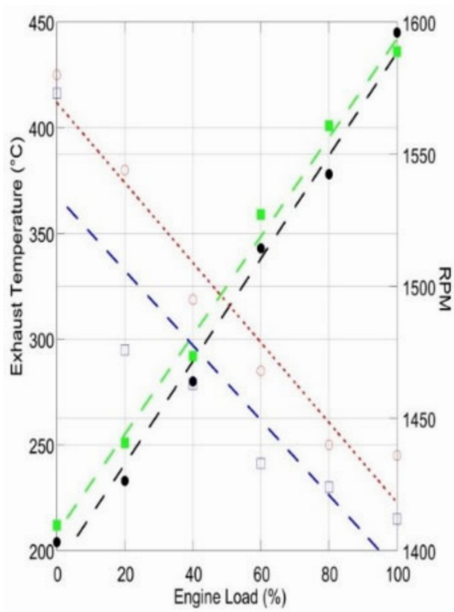
The consumption of the fuel was steady up to 60 watt but after that the consumption of fuel increased significantly. Emission rate also increased with increasing load, at full load rate, the emissions increased significantly.

The emission produced at the full load was black because of incomplete combustion, however the characteristics of the emissions at low load was promising. The emission rate of the biodiesel did not deviate much from the emissions in the case of diesel.

Also after combustion, petroleum fuel generated significant amount of ash particles when compared to biodiesel which generated a very little amount of ash. Therefore, it could be inferred that petroleum fuel operated vehicles are far more damaging in terms of pollution to the atmosphere than when compared to those of algae biodiesel.

3.4. Engine performance: blend vs. diesel

The exhaust temperature as a function of engine load for 10% biodiesel blend ranged from 204°C with no load to 445°C with 100% load, and for the diesel from 212°C to 436°C. As shown in Figure 2, the exhaust temperature and applied engine load are linearly correlated for both the biodiesel blend (at $R^2 = 0.98$) and diesel fuel ($R^2 = 0.99$).



Exhaust temperature and engine RPMs as a function of applied load; (□) Blend Temp; (□) Blend RPM; (□) Diesel Temp; (□) Diesel RPM

Fig. 2. Engine performance with 10% biodiesel blend (circles) as compared to pure diesel (squares)

The correlation between load and engine RPM is not as high ($R^2 = 0.95$ and $R^2 = 0.81$ for blend and diesel, respectively). Interestingly, though exhaust temperature appears to increase linearly with applied load, and the opposite for engine RPMs, there appears to be little difference between the blended and pure diesel.

That is, the values at each engine loading (correlating to intercept) are within 6% and 2% for temperature and RPM, and relative magnitudes of change (i.e. the slopes for each correlation) are only 4% and -8% different for temperature and RPM, respectively. In this sense, there is no penalty for using a blended biodiesel.

4. Conclusion

Algal blooms grows on the water bodies, such as water reservoir and ponds, as a consequence this stagnated water could be considered as being a harmful waste and instead could be utilized as a one of the best sources for biodiesel production. This process does not require high end technology hence being able to be used in energy generation processes in remote areas.

The calorific value of produced biodiesel could be found within the range of 5429-6438 cal/g, which indicates lower caloric value when compared to petroleum fuel. Afterwards, this oil was blended with diesel, furthermore being ignited in a single cylinder diesel engine to analyze the performance of the diesel engine. Thermal and electrical parameters were determined in this current paper and tests performed using algal biodiesel blend with diesel. The obtained results indicated that biodiesel could be comfortably utilized in the place of diesel. The power developed from an engine using biodiesel as a fuel was 6% less as compared to diesel because of the lower heating value of the biodiesel.

It is inferred that as per ASTM standards the fuel characteristics of algae biodiesel can be very qualitative when compared with diesel, biofuels and oils. One advantage of diesel, when compared to algae biodiesel is that it could work at a very low temperature; it will not freeze, however biodiesel freezes at very low temperatures. Therefore such a parameter of this type of biodiesel fuel needs to be improved in future so that this fuel could be utilized for various commercial purposes. Biodiesel has been produced from pond algae and its fuel – properties are in accordance with the ASTM standards, therefore, algae biodiesel could be used in the diesel engine.

References

Adenle, AA., Haslam, GE., Lee, L. (2013). Global assessment of research and development for algae biofuel production and its potential role for sustainable development in developing countries. *Energy Policy, 61,* 182-195. DOI: 10.1016/j.enpol. 2013.05.088

Ahmad, AL., Yasin, NHM., Derek, CJC. & Lim, JK. (2011). Microalgae as a sustainable energy source for biodiesel production: a review. *Renew Sustain Energy Rev., 15*, 584-93. DOI: 10.1016/j.rser.2010.09.018

Amin, A., Gadallah, A, El-Morsi, AK., El-Ibiari, NN., El-Diwani, GI. (2016). Experimental and empirical study of diesel and castor biodiesel blending effect, on kinematic viscosity, density and calorific value. *Egyptian Journal of Petroleum, 25,* 509-514. DOI: 10.1016/j.ejpe.2015.11.002

Arain, S., Sherazi, STH., Bhanger, MI., Talpur, FN., Maheshar, SA. (2009). Oxidative stability assessment of bauhinia purpurea seed oil in comparison to two conventional vegetable oils by differential scanning calorimetry and rancimat methods. *Thermochimica Acta, 484*, 1-3. DOI: 10.1016/j.tca.2008.11.004

B.P. statistical Review of World Energy, London, United Kingdom. Available from: www.bp.com/statisticalreview, June 2012.

Berman, P., Nizri, S., Wiesman, Z. (2011). Castor Biodiesel and its blends as alternative. *Biomass & Bioenergy, 35*, 2861-2866. DOI: 10.1016/j.biombioe.2011.03.024

Bojan, SG., Chelladurai, S. & Durairaj, SK. (2011). Batch type synthesis of high free fatty acid jatropha curcus oil biodiesel – India as supplying country. *ARPN Journal of Engineering and Applied Sciences, 6*(8), 73-78.

Campbell, MN. (2008). Biodiesel: algae as a renewable source for liquid fuel. *Guelph Eng J.*, *1*, 2-7.

Chojnacka, K. & Marquez-Rocha, FJ. (2004). Kinetic and stoichiometric relationships of the energy and carbon metabolism in the culture of microalgae. *Biotechnology, 3,* 21-34. DOI: 10.3923/biotech.2004.21.34

Christi, Y. (2007). Biodiesel from microalgae. *Biotechnology Advances, 25*, 294-306. DOI: 10.1016/j.biotechadv.2007.02.001

Demirbas, A. & Demirbas, MF. (2011). Importance of algae oil as a source of biodiesel. *Energy Convers. Manage, 52*, 163-170. DOI: 10.1016/j.enconman.2010.06.055

Ehimen, EA., Sun, ZF. & Carrington, CG. (2010). Variables affecting the in situ transesterification of microalgae lipids. *Fuel*, 98, 677-684. DOI: 10.1016/j.fuel.2009.10.011

Evangelista, JPC., Chellappa, T., Coriolano, ACF., Fernandes, Jr VF., Souza, LD. & Araújo, AS. (2012). Synthesis of alumina impregnated with potassium iodide catalyst for biodiesel production from rice bran oil. *Fuel Process. Technol. 104,* 90-95. DOI: 10.1016/j.fuproc.2012.04.028

Focke, WW., Westhuizen, IVD., Grobler, ABL., Nshoane, KT., Reddy, JK., Luyt, AS. (2012). The effect of synthetic antioxidants on the oxidative stability of biodiesel. *Fult, 94,* 227-233. DOI: 10.1016/j.fuel.2011.11.061

Fu, J., Turn, SQ., Takushi, BM., Kawamata, CL. (2016). Storage and oxidation stabilities of biodiesel derived from waste cooking oil. *Fuel*, *167,* 89-97. DOI: 10.1016/j.fuel.2015.11.041

Ghosh, A., Khanra, S., Mondal, M., Halder, G., Tiwari, ON., Saini, S., Bhowmick, TK. & Gayen, K. (2016). Progress toward isolation of strains and genetically engineered strains of microalgae for production of biofuel and other value added chemicals: a review. *Energy Converse. Manage., 113*: 104-118. DOI: 10.1016/j.enconman.2016.01.050

Grace, PA., Ahmed, N., Mahmoud, MEH. & Vladimir, M. (2010). Design and analysis of biodiesel production from algae grown through carbon sequestration. *Clean Tech Environ Policy, 12,* 239-254. DOI: 10.1007/s10098-009-0215-6

Hidalgo, P., Toro, C., Ciudad, G. & Navia, R. (2013). Advances in direct transesterification of microalgal biomass for biodiesel production. *Rev. Environ. Sci. Biotechnol., 12*(2), 179-199. DOI: 10.1007/s11157-013-9308-0

Jain, S. & Sharma, MP. (2010). Prospects of biodiesel from Jatropha in India: a review. *Renew. Sust. Energ. Rev. A, 14,* 763-771. DOI: doi.org/10.1016/j.rser.2009.10.005

Jin, B., Duan, P., Xu, Y., Wang, B. & Zhang, L. (2014). Lewis acid-catalyzed in situ transesterification/esterification of microalgae in supercritical ethanol. *Bioresource Technology., 162,* 341-349. DOI: 10.1016/j.biortech.2014.03.157

Karmakar, A., Karmakar, S. & Mukherjee, S. (2012). Biodiesel production from neem towards feedstock diversification: Indian perspective. *Renewable and Sustainable Energy Reviews. 16*, 1050-1060. DOI: 10.1016/j.rser.2011.10.001

Kulkarni, MG. & Dalai, AK. (2006). Waste cooking oil – an economical source for biodiesel: a review. *Ind. Eng. Chem. Resour*., *45.* 2901-2913. DOI: 10.1021/ie0510526

Leung, DYC., Wu, X. & Leung, MKH. (2010). A review on biodiesel production using catalyzed transesterification. *Appl. Energ. 87*, 1083-1095. DOI: 10.1016/j.apenergy.2009.10.006

Liu, Z., Sharma, BK., Erhan, SZ., Biswas, A., Wang, R., Shuman, TP. (2015). Oxidation and low temperature stability of polymerized soybean oil-based lubricants. *Thermochimica Acta., 601*, 9-16. DOI: 10.1016/j.tca.2014.12.010

Mathiyazhagan, M., Ganapathi, A., Jaganath, B., Renganayaki, N. & Sasireka, N. (2011). Production of biodiesel from non-edible plant oils having high FFA content. *Int. J. Chem. Environ. Eng. 2*(2), 119-22.

Mutanda, T., Ramesh, D., Karthikeyan, S., Kumari, S., Anandraj, A. & Bux, F. (2011). Bioprospecting for hyper-lipid producing microalgal strains for sustainable biofuel production. *Bioresour Technol*., *102*, 57-70. DOI: 10.1016/j.biortech.2010.06.077

Nabi, N., Hustad, JE. & Kannan, D. (2008). First generation biodiesel production from nonedible vegetable oil and its effect on diesel emissions. Proceedings of the 4th BSME-ASME international conference on thermal engineering.

Park, JBK. & Craggs, RJ. (2014). Effect of algal recycling rate on the performance of *Pediastrum boryanum* dominated wastewater treatment high rate algal pond. *Water Sci. Technol., 70*(8), 1299-1306. DOI: 10.2166/wst.2014.369

Pienkos, PT. & Darzins, A. (2009). The promise and challenges of microalgal-derived biofuels. *Biofuels Bioprod. Biorefining. 3*, 431-440. DOI: 10.1002/bbb.159

Ramkumar, S. & Kirubakaran, V. (2016). Biodiesel from vegetable oil as an alternate fuel for C.I Engine and feasibility study of thermal cracking: a critical review. *Energy Converse. Manage. 118*, 155-169. DOI: 10.1016/j.enconman.2016.03.071

Sekhar, SC., Karuppasamy, K., Vedaraman, N., Kabeel, AE., Sathyamurthy, R., Elkelawy, M., Bastawissi, HAE. (2018). Biodiesel production process optimization from pithecellobium dulce seed oil: performance, combustion, and emission analysis on compression ignition engine fuelled with diesel/biodiesel blends. *Energy Conversion and Management*, *161,* 141-154. DOI: 10.1016/j.enconman.2018.01.074

Sheehan, J., Dunahay, T., Benemann, J. & Roessler, P. (1998). A look back at the US Department of Energy's Aquatic Species Program – biodiesel from algae. *National Renewable Energy Laboratory (NREL) report. NREL/TP-580-24190.*

Shirvani, T., Yan, X., Inderwildi, OR., Edwards, PP. & King, DA. (2011). Life cycle energy and greenhouse gas analysis for algae-derived biodiesel. *Energy Environ. Sci.*, *4*, 3773-3778. DOI: 10.1039/C1EE01791H

Silva, HKTA., Chellappa, T., Carvalho, FC., Silva, EFB., Nascimento, TA., Araújo, AS. & Fernandes, Jr. VJ. (2011). Thermal stability evaluation of methylic biodiesel obtained for different oilseeds. *J. Therm. Analy. Calorim., 106*, 731-733. DOI: 10.1007 /s10973-011-1376-1

Vicente, G., Bautista, LF., Gutierrez, FJ., Rodriguez, R., Martinez, V. & Rodriguez, RA. (2010). Direct transformation of fungal biomass from submerged cultures into biodiesel. *Energy Fuels*. *24*, 3173-3178. DOI: 10.1021/ef9015872

Wackett, LP. (2008). Biomass to fuels via microbial transformations. *Curr. Opin. Chem. Biol., 12*, 187-193. DOI: 10.1016/j.cbpa.2008.01.025

Wahlen, BD., Willis, RM. & Seefeldt, LC. (2011). Biodiesel production by simultaneous extraction and conversion of total lipids from microalgae, cyanobacteria and wild mixed-cultures. *Bioresource Technology, 102*(3), 2724-2730. DOI: 10.1016/ j.biortech.2010.11.026

Wang, R., Hanna, MA., Zhou, WW., Bhadury, PS., Chen, Q. & Song, BA. (2011). Production and selected fuel properties of biodiesel from promising non-edible oils: Euphorbia lathyris L., Sapiumsebiferum L. and Jatropha curcas L. *Bioresour. Technol., 102*, 1194-1199. DOI: 10.1016/j.biortech.2010.09.066

Xu, H., Xiaoling, M. & Qingyu, W. (2006). High quality biodiesel production from a microalgae Chlorella protothecoides by heterotrophic growth in fermenters. *Journal of Biotechnology*, *126*, 499-507. DOI: 10.1016/j.jbiotec.2006.05.002

Yun, H., Kibong, C. & Chang, SK. (2016). Effects of biobutanol and biobutanol-diesel blends on combustion and emission characteristics in a passenger car diesel engine with pilot inject strategies. *Energy Converse. Manage, 111*, 79-88. DOI: 10.1016/ j.enconman.2015.12.017

Zareh, P., Zare, AA., Ghobadian, B. (2017). Comparative assessment of performance and emission characteristics of castor, coconut and waste cooking based biodiesel as fuel in a diesel engine. *Energy, 139,* 883-894. DOI: 10.1016/j.energy.2017.08.040

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The Influence of Aircraft Noise on the Prices of Residential Properties on the Example of Poznań

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Abstract: The article analyses the influence of aircraft noise on the transaction prices of residential premises within the Poznań property market. The paper analyses the set of properties, subject to the transaction from the first to the fourth quarter of 2020. In total, 1550 properties were examined. The study defined basic attributes of all premises, exhibiting the most significant influence on their price. The research conducted using the hedonic regression allowed for the identification of crucial evidence that aircraft noise negatively affects the property transaction prices.

Keywords: aircraft noise, property prices, hedonic methods

1. Introduction

Noise generated by aviation, as well as any additional, ancillary activities, constitutes an important issue, particularly for market participants, potentially interested in purchasing premises in the vicinity of the airport (Bishop & Laing 2020). It should be noted that, over the past years, as a result of substantial, technological progress, the noise from a single aircraft has been significantly reduced (Zellmann et al. 2019). Activities aimed at reducing noise emissions occur, among others, in connection with the implementation of the principles of sustainable development, which nowadays rise in importance (Dube & Nhamo 2020). However, it should be emphasised that, over the last years, along with the reduction of noise emitted from a single aircraft to the environment, air transport has been gaining in importance (Zhang & Graham 2020). As a consequence, despite the technological progress, the absolute value of noise emitted to the environment from aviation activities has not decreased. In places particularly exposed to noise, it is extremely important to conduct activities involving the local spatial structure, aimed at reducing the negative impact of noise, generated by the transport industry (Podawca & Staniszewski 2019).

Air transport is considered to be the safest means of travelling, fulfilling the fundamental demands of sustainable transport and enabling fast and accessible for everyone movement between distant countries and continents (Bobrova & Stepanov 2019). Regardless of the presented, indisputable advantages of this form of transport, it also generates many crucial, economic and social costs. The most significant costs of such transport are borne by the residents of properties, located in the vicinity of large, international airports, as well as smaller, local ones. An increased number of flights, combined with their duration, directly affect the amount of noise emitted, which, in turn, results in a significant deterioration in the living conditions of the owners of properties adjacent to the airport (Eves & Blake 2016). It is important to examine the consequences of the airport's proximity on people residing in the area of its impact.

This paper aims to examine the impact of aircraft noise on the value of properties. The property market is unique, while the premises are considered to be specific goods, characterised by several individual features, including economic, legal, environmental and institutional ones. The property value, depending on its type, is influenced by its direct features (technical condition of the building, the parcel's size, finishing standard, etc.) and attributes considering the condition of the property's immediate surroundings, i.e. the quality of recreational areas, air pollution, vicinity of troublesome industrial facilities, etc. (Radzewicz & Wiśniewski 2012). The proximity of airports is also placed among the most important, indirect factors (Batóg et al. 2019). Complete analyses determining the impact of significant factors on the property value should involve factors from both the first and the second group.

2. Literature review

The activity of airports generates a number of social and economic consequences. Noise emitted from the airport's operation constitutes one of the most significant social costs, which directly affects residents of the impact zone. One of the available methods for examining the magnitude of the said costs consists in the analysis of changes in the value of properties located in the vicinity of the airport. Most frequently, such an impact is determined based on the preferences of the property market's participants, including transactional data concerning previous sales. The analyses usually apply models of hedonic price or multiple regression (Trojanek et al. 2017, Winke 2017, Thanos et al. 2012).

To analyse the impact of excessive exposure to noise on the property, the study employed the NDI (Noise Depreciation Index), defined as a depreciation/amortisation index or the NSDI (Noise Sensitivity Depreciation Index), understood as an index of sensitivity to the decreasing values. The basic objective of both these indicators is to determine how the price of the property is affected by a 1dB change in the noise level. The subject literature, assessing the impact of noise on the value of properties has been previously analysed (Nelson 2004, Schipper et al. 1998, Bateman et al. 2001, Wadud 2013, Trojanek et al. 2017, Kopsch 2016) (Table 1).

Table 1. A summary of literature reviews conducted in relation to the NDI

Author/ authors	NDI	Study period	Area of the study	Scope of the study
Nelson	0.28-1.49%	1969-1993	USA, Canada	23 airports
Schipper et al.	0.1-3.57%	1967-1996	USA, Canada, Australia, UK	19 airports
Bateman et al.	0.29-2.3%	1960-1996	USA, UK, Canada, Australia	30 reviews
Wadud	0-2.3%	1970-2007	USA, Canada, Australia, UK, Netherlands, France, Switzerland, Norway	65 reviews
Trojanek et al.	-0.8-2.12%	1995-2014	China, Switzerland, Netherlands, Germany, Greece, Poland, Thailand, France	14 reviews
Kopsch	0.13-2.3%	1960-2009	Australia, UK, USA, Germany, Thailand, Netherlands, Canada, Switzerland	44 reviews

The presented NDI values reach different levels for various countries and individual airport examples. Therefore, it can be concluded that the prices of premises react differently to the proximity of the airport, which may be directly related to one of the main characteristics of the property market – its local character. The size and manner of impact may be furthermore associated with the scale of the airport, the spatial structure of existing buildings, different forms of noise measurement and the economic development of the country (Wadud 2013).

Analysing some of the recent studies regarding the impact of noise on the prices of properties located in the vicinity of airports, it can be noticed, that the majority confirms the negative influence of airport proximity on the said values (Chalermpong & Klaiklueng 2012, Püschel & Evangelinos 2012, Nguy et al. 2014). The exceptions are two studies (Huderek-Glapska & Trojanek 2013, Trojanek 2014) including the case of the Warsaw airport, in which, contrary to other studies, apartments and houses located closer to the airport were evaluated higher. Within the analysed studies, the obtained NDI values reached between -0.8 and 2.12% per 1 dB. It should be noted that a direct comparison of indicators received for the purposes of those studies may be misplaced, due to disparities in the type of the analysed properties, different methods of noise measurement, as well as various sources of data.

3. Area and material of the study

3.1. Area of the study

Poznań, located in the central-western part of Poland, constitutes the central part, as well as the capital of the Wielkopolskie Voivodship. According to the Statistics Poland, the city is inhabited by 533,830 residents (as of August 2020). The city area amounts to 261.9 km^2.

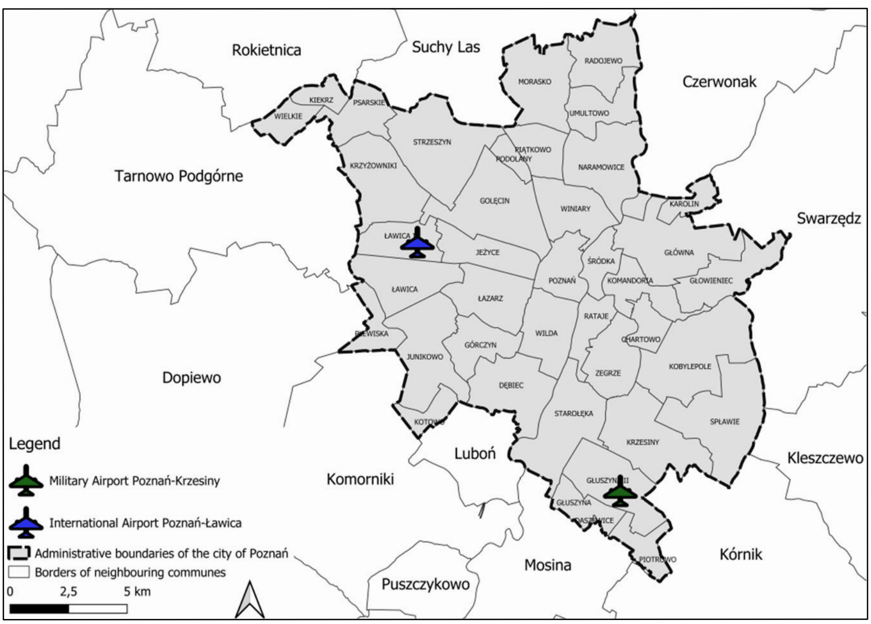

Fig. 1. The location of airports in Poznań. Source: own study

There are two airports in Poznań: Poznań–Ławica Henryk Wieniawski Airport (in the western part of the city) and the 31st Air Base, known as the Poznań-Krzesiny Airport (in the southern part of the city), owned by the National Air Force Command (Fig. 1).

Poznań-Ławica Henryk Wieniawski Airport was opened in 1945. The total area of the airport amounts to 310 ha, while its capacity reaches 3 million (the airport is capable of providing service to 3 million passengers each year). In 2019, the airport held a total of 31,923 air operations (Fig. 2A), within which, 2,379,635 passengers took advantage of flights (Fig. 2B).

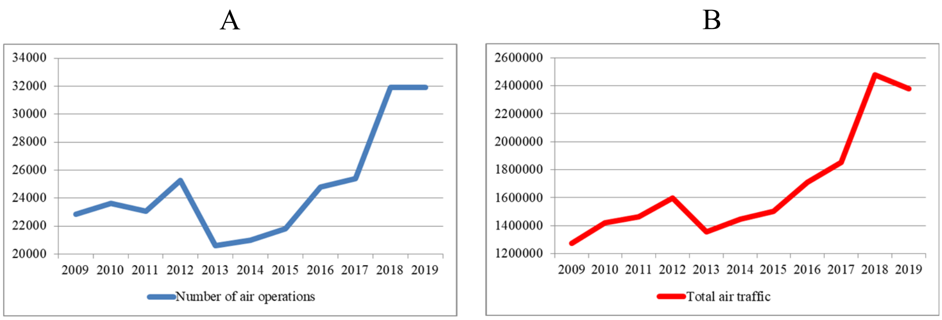

Fig. 2. The number of air operations at Poznań-Ławica Airport in 2009-2019 (A), total air traffic at Poznań-Ławica Airport in 2009-2019 (B)

Poznań-Krzesiny Airport is located within the are of the Military Unit No. 1156. The 31st Tactical Air Base is located in the same area, approximately 8 km from the city centre. Data obtained from the Environmental Noise Protection Programme for the City of Poznan in 2018 indicate that, in 2016, the total number of air operations occurring at the military airport increased by 12.5%, compared to 2011.

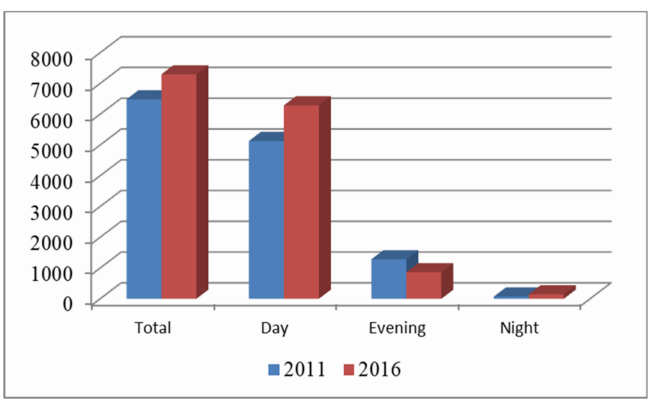

Fig. 3. The number of air operations at Poznań-Krzesiny Airport in 2011 and 2016

3.2. Study material

The following study is based on two groups of source data. The first, basic group, consists of data obtained from the Board of Geodesy and Town Cadastre "GEOPOZ" in Poznań, on the residential property transactions concluded in the city in 2020. The framework of this study does not involve property transactions, concluded in particular conditions, i.e. in non-market conditions, such as sale with a delayed date of release of the property to the buyer, or in the event of a bailiff's auction.

Transactional data obtained from the Board of Geodesy and Town Cadastre in Poznań were based on notarial deeds. The basic information collected in this database includes data on the transaction date and price, surface area (of the apartment), area of auxiliary premises, as well as information regarding the floor on which the dwelling is located. An attempt to determine factors that significantly affect the value of a property on the sole basis of data from such a register cannot be considered an acceptable approach, due to the unique nature of the property, according to which, its value is influenced by several attributes, undefined in the said register. To eliminate the problem related to the absence of complementarity data, additional information about the analysed properties, including the nearest neighbourhood and detailed location, was obtained.

The second group of source data consists of the information derived from the noise map of Poznań from 2017, related to aircraft noise occurring within the areas of restricted use of the Poznań-Ławica Airport and the Poznań-Krzesiny Airport.

The restricted use area of the Poznań-Ławica Airport constitutes an envelope of noise isolines with specified acceptable values, indicated separately for daytime and nighttime. The external zone is limited by: from the outside – a balanced sound level isoline of LAeq = 55dB for daytime and LAeq = 45 dB for nighttime (for noise generated by an aircraft landing, take-off and flight). In the case of noise from other aviation-related sources, the isolines assume the levels of LAeq = 50 dB (daytime) and LAeq = 40 dB (nighttime). From the inside, however, the zone is limited by a line constituting the envelope of the inner region of the restricted use area.

The internal zone of the area is limited by: from the outside – a balanced sound level isoline of LAeq = 60 dB for daytime and LAeq = 50 dB for nighttime (for noise generated by an aircraft landing, take-off and flight). In the case of noise from other sources related to aviation activities, the isolines assume the levels of LAeq = 55 dB (daytime) and LAeq = 45 dB (nighttime). A line running along the border of the airport area limits the zone from the inside.

The restricted use area of the Poznań-Krzesiny military airport is divided into three zones. Each zone strictly defines requirements on, among other aspects, the purpose of the land, the manner in which the land is used and technical requirements for constructions. Zone I is located in the area of Poznań, as well as the municipalities of Luboń, Komorniki and Kórnik. Zone II covers the city of Poznań, as well as the municipalities of Luboń, Kórnik, Mosina and Komorniki. Zone III involves the largest area, including Poznań, as well as municipalities of Luboń, Komorniki, Puszczykowo, Stęszew, Mosina, Kórnik, Kleszczewo and Środa Wielkopolska.

4. Research methodology

The method of statistical analysis has marginal importance in the process of property valuation. In everyday practice, the valuers employ it in an extremely limited extent. On the other hand, however, analyses of the property market based on mathematical statistics find many applications, as well as enable reliable and effective market characterisation established on unambiguous indicators. The most frequently applied methods based on statistical analysis include models, such as hedonic, regression, spatial analysis and artificial neural networks (Trojanek et al. 2017).

In the property market analyses, hedonic methods have been successfully used since the 20th century (Rosen 1974). The basic aim of such models consists in answering the question of how the analysed, specified factors influence the property value. The main idea of hedonic models involves the assumption that the price of a certain good (in this case – a property), is characterised by several selected attributes. As a result, the hedonic model allows determining the value of the analysed features, as elements of the whole, i.e. the property price. The assumed property characteristics, such as the level of aircraft noise or location, constitute the explanatory variables. The property price will result directly from the selected explanatory variables.

$$C = \beta_0 + \sum_{i=1}^{K} \beta_i X_i + u \quad (1)$$

where:
C – property price,
β – regression coefficient,
X – the value of the analysed attribute,
u – random error.

In the analyses of the property market using the hedonic models, the most commonly applied is the regression function, based on the natural logarithm, resulting from the possibility of changing the value of a certain feature proportionally to the changes of others. However, in the case of linear models, it is possible only to determine the influence of the selected feature's improvement (e.g. the finishing standard for all properties in the analysed set), without specifying the impact of the improvement in the standard of apartments with, for instance, different surface areas. Further advantages of the logarithmic function consist in straightforward interpreting of coefficients, as well as eliminating the problem of random element variability (Trojanek 2014). Therefore, the following study is also based on a logarithmic model.

Moreover, the key issue consists in the selection of features that most significantly affect the property price. One of the basic functions of properties is their diversity, which entails, among other things, that attributes affecting the value of a given type of property are not necessarily relevant for premises of different types. In the case of residential properties, the most important features appear to involve location, neighbourhood, form of ownership, upper-floor location and surface area (Radzewicz & Wiśniewski 2012). The following study analyses an additional feature, defined in the property price – the level of noise emitted from air transport. Considering the above-mentioned assumptions, the hedonic function of the price may be presented in the following manner:

$$\ln(C) = f\,(\text{location, neighbourhood, the form of ownership, upper-floor location, surface area, aircraft noise}) \qquad (2)$$

5. Results

To determine the impact of aircraft noise – imposed by the location of the property in the restricted use zone – on apartment prices, the paper collected information on the transactions of residential premises within the city of Poznań, from the first to the fourth quarter of 2020. The data were initially used to conduct a preliminary analysis of correlations between aircraft noise and the property market in 2020 in Poznań.

The analysis shows that only two transactions originate from the area located in the airport's immediate vicinity, namely the premises in Jeżyce, which are partly situated in the zone of the restricted use of the Poznań-Ławica Airport. A total of 168 transactions were recorded in the zones of limited external use in both Poznań-Ławica and Poznań-Krzesiny airports, the highest number of which occurred in Grunwald (57) and Jeżyce (41). Outside the restricted use zones of both airports, the study collected data on 1380 residential unit transactions, mainly from districts of Rataje (161), Nowe Miasto and Winogrady (145). In total, data on 1550 transactions were recorded, while the vast majority involved premises located outside the restricted zones (Table 2).

Table 2. The number of offers regarding residential units in each district of Poznań

District	Inside the zone		Outside the zone	Total
	Zone I	Zones II and III		
Central Poznań	0	0	111	111
Górczyn	0	35	86	121
Grunwald	0	57	80	137
Jeżyce	2	39	79	120
Łazarz	0	29	84	113
Nowe Miasto	0	0	145	145
Piątkowo	0	0	130	130
Rataje	0	0	161	161
Sołacz	0	8	55	63
Stare Miasto	0	0	109	109
Wilda	0	0	109	109
Winiary	0	0	86	86
Winogrady	0	0	145	145
Total	2	168	1380	1550

To initially verify the impact of aircraft noise on the transaction price, a median of prices was determined in districts, where the offers occurred within the restricted use zone (Table 3).

Table 3. The median of offer prices inside and outside the restricted use zone, including the districts of Poznań

District	Inside the zone	Outside the zone	The median difference (%)
Górczyn	6954	7679	-9.44
Grunwald	6242	6990	-10.70
Jeżyce	6298	7400	-14.89
Łazarz	5882	6990	-15.85
Sołacz	7950	8789	-9.55

In each of the analysed districts, the median of property transactional prices is lower among those located in the restricted use zone, compared to those located outside the zones. However, based on the median of prices, one cannot derive any significant conclusions about the influence of the analysed factors on the property price, as it does not include the most important features that significantly determine the price.

A multi-factor analysis of the price function was applied in order to include several analysed factors affecting the property price. With regard to property prices, the most frequently used is the hedonic method. Therefore, to determine the impact of the restricted use zone on property prices, the hedonic regression was conducted. The selection of variables applied in the model resulted, among others, from the availability of data. The study used the following variables: location, neighbourhood, the form of ownership, upper-floor location, surface area and aircraft noise (Table 4).

Table 4. The values of qualitative and quantitative variables applied in the model

Variable	Symbol	Characteristics of the feature
Location (district)	d_1 – Poznań Centrum, d_2 – Górczyn, d_3 – Grunwald, d_4 – Jeżyce, d_5 – Łazarz, d_6 – Nowe Miasto, d_7 – Piątkowo, d_8 – Rataje, d_9 – Sołacz, d_{10} – Stare Miasto, d_{11} – Wilda, d_{12} – Winiary, d_{13} – Winogrady	13 variables were assumed – if the property is located in a given district, it adopts the value of 1. For the remaining variables, the value amounts to 0.
Neighbourhood	s_1 – neighbourhood	One variable was assumed. If the apartment is located in a well-developed neighbourhood, it receives the value of 1. Otherwise, the value amounts to 0.
Form of ownership	w – ownership	If the apartment is the subject of ownership, it receives the value of 1. Otherwise, the value amounts to 0.

Table 4. cont.

Variable	Symbol	Characteristics of the feature
Upper-floor location	pp – upper-floor location	The variable assumes the value of 1 for a location on the first, or higher floors if the building has an elevator. Otherwise, the value amounts to 0.
Surface area	pow – useful floor area	Useful floor area measured in square meters.
Aircraft noise	hl – restricted use zone	Two variables of the feature were adopted. If the property is located in an area where aircraft noise exceeds 55 dB, it receives the value of 1. Otherwise, the value amounts to 0.

In the following stage, appropriate function parameters were estimated with the use of RStudio software. Both the property price included in the model, as well as the analysed attributes, were explanatory variables.

Table 5. Estimation of function parameters, dependent variable – price

	Coefficient	Standard error	T-value	P-value
constant	8.92497	0.08937	99.863	< 2.00E-16
d_1	-0.05911	0.03150	-1.877	0.06075
d_2	0.06738	0.03137	2.148	0.03189
d_3	-0.06613	0.03165	-2.089	0.03683
d_4	-0.02831	0.03195	-0.886	0.37577
d_5	-0.09761	0.03234	-3.018	0.00259
d_6	-0.07252	0.02965	-2.446	0.01455
d_7	-0.00577	0.03161	-0.183	0.85518
d_8	-0.09141	0.02849	-3.209	0.00136
d_9	0.17095	0.03890	4.394	1.19E-05
d_{10}	0.10581	0.03136	3.374	0.00076
d_{11}	-0.02647	0.03139	-0.843	0.39914
d_{12}	0.14069	0.03395	4.144	3.61E-05

Table 5. cont.

	Coefficient	Standard error	T-value	P-value
constant	8.92497	0.08937	99.863	< 2.00E-16
S1	0.08404	0.01501	5.598	2.56E-08
w	0.06381	0.02035	3.136	0.00175
pp	0.12829	0.01497	8.571	<2.00E-16
pow	-0.05606	0.02107	-2.661	0.00788
hl	-0.04578	0.02401	-1.907	0.05668

The analyses conducted on the basis of collected data did not allow for the identification of one of the coefficients for variable d_{13}, due to its absent differentiation. The difference between the observed values and the dependent variable defined by the standard error amounted to 0.2468, with 1528 degrees of freedom.

Based on the conducted analyses, it can be observed that in the examines period (2020), the residential property prices were significantly affected by their location in specified districts of Poznań. Location in the districts of Sołacz, Stare Miasto and Winiary was particularly important for the increase in prices. Moreover, while analysing the results, one can undeniably state that the price was significantly influenced by its closest neighbourhood and upper-floor location (Table 5).

Moving to the main purpose of this paper, the explanatory variable related to aircraft noise is statistically significant. The application of the hedonic regression based on the natural logarithm allowed for the identification of the percentage change in the difference of property prices with comparable characteristics, located in the area exposed to noise above 55 dB, as well as below this value. The coefficient of the feature (hl) assumed the value of -0.04578 (Table 5), which indicates that premises exposed to aircraft noise on average, adopt a value lower than 4.58%, compared to properties located outside the impact zone of the airport.

6. Discussion of the results

The study conducted within the framework of this paper constitutes one of the first studies related to the analysis of the impact of aircraft noise on the value of the residential properties in Poland. The vast majority of available studies involve the analysis of the impact of airport proximity, primarily in the United States (Cohen & Coughlin 2009, McMillen 2004), Western European countries (Püschel & Evangelinos 2012, Le Boennec & Salladarré 2017) and Canada (Maguire & El-Geneidy 2018).

A direct comparison of the obtained results with the previous studies may be restricted due to the differences in the location of the airport or the conditions of the local property market. The fact that the analysis covered a specific type of property should be taken into consideration as well. Taking into account the study (Trojanek et al. 2017) presenting the correlations between aircraft noise and prices of different types of properties within a single market, it should be emphasised, that the impact of this feature may vary. As a consequence, the obtained results and conclusions formulated on their basis, apply solely to the residential properties.

However, referencing to the existing studies which summarise the previous research on the impact of aircraft noise on the property value (Wadud 2013, Kopsch 2016, Batóg & Foryś & Konowalczuk 2019), one can notice a certain similarity between the results obtained in this study and the literature on the subject. The conducted analyses allowed for the identification of a statistically significant, negative impact of the airport's proximity on the property value, similarly to recent studies (Zheng et al. 2020, Bełej et al. 2020, Cellmer et al. 2019).

The analysis was performed according to the modified methodology, relating to the previous analyses (Huderek-Glapska & Trojanek 2013, Trojanek et al. 2017). Within the framework of this study, the variable related to aircraft noise was defined by two variables. As a result of preliminary analyses, it was possible to identify that, due to the criteria by which the existing restricted use zones in both local airports are designated, the ones located in areas where the value of aircraft noise exceeds 55 dB are particularly exposed to noise. In connection with the adopted criteria, we have determined how the location in the area in which the value exceeds 55 dB affects the transaction prices.

The analyses were conducted based on the 2017 noise map of Poznań. The obtained results are properly justified, there are some certain limitations to the solution mainly resulting from the lack of data. In this situation, the problem may arise in connection with the validity of data, as the noise maps are prepared in a five-year perspective. Therefore, the analyses were performed in accordance with the available materials, which, however, are not necessarily consistent with the actual state of affairs during the research. It is necessary to consider the fact that the acoustic conditions in the city may change over time as a result of, among other things, the intensification of air traffic. The obtained results may not be valid in the following years, due to modifications in actual conditions. Moreover, the restrictions of the presented method may be related to the fact that the impact of proximity to airports in other regions/cities of Poland may be different as it depends on local conditions. Finally, it is worth noting that the research area covers several districts of Poznań, which means it doesn't take up much area. Consequently, it is difficult to draw universal conclusions that could be formulated for other larger study sites. Monitoring of the impact of aircraft noise on the property market should be conducted in a continuous and systematised manner, which enables the observation of dependencies occurring over a longer period of time.

7. Conclusions

1. The application of a logarithmic model allows for determining the percentage difference in the transaction price of a residential unit, located within a zone particularly exposed to noise (55 dB), as well as outside that zone.
2. Within the local property market, aircraft noise constitutes a statistically significant attribute reducing the prices of premises.
3. Properties are considered to be special goods. Their price is influenced by several of factors, resulting directly from the local character of the property market.
4. The manner in which the selected attributes interact with one another may vary, depending on the type and spatial extent of the property market. The impact of relevant factors on price may also vary with time and local planning, social and economic conditions.

References

Bateman, I., Day, B., Lake, I. & Lovett, A. (2001). The Effect of Road Traffic on Residential Property Values: A Literature Review and Hedonic Pricing Study. *Scottish Executive Transport Research Series*. The Stationary Office, Edinburgh.

Batóg, J., Foryś, I., Gaca, R., Głuszak, M. & Konowalczuk, J. (2019). Investigating the Impact of Airport Noise and Land Use Restrictions on House Prices: Evidence from Selected Regional Airports in Poland. *Sustainability*, *11*, 412.

Batóg, J., Foryś, I. & Konowalczuk, J. (2019). Airport noise compensation: real estate perspective. *Journal of European Real Estate Research*, *12*(2), 250-266.

Bełej, M., Cellmer, R. & Głuszak, M. (2020). The Impact of Airport Proximity on Single-Family House Prices-Evidence from Poland. *Sustainability, 12*(19), 7928. DOI: https://doi.org/10.3390/su12197928

Bishop, R., Laing, K. (2020). Impact of Airport Noise on Residential Property Values: Cairns Airport. *Journal of New Bussiness Ideas & Trends*, *18*(1), 12-20.

Bobrova, A. V., Stepanov, E., A. (2019). Model (Methodology and Calculation Formula) Combining the Influencing Factors of Transport Logistics Efficiency and Advantages by Type of Transport for Risk Reduction and Decision-making When Choosing the Best Routes. *Journal of Advanced Research in Law and Eonomics*, *10, 2*(40), 448-460. DOI:10.14505/jarle.v10.2(40).04

Cellmer, R., Bełej, M. & Konowalczuk, J. (2019). Impact of a Vicinity of Airport on the Prices of Single-Family Houses with the Use of Geospatial Analysis. *ISPRS International Journal of Geo-Information*, *8*(11), 471.

Chalermpong, S., Klaiklueng, A. (2012). Valuing Aviation Noise with the Contingent Valuation Method: Case of Suvarnabhumi Airport, Bangkok, Thailand. *Transportation Research Record: Journal of the Transportation Research Board*, *2300*(1), 42-48.

Cohen, J.P., Coughlin, C.C. (2009). Changing noise levels and housing prices near the Atlanta airport. *Growth Chang*., *40*, 287-313.

Dube, K., Nhamo, G. (2020). Major Global Aircraft Manufacturers and Emerging Responses to the SDGs Agenda. Scaling up SDGs Implementation, *Springer*, 99-113. DOI: https://doi.org/10.1007/978-3-030-33216-7_7

Eves, Ch., Blake, A. (2016). The impact of aircraft noise and complaints on Brisbane residential property performance. In Hefferan, M (Ed.) Proceedings of the 22nd Pacific Rim Real Estate Society (PRRES) Annual Conference. *Pacific Rim Real Estate Society (PRRES)*, http://www.prres.net/, 1-12.

Huderek-Glapska, S., Trojanek, R. (2013). The impact of aircraft noise on house prices. *Int. J. Acad. Res. Int. J. Acad. Res*. Part B, 5, 397-408.

Kopsch, F. (2016). The cost of aircraft noise – Does it differ from road noise? A meta-analysis. *Journal of Air Transport Management*, *57*, 138-142.

Le Boennec, R., Salladarré, F. (2017). The impact of air pollution and noise on the real estate market. The case of the 2013 European Green Capital: Nantes, France. *Ecol. Econ. 138*, 82-89.

Maguire, M., El-Geneidy, A. (2018). The impact of changes in airport noise contours on residential sales: A multilevel longitudinal analysis for Montréal-Pierre Elliott Trudeau International Airport (No. 18-01067).

Acoustic map 2017 for the city of Poznań. Online access: https://www.poznan.pl /mim/wos/-,p,11105,40435.html (access date: 08.11.2020).

McMillen, D. P. (2004). Airport expansions and property values: The case of Chicago O'Hare Airport. *Journal of Urban Economics*, *55*, 627-640.

Nelson, J. P. (2004). Meta-Analysis of Airport Noise and Hedonic Property Values: Problems and Prospects. *J. Transp. Econ. Policy*, *38*, 1-28.

Nguy, A., Sun, C. & Zheng, S. (2014). Airport noise and residential property values: Evidence from Beijing. In Proceedings of the 17th International Symposium on Advancement of Construction Management and Real Estate. *Springer: Berlin/Heidelberg*, Germany, *1*, 473-481.

Podawca, K., Staniszewski, R. (2019). Impact of Changes of the Permissible Railway Noise Levels. *Rocznik Ochrona Środowiska*, *21*(2), 1378-1392.

Environmental protection programme against noise 2018. (Dz. Urz. Woj. Wlkp. of the 2018 r. poz. 5498 and 7984). Online access: https://www.poznan.pl/mim/wos/ program-ochrony-srodowiska-przed-halasem-2018,11105,43243.html (access date: 10.11.2020).

Püschel, R., Evangelinos, Ch. (2012). Evaluating noise annoyance cost recovery at Düsseldorf International Airport. *Transportation Research Part D: Transport and Environment, 17*(8), 598-604.

Radzewicz, A., Wiśniewski, R. (2012). Property variables, characteristics and attributes. *Studia i Materiały Towarzystwa Naukowego Nieruchomości*, *20*(1), 5-14 (in Polish).

Rosen, S. (1974). Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition. *J. Political Econ*., *82*, 34-55.

Schipper, Y., Nijkamp, P. & Rietveld, P. (1998). Why do aircraft noise value estimates differ? A meta-analysis. *J. Air Transp. Manag.*, *4*, 117-124.

Thanos, S., Bristow, A. L. & Wardman, M. R. (2012). Theoretically consistent temporal ordering specification in spatial hedonic pricing models applied to the valuation of aircraft noise. *Journal of Environmental Economics and Policy*, *1*(2), 103-126, DOI: 10.1080/21606544.2012.692862

Trojanek, R. (2014). The impact of aircraft noise on the value of dwellings – The case of Warsaw Chopin airport in Poland. *J. Int. Stud*., 7.

Trojanek, R., Tanas, J., Raslanas, S. & Banaitis, A. (2017). The Impact of Aircraft Noise on Housing Prices in Poznan. *Sustainability*, *9*, 2088.

Wadud, Z. (2013). Using meta-regression to determine Noise Depreciation Indices for Asian airports. *Asian Geogr., 30*, 127-141.

Winke, T. (2017). The impact of aircraft noise on apartment prices: a differences-in-differences hedonic approach for Frankfurt, Germany. *Journal of Economic Geography*, *17*(6), 1283-1300. DOI: https://doi.org/10.1093/jeg/lbw040

Zellmann, Ch., Bertsh, L., Schwab, O., Wolters, F. & Delfs, J. (2019). Aircraft noise assessment of next-generation narrow-body aircraft. *Institute of Noise Control Engineering*, InterNoise19, 6389-6400(12).

Zhang, F., Graham, D. J. (2020). Air transport and economic growth: a review of the impact mechanism and causal relationships. *Transport Reviews, 40*(4), 506-528, DOI: 10.1080/01441647.2020.1738587

Zheng, X., Peng, W., & Hu, M. (2020). Airport noise and house prices: A quasi-experimental design study. *Land Use Policy*, *90*, 104287.

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Impact of Nitrogen Oxides Emission Reduction Methods on Specific Fuel Consumption of Marine Diesel Engines

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Abstract The paper has been presented the methods of nitrogen oxides emission reduction to fulfill the Tier 2 and Tier 3 requirements of the Annex VI of MARPOL Convention. It has been shown the development of marine two-stroke diesel engines and the change of nitrogen oxides emission from 1960 to 2000 and later up to 2020 after the implementation of NO_x emission reduction methods. Specific fuel consumption before 2000, and as a prediction and given data in the manufacturers manuals for Tier 3 engines up to 2020, and as only a prediction up to 2030 has been analyzed and elaborated. Impact of nitrogen oxides reduction methods on the specific fuel consumption of the marine diesel engine has been evaluated. Additional emission of some gases to the atmosphere due to the implementation of reduction methods has been determined. EGR and SCR systems have got a lot of imperfections: required to install additional reduction systems (investment cost, required volume in the engine room), need maintenance and operation costs, produced wastes during treatment process. The estimated additional cost is about 0.8 USD/MWh of produced energy, taking into account only the cost of excessive used fuel. The whole increased cost may reach the level two-three times more due to cleaning systems investment costs, their operational cost and waste disposal. It has been the one of the reasons of worsening the transport effectiveness and competitiveness.

Keywords: ship operation: marine slow and medium speed diesel engine, emission to atmosphere, nitrogen oxides, nitrogen oxides emission reduction: specific fuel consumption

1. Introduction

The limited level of nitrogen oxides (NO_x) emission is a requirement due to Annex 6 of the International Convention on the Prevention of the Pollution from Ships, known as MARPOL 73/78 (IMO 1997, IMO 2005, IMO 2008b). The revised Annex 6, prepared in 2008, entered into force on 1st July 2010 (IMO 2008a). The amendments introduced:

- new fuel quality requirements beginning from 1st July 2010,
- Tier II and III emission standards for new built marine engines,
- Tier I requirements for existing pre-2000 engines.

It may be seen that global requirement is the Tier II, more stringent requirements applicable to ships in Emission Control Areas (ECA). On 1st January 2021 existing Emission Control Areas include (ABS 2015, ABS 2017, Dulebenets 2016, IMO 2018, IMO 2019):

- Baltic Sea (SO_x: adopted 1997, entered into force 2005; NO_x: 2016/2021),
- North Sea (SO_x: 2005/2006; NO_x: 2016/2021),
- North American ECA, including most of US and Canadian coast (NO_x & SO_x: 2010/2012),
- US Caribbean ECA, including Puerto Rico and Virgin Islands (NO_x & SO_x: 2011/2014).

Looking for undertaken measures to fulfill the requirements of Tier II, it may be enumerated the following methods: combustion process optimization, fuel injection timing, limitation of maximal combustion pressure, optimization of fuel nozzle flow area, implementation of electronic injection systems (with common rail), exhaust valve timing, change of cylinder compression volume etc. Because the Tier III NO_x emission requirement is four times lower than Tier II, the following technologies should be introduced: fresh water induction into the combustion process (with fuel as fuel-water mixture, wet scavenging air, or in-cylinder direct injection), exhaust gas recirculation (EGR), or selective catalytic reduction (SCR) systems (Herdzik 2011, Herdzik 2019, IMO 2009, IMO 2015). The target is to reach the emission limits according to various types of engine testing procedures incorporated in (Dieselnet 2021, ISO 2020). Engine emissions are tested on various cycles: E2 & E3 for various types of propulsion engines, D2 for constant speed auxiliary engines, C1 for variable speed and load auxiliary engines. Because the emission is measured in specified points of load and/or engine rotational speed, addition of "not-to-exceed" (NTE) testing requirements to the Tier III standards is being debated. NTE limits with a multiplier of 1.5 would be applicable to NO_x emissions at any individual load point in the E2/E3 cycle. Further technical details pertaining to NO_x emissions, such as emission control methods, are included in the mandatory "NO_x Technical Code" (IMO 2005, IMO 2019, IMO 2021, PRS 2020). As it was above mentioned, all new built marine diesel engines after 2010, should comply the Tier II limits. Complying the Tier III requires an implementation of additional systems. As important, currently the Tier III requirements should be fulfilled only on appointed ECA areas, outside ECA areas the same engines may work on Tier II limits. It means that the by-pas systems are in use and the earlier mentioned additional systems (EGR or SCR) are switched off. The by-pass systems are necessary in emergency situations as well.

2. Reasons of nitrogen oxides emission reduction on increased specific fuel consumption and performance of marine engines

Till 2000, the target of marine diesel engines manufacturers was the engine reliability, an increasing of engine power and medium effective pressure, a possibility of simple maintenance and the most important to reach the highest thermal and effective efficiency and as a consequence the decreasing of specific fuel consumption, especially in the range of 50-85% of nominal power, where the engines should mostly work. The information about 50-53% for the best marine diesel engine efficiency has been given (MAN 2021).

An implementation of NO_x emission reduction methods have induced disorders leading to the decreasing the engine efficiency and increasing the specific fuel consumption. How it was possible? Due to the main effect of maximal combustion temperature leading to producing the thermal NO_x, it has been decided to reduce the maximal combustion pressure and temperature by (Lloyd's 2002):

- decreasing the cylinder compression volume (geometric compression ratio) and as an effect, decreasing the maximal compression pressure,
- delaying the fuel injection and dividing onto two cycles,
- exhaust valve timing, mainly earlier opening and later closing, leading to engine power reducing.

It leads directly to decreasing the engine thermal efficiency (on a level 1-8% depends on the engine load). The other methods like: optimization of fuel nozzle flow area and implementation of electronic injection systems have a different impact on diesel engine performance.

To achieve the Tier III limits needs more radical steps. Preparing fuel-water mixtures, wet scavenging air and/or in-cylinder water injection cause the decreasing of maximal combustion temperature (due to water evaporation during that process) but increase the mass of work medium, and as a final result, complicate the engine systems having different effect on engine efficiency (approximately without any essential impact on efficiency).

These mentioned methods are not to be sufficient to fulfill the limit of Tier III. It must be implementing one of these (MAN 2012b):

- exhaust gas recirculation (EGR),
- or selective catalytic reduction (SCR) systems.

Exhaust gas recirculation method mixes the fresh compressed air with a part of cleaned and compressed exhaust gases before the inlet to engine (in the scavenge receiver). The rate of exhaust gases comprise from 5 to 30%. Exceeding the 30% of rate leads to significant deterioration of diesel engine performance. Due to addition flow resistance of exhaust gases system and the usage of electric energy for driving the exhaust gas compressor, EGR results in power and efficiency reduction of diesel engine.

Selective Catalytic Reduction method gives an addition flow resistance in exhaust gas system. The resistance is increasing during engine operation due to contamination and choking process inside the flow channels. Increased fuel consumption and decreasing of engine power are the final effect. An operation of SCR system needs an additional preparing process of ammonia or urea solution, control and dosing process to SCR system and possible overdosing the chemicals leading to ammonia slip to the atmosphere (Herdzik 2019).

3. Impact of NO_x emission reduction on specific fuel consumption and efficiency of marine diesel engines

During last 50 years it may be seen a significant development of two stroke low speed marine diesel engines. The output has grown up to 100,000 kW from one engine. From sixties years last century it was possible that only one diesel engine has been used for vessels propulsion. Due to first fuel crisis (seventies years last century) the decision of ship-owners has been to change the type of prime movers of vessels from steam turbines on diesel engines. The efficiency of diesel engines substantially has exceeded the steam turbine efficiency.

Diesel engines have emitted to the atmosphere many different substances, like: carbon dioxide and monoxide, water vapor, sulfur oxides, nitrogen oxides, unburnt hydrocarbons, particulate matters and many others. The emission quantity depends on the engine load, fuel and lubricating oil consumption, engine rotational speed, fuel type used, etc. Sulfur oxides emission has been meaningfully decreased by the usage of low-sulfur fuels or scrubbers. Ship speed reduction has been introduced to marine transport as a simple remedy for constricting shipping costs and CO_2 emission (Chang & Wang 2014, Faber et al. 2012). Carbon dioxide emission from marine transport has been monitored due to (Directive 2015). How to influence CO_2 emission and constrict has been indicated in (MAN 2014).

Typical emission level from the two-stroke marine diesel engines, before introducing the limitations in 2000, has been presented in Table 1.

Table 1. Typical main diesel engine fuel consumption and emission before 2000 per 1000 kWh produced mechanical energy (own elaboration)

Type of main engine	Specific fuel consumption	Lubricating oil consumption	Carbon dioxide emission	Nitrogen oxides emission	Sulfur oxides emission*	Hydrocarbons emission
Low speed, two-stroke	170 kg	1.5 kg	530 kg	17-20 kg	15.3 kg	0.15-0.2 kg

* for 4.5% sulfur content in the heavy fuel oil (HFO)

An implementation, of the NO_x emission reduction from 2000, has been constituted a new era in the diesel engines development (MAN 2018). A usage of different methods constricted NO_x emission has been caused the increase of specific fuel consumption (SFC) and decrease the efficiency of marine diesel engines. Data concerning to SFC and efficiency up to 2020 and between 2000 and 2030 with a prediction for diesel engines performance with and without NO_x limitation has been presented in Table 2.

Table 2. Specific fuel consumption and efficiency of marine diesel engines for vessel's propulsion in 1970-2030, a prediction beyond 2020 (own elaboration)

Year	**1970**	**1975**	**1980**	**1985**	**1990**	**1995**	**2000**
SFC [kg/kWh]	0.213	0.208	0.185	0.178	0.170	0.168	0.170
SFC without NO_x limitation [kg/kWh]	0.213	0.208	0.185	0.178	0.170	0.168	0.160
Efficiency [%]	39.58	40.53	45.57	47.36	49.59	50.18	49.59
Efficiency without NO_x limitation [%]	39.58	40.53	45.57	47.36	49.59	50.18	52.68
Year	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	–
SFC [kg/kWh]	0.167	0.170	0.168	0.165	0.163	0.160	–
SFC without NO_x limitation [kg/kWh]	0.155	0.150	0.147	0.145	0.142	0.140	–
Efficiency [%]	50.48	49.59	50.18	51.09	51.71	52.68	–
Efficiency without NO_x limitation [%]	54.38	56.20	57.34	58.13	59.36	60.21	–

It has been elaborated on a base of accessible information from manuals, and project guides issued by the marine diesel engines manufacturers (Sulzer, B&W, MAN, Mitsubishi, Wartsila and others) from 1970s up to 2020.

It may be seen the difference between SFCs after 2010 on a level of 0.02 kg/kWh. It means that the difference of fuel consumption comprises about 14% and as a consequence the total emission to the atmosphere has been increased at the same level.

4. Additional carbon dioxide emission due to increased fuel consumption as a result of nitrogen oxides reduction systems implementation

An increased specific fuel consumption, due to a use of NO_x emission reduction methods, leads to an additional emission to the atmosphere all substances mentioned above. A profit and loss account for selected parameters has been presented in Table 3. It has been elaborated on a base of information and prediction in Table 2 and (Dulebenets 2016, Herdzik 2019, MAN 2012a, MAN 2012b, MAN 2018).

Table 3. Profit and loss account due to the usage of NO_x reduction methods (own elaboration)

Parameter	profit		loss	
Decreasing of NO_x emission	13.6 g/kWh*	80%		
Specific fuel consumption			20 g/kWh	14%
Additional cost of HFO**			0.8 US¢/kWh 0.8 USD/MWh	
Real decreasing of NO_x emission	11.7 g/kWh	68.8%	1.9 g/kWh	14%
Additional CO_2 emission			62.4 g/kWh	14%
Total CO_2 emission			500 g/kWh	
Electric energy demand for SCR			5 kW/MW SMCR	0.5%
Electric energy demand for EGR blower			7 kW/MW SMCR	0.7%
Diesel engine output				2%

* difference between NO_x emission Tier 1 and Tier 3
** HFO price – 400 USD/mt

It may be seen that a profit of 11.7 g/kWh lower NO_x emission effects on 62.4 g/kWh increased CO_2 emission (it gives 5.3 g CO_2/g NO_x). Other losses – like: additional investment cost of NO_x reduction system, additional required volume in the vessel power plant, operational cost, additional labor expenditure, waste management of residues after cleaning treatment – are not evaluated.

Additional required volume for EGR or SCR systems has a significant meaning during design process of the vessel power plant. Two way approach for Tier 3 engines – EGR and SCR (here - high pressure) has been presented in Figure 1.

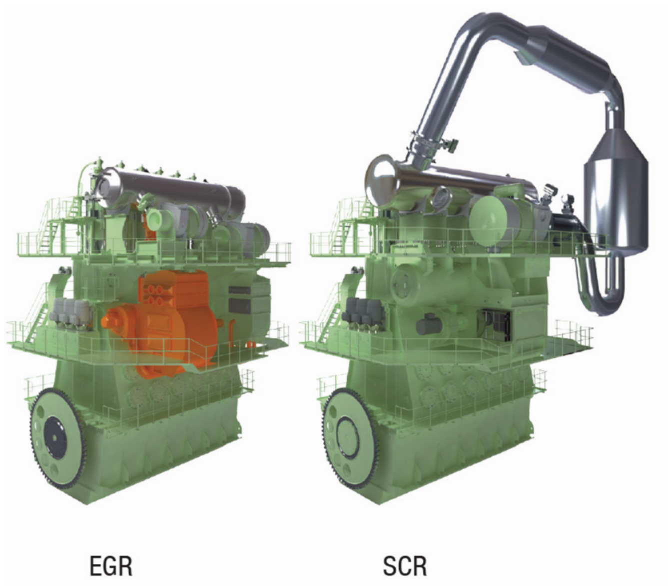

Fig. 1. Two way approach for Tier 3 engines – EGR and SCR solutions (MAN 2012)

5. Environment effect of nitrogen oxides reduction systems operation

Due to the increasing of marine diesel engine power and load through the construction of the bigger cylinder liner diameters, longer piston stroke up to superlong-stroke (stroke/diameter ratio = 4.5) and more number of cylinders (up to 14 for two-stroke and 20 for four-stroke V type engines), and mainly through the increasing mean effective pressure (MEP) starting in 1960s from 6 bar up to 22 bar (for two-stroke) and 27.5 bar (for four-stroke) in 2010s – the NO_x emission has been still increased reaching the level over 20 g NO_x/kWh in 1990s. Two-stroke marine diesel engine NO_x emission development has been shown in Figure 2.

From 2000, it may be seen the process of decreased NO_x emission due to Annex VI of MARPOL 73/78 requirements up to reach the level of Tier 3 on ECA areas.

NO_x reduction emission systems – EGR and SCR, have been caused in the increased fuel consumption. Apart from this fact, it makes an additional fuel cost, it comprises the influence on the marine environment. Decreasing the NO_x emission has had a direct effect on the increasing of CO_2 emission, about 5.3 g CO_2/g NO_x approximately. The global warming potential (GWP) for NO_x is estimated as 30-33 and 7-10 for the respective time horizon 20 and 100 years. So, it may be said that the reduction of NO_x emission decreases, in that part of NO_x effect, about six times the warming effect. The result is that through various processes the nitrogen oxides interact with trace gases in the troposphere and stratosphere which do absorb in the spectral range to the greenhouse effect (infrared wavelengths). Additional result is (Lammel & Grassl 1995) the catalytic role of NO_x in the production of tropospheric ozone provides the most prominent contribution.

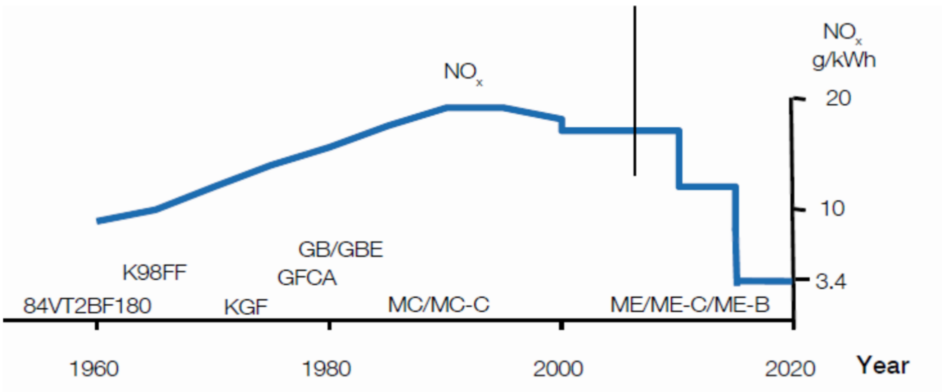

Fig. 2. Engine NO_x emission development (MAN 2014)

An official data for marine two-stroke diesel engine performance only at 75% of nominal load for variations of different EGR system configuration has presented in Table 4. Without EGR system, the engine fulfill the Tier 2 of NO_x emission reduction. A use of EGR system, allows to fulfill the Tier 3 level for tested engine. An increase of SFC (dSFC, SFC penalty) is observed without consideration of required additional electric energy for the EGR auxiliaries. It should be mentioned an increase of carbon monoxide emission from 2 up to 7 times (for max. EGR) and a decrease of oxygen (O_2) content in the scavenge air receiver from 21% down to 16% (average decreased about 21%).

The decreasing of NO_x emission reduction has observed during the tests above mentioned. The investigation on the 4T50ME-X test engine has shown that IMO Tier 3 NO_x compliance is achievable by the use of high pressure EGR system. Additionally, the not-to-exceed (NTE) level of 5.1 g NO_x/kWh was obtained at each engine load point 25, 50, 75 and 100%. The obtained results has shown in Fig. 3 (sign ◆ means the points at 100% of load).

Similar effects of NO_x emission reduction may be obtained by the use of the Selective Catalytic Reduction (SCR) system (MAN 2012a, MAN 2012b, MAN 2018).

Table 4. Test results from 4T50ME-X engine parameter variations at 75% engine load (MAN 2012b)

	NO_x (g/kWh)	dSFC* (g/kWh)	CO (g/kWh)	P_{max} (bar a)	EGR rate (%)	O_2 (vol. %)
No EGR	17.8	0	0.65	152	0	21
Max. EGR	2.3	+4.9	4.17	151	39	16
EGR ref.	3.7	+3.0	2.57	151	36	16.8
Incr. P_{comp}/P_{scav}	4.0	+2.5	2.18	156	36	16.8
Incr. P_{hyd}**	4.2	+2.8	1.83	151	37	16.6
Incr. P_{scav}	3.6	+1.9	2.12	156	37	16.6
Incr. T_{scav}	3.9	+3.6	2.82	156	34	16.8
Tier 3 setup	3.4	+0.6	1.34	157	41	16.2

* auxiliary power for EGR lower, separator and pumps are not included in dSFC, SFC penalty
** hydraulic pressure in fuel system

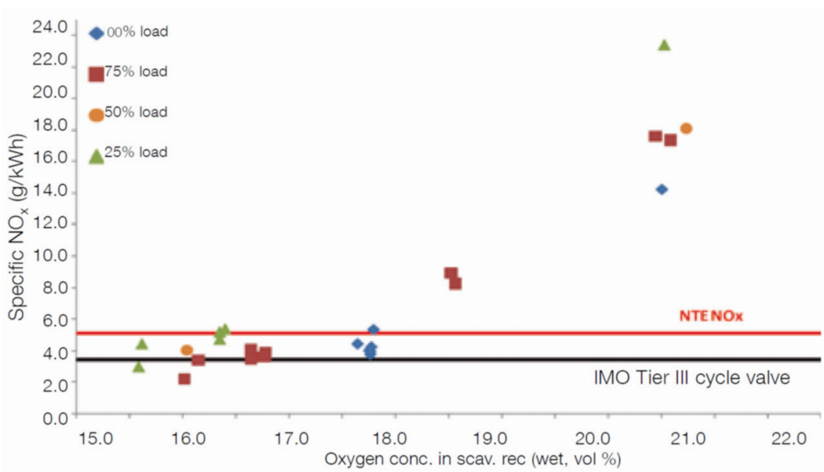

Fig. 3. NO_x emission at different 4T50ME-X engine loads as a function of oxygen content in the scavenge air (MAN 2012b)

Very interesting results have been achieved during the test bed investigation of marine diesel engine operating on ammonia (MAN 2020). Full decarbonization of marine fuels is the aim. Ammonia seems to be an attractive product as a marine fuel, more accessible and transport friendly than hydrogen or methane (LNG or CNG). Physical and chemical properties of anhydrous ammonia govern many of the design aspects of an ammonia-fueled propulsion system and auxiliary systems.

6. Final remarks

Searches, for the fuel additives preventing the NO_x emission, have turned out fruitless. Forementioned, applied methods, lowering the nitrogen oxides emission to atmosphere to required limits from marine diesel engines, have had an essential impact on their performance and specific fuel consumption.

They have got a lot of imperfections: required to install additional reduction systems, need maintenance and operation costs, produced wastes during treatment process and the most important – increased the total fuel consumption (on a level 2-10%) and decreased the available power of the marine diesel engines (on the level 1-5%). The estimated additional cost is about 0.8 USD/MWh of produced energy, taking into account only the cost of excessive used fuel. The whole increased cost may reach the level two-three times more. It has been the one of the reasons of worsening the transport effectiveness and competitiveness.

It may be seen, the NO_x emission reduction methods have been increased the emission to the atmosphere other substances like: carbon dioxide, carbon monoxide, ammonia (the slip from SCR systems).

Improvement of NO_x reduction emission methods is a challenge for the engine manufacturers and researchers.

References

ABS (2015), Nitrogen Oxides (NO_x) Emission Compliance Inside Emission Control Areas (ECAs), ABS, Dec 2015.

ABS (2017), Guide for exhaust emission abatement, American Bureau of Shipping, Jan 2018.

Chang, C. & Wang, C. (2014). Evaluating the effects of speed reduce for shipping costs and CO_2 emission. *Transportation Research Part D: Transport and Environment 31*, 110-115.

Dieselnet (2021). https://dieselnet.com/standards/cycles/iso8178.php (accessed: 04th January, 2021).

Directive (2015), 2015/757 of the European Parliament and of the Council of 29 April 2015, as amended by Delegated Regulation 2016/2071 on monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amended Directive 2009/16/EC.

Dulebenets, M.A. (2016). Advantages and disadvantages from enforcing emission restrictions within emission control areas. *Maritime Business Review 1*(2), 107-132.

Faber, J., et al. (2012). Regulated Slow Steaming in Maritime Transport, An Assessment of Options, Costs and Benefits, Delft.

Herdzik, J. (2011). Emissions from Marine Engines versus IMO Certification and Requirements of Tier3. *Journal of Kones Powertrain and Transport, 18*(2), 161-167.

Herdzik, J. (2019). Problems of Nitrogen Oxides Emission Decreasing from Marine Diesel Engines to Fulfill the Limits of Tier 3, *Rocznik Ochrona Środowiska, 21*, 659-671.

IMO (1997). Regulations for the Prevention of Air Pollution from Ships – Resolution 2, the Technical Code on Control of Emission of Nitrogen Oxides from Marine Engines (NO_x Technical Code). Protocol of 1997 to MARPOL 73/78 – Annex VI.

IMO (2005). Amendments to the Annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the protocol of 1978 relating thereto (Amendments to MARPOL Annex VI and the NO_x Technical Code). IMO Resolution MEPC.132(53).

IMO (2008a). Amendment to the Annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the protocol of 1978 relating thereto (Revised MARPOL Annex VI), IMO Resolution MEPC.176(58).

IMO (2008b). Amendments to the Technical Code on Control of Emission Nitrogen Oxides from Marine Diesel Engines (NO_x Technical Code, 2008), IMO Resolution MEPC.177(58).

IMO (2009). Guidelines for Exhaust Gas Cleaning Systems, IMO Resolution MEPC. 184(59).

IMO (2015). Guidelines for Exhaust Gas Cleaning Systems, IMO Resolution MEPC. 259(68).

IMO (2018). To Reduce Greenhouse Gas Emission From International Shipping, IMO Action 2018.

IMO (2019). *http://www.imo.org/en/OurWork/Environment/PollutionPrevention/ AirPollution/Pages/GHG-Emissions.aspx* (accessed: 15th March, 2019).

ISO (2020). Reciprocating internal combustion engines – Exhaust emission measurement – Part 1: Test-bed measurement systems of gaseous and particulate emissions, ISO 8178-1:2020.

IMO (2021). https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NO_x)-%E2%80%93-Regulation-13.aspx (accessed: 04th January, 2021).

Lammel, G., Grassl, H. (1995). Greenhouse effect of NO_x. *Environ Sci Pollut Res Int*. DOI: 10.1007/BF02987512.

Lloyd's (2002). Emissions of Nitrogen Oxides from Marine Diesel Engines. Questions and Answers, Lloyd's Register of Shipping.

MAN (2012a). Emission Project Guide, MAN B&W Two-stroke Marine Engines, MAN Diesel & Turbo, Copenhagen, Jun 2013.

MAN (2012b). Tier III two-stroke technology, MAN Diesel & Turbo, Copenhagen.

MAN (2014). How to influence CO_2, MAN Diesel & Turbo, Copenhagen.

MAN (2018). Emission Project Guide MAN B&W Two-stroke Marine Engines, MAN Energy Solutions, 9th Edition, Oct 2018.

MAN (2020a). MAN B&W two-stroke engine operating on ammonia, MAN Energy Solutions, Nov 2020, Denmark.

MAN (2021). Low-speed engines, 2021, https://www.wingd.com/en/documents/general/ brochures/wingd-low-speed-engines-booklet-2021.pdf (accessed: 24th May, 2021).

PRS (2020). Przepisy nadzoru konwencyjnego statków morskich, część IX, Ochrona Środowiska. Polish Register of Shipping, Gdańsk (in Polish).

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Treatment of Craft Brewery Sewage with SS VF and FWS Constructed Wetland – Lab Scale Experiment

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Abstract: The problem of wastewater treatment from craft breweries emerged in Poland about 10 years ago when an increase in the number of small breweries was observed. Plants located in small towns are forced to solve the problem on their own. One of the possibilities is to use low-cost technology of constructed wetlands with subsurface and surface flow. The purpose of the research was to test the possibility of effective treatment of sewage from a craft brewery in a lab-scale research installation and to determine the parameters for designing a real scale plant. Wastewater from the Waszczukowe brewery was used in the study. The research system consisted of a retention and aeration tank, SS-VF subsurface flow and FWS surface flow beds. An innovative Certyd filling produced by LSA company was used. The high efficiency of SS-VF bed and the entire research system was found. The removal efficiency in SS VF was on average 89.7% for BOD5, 90.5% for COD, 54.6% for TN and 52.1% for TP. For whole treatment it was respectively 97.1%, 96.7%, 72.6% and 61.3%. A high organic matter removal effect was found for the SS-VF bed (87.1 g BOD_5 m^{-2} d^{-1}) and a relatively low for the FWS (3.0 BOD_5 g m^{-2} d^{-1}). The study confirmed the need for plant design based on hydraulic load and required load removed per unit area.

Keywords: craft brewery, sewage treatment, constructed wetlands, subsurface and surface flow system

1. Introduction

According to a report by the Polish Craft Brewers Association, the share of craft beers in total beer production in Poland was about 0.4-0.5% in 2018. The estimated production was about 200000 hl with the total beer production in Polish breweries amounting to about 41 million hl in 2017. Currently, the number of craft breweries in Poland is approaching 500 (Wojtyra & Grudzień 2017).

The amount of wastewater generated by craft breweries in relation to the product unit (hl) does not differ significantly from the amount characteristic for large corporate breweries. Assuming a ratio of about 5 hl of wastewater per 1 hl of beer produced, it can be estimated that craft breweries generated about 100,000 m^3 of wastewater in 2017. While this is a small amount, it can be a significant impediment for investors who plan to locate breweries outside of urban areas without access to sewage network system. Water can be drawn from the brewery's own intakes or from the water supply network, which is usually fed by good quality groundwater, but properly addressing wastewater management is one of the most important environmental issues.

Assuming that one craft brewery in Poland produces about 3000 to 6000 hl of beer per year, the daily amount of wastewater is about 5-10 m^3. Irrespective of the size of the brewery, this sewage has to be disposed either in the sewer network and the municipal wastewater treatment plant (WWTP), or in the brewery's individual WWTP. Craft breweries located in large cities are in the best situation as they can discharge their wastewater to municipal WWTPs. Small amounts of wastewater in relation to the total amount of wastewater discharged from the city have no impact on the treatment process in large WWTPs utilizing sludge activated system. Larger breweries use anaerobic pretreatment of wastewater before its discharging into the sewer system, obtaining biogas for electricity generation (Umiejewska 2019, Simate et al. 2011, Driessen & Vereijken 2003, Enitan et al. 2014, BAT 2008, Okunola et al. 2019). In the case of small towns with daily flow up to a few hundred cubic meters per day, even a small amount of wastewater from a craft brewery can significantly interfere with the proper operation of the WWTP (Dąbrowski 2009). One solution is to use retention tanks which allow the wastewater to be evenly discharged to the sewer network and the municipal WWTP.

During authors research conducted since 2018 on the composition and treatment capabilities of craft brewery wastewater using a system based on a trickling filter and subsurface vertical flow constructed wetland (SS VF) has shown that the wastewater has significantly higher organic content and nutrient concentrations compared to domestic and municipal wastewater.

The craft brewery wastewater used in this study had values in the range of: BOD_5 1940-2360 mg O_2 dm^{-3}, COD 3600-4200 mg O_2 dm^{-3}, TN 37.2-52.0 mg dm^{-3} and TP 19.8-28.0 mg dm^{-3} (Dąbrowski & Karolinczak 2019). Similar effluent parameters are confirmed by different authors (Janczukowicz et al. 2013, Umiejewska 2019, Mielcarek et al. 2013).

A separate problem of craft breweries that is not present at large industrial breweries is the periodicity of production. A typical craft brewery is characterized by frequent production interruptions, a normal phenomenon resulting from the specific nature of these plants. However, this causes limitations in the application of wastewater treatment technology based on the sludge activated system, which requires a constant supply of wastewater. Therefore, it is advisable to look for other solutions that can be used for treatment or pretreatment of this type of brewery wastewater.

One alternative method is constructed wetlands (CWs) technology. It has a number of advantages, including being immune to periodic wastewater supplying. CWs are characterized by simple construction and operation, properly constructed can provide a high treatment effect with very low energy consumption compared to conventional systems such as activated sludge or trickling filter (Kolecka et al. 2018, Karolinczak et al. 2015). Pollutants removal is possible, thanks to creating specific conditions allowing the plants' growth, as well as intensifying the processes of oxidation, reduction, sorption, precipitation, sedimentation and assimilation. Currently, SS VFs are the most widespread and are used, among others, to treat domestic wastewater, rainwater, septage, wastewater from selected industries or specific wastewaters such as leachate from landfills, from sludge treatment (Kadlec & Wallace 2009, Karolinczak & Dąbrowski 2017, Obarska-Pempkowiak et al. 2015, Vymazal 2010, Karolinczak et al. 2020). Only a few applications of CWs can be found for treatment of brewery sewage (Massi et al. 2018, Kadlec & Wallace, 2009).

Due to limited information on the application of CWs systems for brewery wastewater treatment, it was decided to precede the real-scale studies with a laboratory-scale experiment. The objective of this study was to determine the effectiveness of a SS VF and free water surface (FWS) bed system with floating plants. The results of the research will be used to design a full scale installation for a craft brewery wastewater treatment.

2. Methods and research installation

Wastewater used in this study originated from Waszczukowe brewery with annual production of 5000 hl. It is one of the largest craft breweries in Podlaskie province. The average volume of wastewater in 2019 was about 9 m^3/d, and the ratio of wastewater volume per unit of production was 5.6 hl/hl of beer and was similar to the values characteristic for the concern breweries (Janczukowicz et al. 2013).

Wastewater treatment process studies were conducted in the laboratory of the Department of Technology in Environmental Engineering at BUT from November 2019 to March 2020. The research installation was designed by one of the authors using earlier experience with different kinds of sewage treated with CWs system. Its main elements are: SS VF planted with *Phragmitiesaustra*lis and FWS with floating plants: *Salvinia natans*. The installation also includes a retention - aeration tank (RAT) and pump supplying FWS with sewage treated in SS VF. The beds were used in series. Research installation with sampling points (I-IV) is presented in Figure 1, view of the beds and cross section of SS VF in Figure 2. SS VF bed with total highest 0.8 m, was built of three layers (A, B, C) of lightweight sintered aggregate *Certyd* with a granulation of 3 to 9 mm. The use of *Certyd* instead of gravel and sand has a significant environmental impact. It is a ceramic and porous material obtained by the thermal processing of ash. It has a certificate from the National Institute of Hygiene HR/B/86/2015.

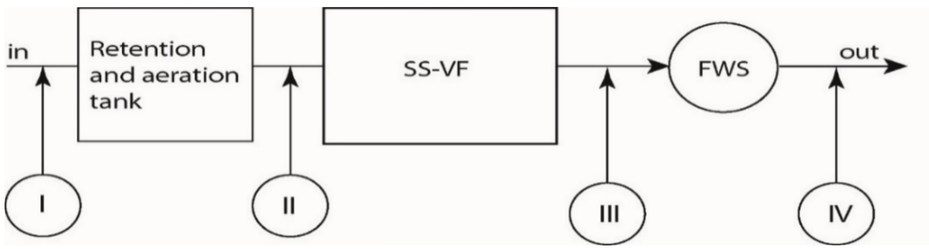

Fig. 1. Research installation with sampling points

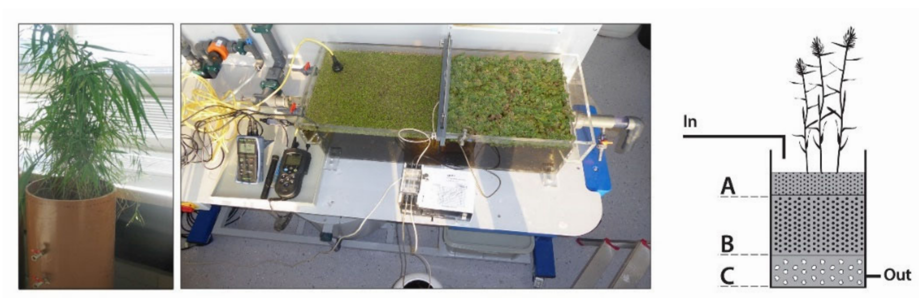

Fig. 2. View on SS VF and FWS and cross section of SS VF

The experiment was conducted at approximately 20°C with a hydraulic load of 0.05 $m^3m^{-2}d^{-1}$ for the SS VF bed and 0.035 $m^3m^{-2}d^{-1}$ for the FWS beds. The hydraulic retention time (HRT) for the FWS was approximately 3 days. Before starting the experiment, the whole installation was started-up for one month.

2.1. Sampling and analytical procedures

During the study period, 12 test series were performed, each including the determination of raw wastewater parameters (sampling point I), wastewater feeding the SS VF and FWS (sampling points II and III) and treated wastewater (sampling point IV). Concentrations of organic matter (BOD_5, COD), total nitrogen (TN), ammonia nitrogen (NH_4-N), nitrate nitrogen (N-NO_3) and nitrite nitrogen (N-NO_2) and total phosphorus (TP) were analysed. In addition, dissolved oxygen concentration and pH were monitored. Determinations were conducted in a BUT laboratory in accordance with the procedures set out in the Regulation of the Minister of Maritime and Inland Waterway Economy from 12th July 2019 and in accordance with the American Public Health Association APHA (2005). Tests for the analysis of COD, TN, NH_4-N, NO_3-N, N-NO_2 and TP recommended by Merck were applied. Spectrophotometer Spectroquant Pharo 100 was used. BOD_5 was determined using OXI-TOP®.

The scope of the research made it possible to determine the pollutant loads removed at particular stages and in the entire treatment system. Removal efficiency was calculated as a concentration reduction according to the terminology given by Kadlec & Wallace (2009).

3. Results and discussion

The largest impact on the amount and load of wastewater generated in the brewery is generated by washing processes. This is characteristic of agri-food plants (Żyłka et al. 2020). Large breweries generally use Cleaning in Place (CIP) stations, while most small breweries do not use them. This affects possible higher raw wastewater parameters, especially TP concentration. Analyzing the parameters of raw wastewater from the Waszczukowe brewery (Table 1) it can be concluded that the values obtained do not differ from those presented by other authors dealing with wastewater from other breweries (Driessen & Vereijeken 2003, Simate et al. 2011, Enitan et al. 2014, Janczukowicz et al. 2013, Budgen & Le-Cech, 2020).

Table 1. Characteristics of raw sewage from craft brewery plant (sampling point I)

Parameter	Unit	Mean ±st. dev.	Min-max
BOD_5	mg O_2 dm^{-3}	1942 ±75	1807-2050
COD	mg O_2 dm^{-3}	3704 ±206	3480-4030
N-NH_4	mg N-NH_4 dm^{-3}	7.5 ±1.1	4.9-9.2
N-NO_3	mg N-NO_3 dm^{-3}	1.0 ±0.2	0.6-1.4
TN	mg N dm^{-3}	42.1 ±3.5	37.0-49.0
TP	mg P dm^{-3}	17.4 ±2.4	12.0-21.0

Source: own research

The analysis of the data presented in Table 1 shows that the concentration of organic matter in the brewery effluent measured by the BOD_5 and COD values is 2-3 times higher compared to the municipal wastewater. In terms of organic matter content, the raw brewery wastewater parameters are similar to those observed in the dairy and meat processing industries. The brewery wastewater does not contain, for example, fats present in dairy or meat processing wastewater (Dąbrowski et al. 2016, Struk-Sokołowska et al. 2018). Analyzing nitrogen and phosphorus it was concluded that total nitrogen concentration is lower than in municipal sewage, while the phosphorous concentration is higher (Heidrich & Witkowski 2015, Klimiuk & Łebkowska 2004). Due to the safety of the product, there is no way to decrease raw sewage parameters, which is typical of the entire food industry (BAT, 2019).

Results of laboratory scale of craft brewery treatment in SS VF and FWS are presented in Table 2.

Table 2. Characteristics of inflow to SS VF (sampling point II), outflow from SS VF (sampling point III) and outflow from FWS (sampling point IV)

Parameter Unit	Inflow to SS VF		Outflow from SS VF		Outflow from FWS	
	Mean ±st.dev.	Min-max	Mean ±st.dev.	Min-max	Mean ±st.dev.	Min-max
BOD_5 mg O_2 dm^{-3}	1883 ±86	1740-2010	141 ±9	128-160	55 ±12	38-70
COD mg O_2 dm^{-3}	3618 ±191	3390-3880	265 ±34	215-320	119 ±22	90-155
$N\text{-}NH_4$ mg dm^{-3}	5.8 ±1.3	3.7-8.1	1.0 ±0.3	0.5-1.5	0.7 ±0.3	0.3-1.1
$N\text{-}NO_3$ mg dm^{-3}	1.7 ±0.4	1.0-2.2	5.4 ±1.1	4.0-7.4	2.7 ±0.6	4.5-8.1
TN mg dm^{-3}	35.0 ±3.7	30.0-42.0	12.0 ±1.5	10.0-15.0	9.6 ±1.1	7.4-11.3
TP mg dm^{-3}	16.9 ±2.4	11.0-21.0	7.9 ±1.5	4.6-10.4	6.5 ±1.0	4.5-8.1

Source: own research

From the analysis of the results presented in Tables 1 and 2, it can be seen that retention – aeration tank does not significantly affect the reduction of wastewater parameters. For example, the average values of BOD_5 decreased by 3%, while COD only 2.3%. For TN and TP it was 16.9% and 2.8%. The role of this device is mainly to equalize the wastewater load entering the SS VF and to aerate the raw wastewater. Average dissolved oxygen in sewage discharged to SS VF was 2.0 mg O_2 dm^{-3}.

Considering the wastewater parameters shown in Table 2 and the hydraulic load, the average pollutant load of SS VF was 94.2 g O_2 $m^{-2}d^{-1}$ for BOD_5 and 180.9 g O_2 $m^{-2}d^{-1}$ for COD. Low hydraulic load (0.05 $m^3m^{-2}d^{-1}$) allowed efficient removal of organic substances. The average BOD_5 value decreased from 1883 to 141 mg O_2 dm^{-3}, while COD from 3618 to 265 mg O_2 dm^{-3}. The average load for TN and TP was 1.75 g N $m^{-2}d^{-1}$ and 0.84 g P $m^{-2}d^{-1}$. A decrease in phosphorus concentration from 16.9 to 7.9 mg P dm^{-3} was observed. Due to high organic substances concentration pollutants loads were higher in compare with municipal or household sewage treatment with CWs (Obarska-Pempkowiak et al. 2015, Kadlec & Wallace 2009, Vymazal 2010). Hydraulic load for FWS was 0.035 $m^3m^{-2}d^{-1}$ while pollutant loads were 4.9 g O_2 $m^{-2}d^{-1}$ for BOD_5 and 9.3 g O_2 $m^{-2}d^{-1}$ for COD. Respectively for TN and TP it was 0.42 g $m^{-2}d^{-1}$ and 0.3 g $m^{-2}d^{-1}$. Due to Vymazal (2010) loading rates for FWS recommended to achieve 30 mg dm^{-3} of BOD_5 in effluent are 6 g O_2 $m^{-2}d^{-1}$. During treatment in FWS, BOD_5 decreased from 141 to 90 mg O_2 dm^{-3}, while COD from 265 to 119 mg O_2 dm^{-3}. TN decreased from 12 to 9.6 mg N dm^{-3}, while phosphorus from 7.9 to 6.5 mg P dm^{-3}.

Removal efficiency obtained during research is presented in Figure 3.

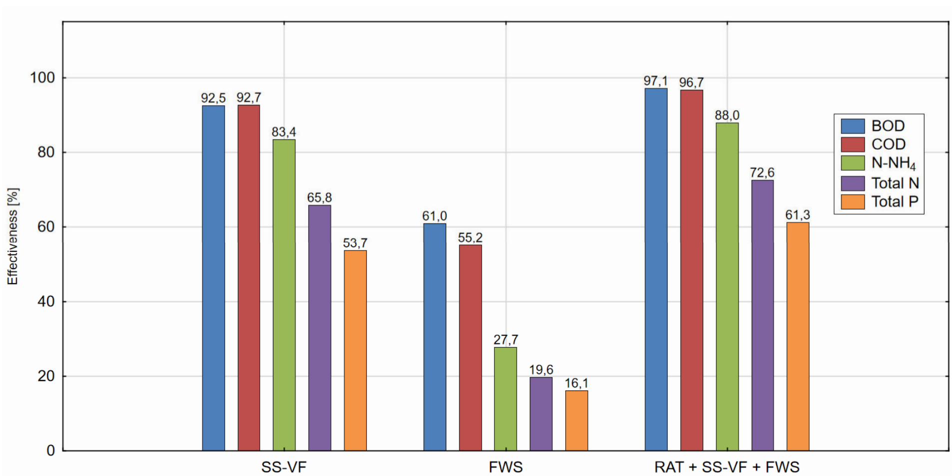

Fig. 3. Treatment efficiency of SS-VF, FWS and hybrid system

The removal efficiency for the whole treatment (RAT + SS-VF + FWS) was on average 97.1% for BOD_5, 96.7% for COD, 72.6% for TN and 61.3% for TP. The removal efficiency in SS VF bed was respectively: 89.7%, 90.5%, 54.6% and 52.1%. The treatment results achieved are similar to presented by other authors analyzing real and pilot scale systems (Kadlec & Wallace 2009). Efficiency of BOD_5, COD, TN and TP removal in FWS was respectively: 61%, 55.2%, 19.6% and 16.1%. De Stefani et al. (2011) reported efficiency of TN removal from 13 to 29% and 65% for TP in FWS, while Lopardo (2019) reached TP removal from 17.4 to 39.5%. Ozengin & Elmaci (2007) reached 50 to 95.5% efficiency for COD, 80.8 to 82.4% for TN and 71.2 to 85.4% for TP. They investigated FWS system with *Lemna minor* for municipal and industrial sewage treatment.

Table 3 shows the pollutant loads removed during SS VF, FWS and entire treatment system, which is an important parameter in evaluation of the effectiveness of CWs.

Table 3. SS VF, FWS and total load removed

Parameter	Load removed		
	SS-VF	FWS	Total
	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}
BOD_5	87.11 ±4.02	3.00 ±0.28	90.11 ±3.93
COD	167.65 ±8.53	5.08 ±0.49	172.73 ±8.79
NH_4^+-N	0.24 ±0.05	0.01 ±0.004	0.25 ±0.05
TN	1.15 ±0.05	0.08 ±0.04	1.24 ±0.15
TP	0.45 ±0.06	0.05 ±0.02	0.50 ±0.07

Source: own research

There was a high organic matter removal effect per unit area of SS VF bed (87.11 g m^{-2} d^{-1} for BOD_5) and relatively low in FWS bed (3.0 g m^{-2} d^{-1} for BOD_5). The significantly lower removal efficiencies of NH_4^+- N, TN and TP were due to the low hydraulic loading and low concentrations of nitrogen and phosphorus in sewage supplying FWS. On the other hand, the main task of the entire plant was to ensure efficient removal of organic matter. Small WWTPs are obligated to remove efficiently organic matter (BOD_5 and COD), while phosphorus and nitrogen are not limited (Regulation of the Minister of Maritime and Inland Waterway Economy from 12th July 2019).

4. Conclusions

According to the authors, the problem of treating wastewater from craft breweries can be solved applying CWs method. It can be used as an individual WWTP in case of no access to a sewer system. It can be also used for craft brewery pretreatment before its discharging to small municipal WWTP. The laboratory scale tests were used to develop parameters for the real scale experiments. The main parameters for the design of such an installation should be: the hydraulic load and the pollutant loads removed per unit area of the bed. Own research has confirmed the possibility of replacing the typical SS-VF bed filling (sand and gravel) with a waste material *Certyd*. Results from this study confirm high efficiency of SS-VF bed planted with *Phragmities australis* and much lower for FWS planted with

Salvinia natans for craft brewery sewage treatment. The efficiency of organic substances removal for entire system measured by BOD_5 was on average 97.1% while for SS-VF 92.7% and 61% for FWS. TN removal was respectively 72.6%, 65.8% and 19.6%, while for TP it was 61.3%, 53.7% and 16.1%. It is recommended to design real scale system to ensure required effect of wastewater treatment during winter period only by means of SS-VF bed operation. An important aspect of the application of such low-cost system is the fact that the amount of wastewater discharged to the receiver or to the municipal WWTP can be significantly reduced in the transpiration and evaporation processes. This will be the subject of further research.

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References

American Public Health Association (APHA) (2005). *Standard Methods for Examination of Water and Wastewater*. 21st edition. Washington: American Public Health Association.

Best Available Techniques (2008). *Guidance Note on Best Available Techniques for the Brewing*, Malting & Distilling Sector (1st Edition) Environmental Protection Agency Website: www.epa.ie.

Best Available Techniques (2019). *Reference Document in the Food, Drink and Milk Industries. Industrial Emissions Directive 2010/75/EU* (Integrated Pollution Prevention and Control) Joint Research Centre, Directorate B – Growth and Innovation Circular Economy and Industrial Leadership Unit European IPPC Bureau Final Draft. www.ec.europa.eu (accessed on 10 December 2020).

Budgen, J., Le-Clech, P. (2020). Assessment of brewery wastewater treatment by an attached growth bioreactor. *H2Open Journal,* 3(1), 32-45, DOI: 10.2166/h2oj.2020.023.

Dąbrowski, W. (2009). Sewage treatment plants in Podlaskie voivodeship - challenges of XXI century. Water, sewage and waste in small towns of the Podlaskie voivodeship. Low-cost systems for wastewater and sewage sludge treatment. Eds. D. Boruszko, W. Dąbrowski, Eko Press, 24-31 (in Polish).

Dąbrowski, W., Żyłka, R., Rynkiewicz, M. (2016). Evaluation of energy consumption in agro-industrial wastewater treatment plant. *Journal of Ecological Engineering*, 17(3), 73-78, DOI: 10.12911/22998993/63306.

Dąbrowski, W., Karolinczak, B. (2019). Application of trickling filter and vertical flow constructed wetland bed to treat sewage from craft brewery. *Journal of Ecological Engineering*, *20*(9), 211-217. DOI: https://doi.org/10.12911/22998993/112488.

De Stefani, G., Tochetto, D., Salvato, M., Borin, M. (2011). Performance of floating treatment wetland for in-stream water amelioration in NE Italy, *Hydrobiologia 674*, 157-167.

Driessen, W., Vereijken, T. (2003). *Recent developments in biological treatment of brewery effluent*. The Institute and Guild Brewing Convention, Livingstone, Zambia.

Enitan, A. M., Swalaha, F. M, Adeyemo, J., Bux, F. (2014). Assessement of Brewery Effluent Compostion from beer producing industry in Kwazulu – Natal, South Africa, *Fresenius Environmental Bulletin, 23*(3), 693-701.

Heidrich, Z., Witkowski, A. (2015). *Facilities for wastewater treatment – design, calculation examples.* „Seidel-Przywecki" Sp. z o.o., Warsaw (in Polish).

Janczukowicz, W., Rodziewicz, J., Mielcarek, A., Filipkowska, U., Kłodowska I., Ostrowska, K., Jóżwiak, T., Kordas, M. (2013). Quality Characteristics of Wastewater from Malt and Beer Production. *Rocznik Ochrona Środowiska*, 15, 729-748.

Kadlec, R. H., Wallace, S. D. (2009). *Treatment Wetlands*, 2nd ed. CRC Press: Boca Raton, FL, USA.

Karolinczak, B., Miłaszewski, R., Sztuk, A. (2015). Cost-effectiveness analysis of different technological variants of single-house sewage treatment plants. *Rocznik Ochrona Środowiska*, *17*, 726-746 (in Polish).

Karolinczak, B., Dąbrowski, W. (2017). Effectiveness of septage pre-treatment in subsurface vertical flow constructed wetlands, *Water Sci. Technol*. *76*(9), 2544-2553, DOI: 10.2166/wst.2017.398.

Karolinczak, B.; Miłaszewski, R.; Dąbrowski, W. (2020). Cost Optimization of Wastewater and Septage Treatment Process. *Energies 13*, 6406. DOI: https://doi.org/10.3390/en13236406.

Klimiuk, E., Łebkowska, M. (2004). *Biotechnologia w ochronie środowiska*. Wydawnictwo Naukowe PWN, Warszawa (in Polish).

Kołecka, K., Obarska-Pempkowiak, H., Gajewska, M. (2018). Treatment wetlands as the implementation of the circular economy. *Rocznik Ochrona Środowiska,* 20(2), 1350-1371 (in Polish).

Lopardo, C., Zhang, LI., Mitsch, Wiliam J., Urakawa, H. (2019). Comparison of nutrient retention efficiency between vertical-flow and floating treatment wetland mesocosms with and without biodegradable plastic. *Ecological Engineering, 131*, 120-130. DOI: https://doi.org/10.1016/j.ecoleng.2019.01.024.

Massi, F., Rizzo, A., Bresciani, R. (2018). Treatment of Wineries and Breweries Effluents Using Constructed Wetlands, *Constructed Wetlands for Industrial Wastewater Treatment*, First Edition Edit. Stefanakis A., John Willey & Sons Ltd., 96-104.

Mielcarek, A., Janczukowicz, W., Ostrowska, K., Jóźwiak, T., Kłodowska, I., Rodziewicz, J., Zieliński, M. (2013). *Biodegradability evaluation of wastewaters from malt and beer production*, Published online in Wiley Online Library: DOI: 10.1002/jib.92o.

Obarska-Pempkowiak, H., Gajewska, M., Wojciechowska, E., Pempkowiak, J. (2015). Domestic Wastewater Treatment/ Treatment Wetlands for Environmental Pollution Control/ Springer International Publishing Switzerland: Springer International Publishing, 15-87, DOI: 10.1007/978-3-319-13794-0_4.

Okunola, A.A., Ayayi, A.E., Daniya, A.I., Olasehinde, D.A. (2019). Performance evaluation of anaerobic technology in handling high strength effluent brewery, *Journal of Engineering and Applied Sciences*, *14*(22), 8373-8378. DOI: 10.36478/jeasci.2019.8373.8378.

Ozengin, N., Elmaci A. (2007). Performance of Duckweed (Lemna minor L.) on different types of wastewater treatment. *J. Environ. Biol. 28*(2), 307-314.
Regulation of the Minister of Maritime and Inland Waterway Economy from 12th July 2019 on substances that are particularly harmful to the aquatic environment and the conditions to be met for the introduction of sewage into water or soil and for the discharge of rainwater or snowmelt into water or into water facilities. Journal of Laws 2019 item 1311 (in Polish).
Simate, G., Cluett, J., Iyuke, E., Musaptika, E.T., Ndlovu, S., Walubita, F., Alvarez, A.E. (2011). The treatment of brewery wastewater for reuse: State of the Art, *Desalination*, 273, 235-247, DOI: 10.1016/j.desal.2011.02.035.
Struk-Sokołowska, J., Rodziewicz, J., Mielcarek, A. (2018) Effect of dairy wastewater on changes in COD fractions in technical-scale SBR type reactors. *Water Science and Technology*, *1*, 156-169. DOI: doi.org/10.2166/wst.2018.099.
Umiejewska, K. (2019). *Conversion of organic compounds into biogas on a full scale brewery WWTP using IC reactor.* E3S Web of Conferences 116, 00095, DOI: doi.org/10.1051/e3sconf/201911600095.
Wojtyra, B., Grudzień, Ł. (2017). The Development of the Beer Industry in Poland During "The Craft Beer Revolution" (2011-2016). Studies of the Industrial Geography Commission of the Polish Geographical Society. 31(*1), DOI: 10.24917/2080 1653.311.4.
Vymazal, J. (2010). Constructed Wetlands for Wastewater Treatment. *Water*, *2*, 530-549, DOI: 10.3390/w203053.
Żyłka, R., Dąbrowski, W., Malinowski, P., Karolinczak, B. (2020). Modeling of Electric Energy Consumption during Dairy Wastewater Treatment Plant Operation. *Energies, 13*, 3769. DOI: https://doi.org/10.3390/en13153769.

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Visual Analysis of the Cultural Landscape in Terms of Vegetation for the Purposes of Revitalization of Rural Areas

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Abstract: The article presents a visual analysis of the landscape, based on the modified SBE method and the possibility of using this type of research for the purposes of revitalization of rural areas. The scope of the research covered the Puchaczów commune in which, due to environmental conditions, mining related to hard coal extraction has developed. The aim of the study was to test the hypothesis that the existence of diverse hight structure of the plant cover increases the attractiveness of the landscape. The research method consisted in using the SBE analysis for 13 landscape units, presented as actual illustrations and modified pictures (as computer visualizations) by adding trees and shrubs. Then, using the one-way analysis of variance (ANOVA) and Tukey post hoc test, it was examined whether there is a significant difference for the average visual value evaluation between original and modified sketches.

Keywords: Scenic Beauty Estimation, rural landscape, group of trees and shrubs

1. Introduction

The concept of sustainable development facilitates the development of rural areas and their revitalization (Kożuch 2010). It consists in integrating activities at the economic and social level, maintaining the balance of the natural environment and the sustainability of the natural processes, in order to meet the needs of current and future generations (Environmental Protection Act of 27 April 2001). In the context of the Common Agricultural Policy implemented by the European Union countries, sustainable development of rural areas is based on multifunctionality, gradual disagrarisation for the benefit of the intensification of the other economic branches, e.g. tourism (Rizov 2005), which in turn influences the transformation of the landscape. The implementation of the principles of sustainable development in rural areas is a problematic and complicated process, in which local politics is of great importance. In Poland, the tasks of municipalities include environmental protection and preservation of spatial order, carried out by developing a study of the conditions and directions of spatial development, local spatial development plans and the related determination of development conditions (Guzal-Dec 2015). The spatial policy of the communes, built that way, influences their comprehensive modernization using the social and economic potential (Feltynowski 2009). The polyfunctional development of rural areas is inextricably linked with the conscious shaping of the living conditions of the population, but also with revitalization understood as the process of reconstruction of degraded areas, integrated at the social, spatial and economic level (The Revitalization Act of 9 October 2015). The tools supporting the designing and spatial planning process are analyzes of the landscape quality, including visual analyzes.

In studies of landscape, it is noted that its perception is influenced by the components that build it, but also by the memories of inhabitants of specific areas and cultural conditions (Sonnenfeld 1967, Herzog et al. 2000). As Bernat noted, through perception we establish a relationship with the landscape that affects our health not only in the mental, but also physical, spiritual and social context (Bernat 2019). People perceive an unattractive landscape as inferior, and it reduces the quality and comfort of life. One of the elements influencing the aesthetics of the landscape is the vegetation and its appropriate shape. Considering the above, the article hypothesized that the existence of vegetation with a varied height structure increases the attractiveness of the landscape. In order to prove the research hypothesis, a visual analysis of the landscape was performed, based on the modified SBE method, with particular emphasis on plant cover. The innovation of the proposed method consists in comparing the drawings showing the actual appearance of the landscape with the drawings presenting the same areas, where visualizations of vegetation clusters have been added. In further stages of the work, it allowed to examine only a feature related to the type of vegetation (medium and high greenery – shrubs and trees) and its impact on the visual assessment of the landscape. Statistical analysis of the results made it possible to unambiguously answer the question whether the existence of vegetation with a diversified composition structure influences the assessment of the attractiveness of the landscape. The results of the research will facilitate activities related to the conscious shaping of the structure of vegetation at the local level in the context of revitalization of rural areas. The territorial scope of the research covered the rural commune of Puchaczów located in the Lubelskie Voivodeship, where due to natural conditions, in addition to the traditional agricultural function, mining was developed in the second half of the 20th century. These factors have a huge impact on the contemporary shaping of the landscape of the commune and its environmental conditions.

2. The use of visual assessment of the cultural landscape for the purposes of revitalization of the rural areas – the state of research

In Poland, the revitalization of degraded areas is legally regulated by the Revitalization Act (Journal of Laws of 2015, item 1777) and the Spatial Planning and Development Act (Journal of Laws of 2003, No. 80, item 717). The commune's own tasks include designating the areas requiring revitalization works, where there are unfavorable social phenomena and negative factors located at the economic, environmental or spatial-functional level. A low level of forestation should be considered a negative factor that affects the deterioration of the quality of the natural environment, but also affects the spatial structure of the commune. Identifying degraded areas in terms of nature or landscape requires an appropriate diagnosis, adjusted to the local conditions (the Revitalization Act of 9 October 2015, Journal of Laws of 2015, item 1777).

The research on the valorization of landscape resources is considered to be one of the most complex in terms of methodology (Kistowski 2007). The visual assessment of the landscape very often serves utilitarian purposes (Richling, Solon 2011). Most often, such studies are used to determine the tourism potential or to designate areas, which are attractive for recreation (Rylke, Gąsowska 2009), less often areas of natural value and in the process of real estate valuation (Bajerowski et al. 2007). As Jakiel (2015) emphasizes, visual landscape analyzes are very rarely used in the process of spatial planning, and thus in the rural revitalization activities. However, they have the potential that can be used to designate degraded areas with the accumulation of negative spatial-functional and environmental features, and consequently to undertake corrective activities.

There are numerous studies in the field of ecology and landscape architecture and geography related to the subject of research in the field of the visual landscape assessment. The Professor's Bogdanowski JARK-WAK (1994), Wejchert's Impression Curve Method (Wejchert 1984), the Bajerowski's Method of Value Matrix (1996) can be classified as the most popular methods in Poland. Among the foreign methods which are commonly used in Poland, the assessment of the beauty of scenery SBE – Scenic Beauty Estimation (Daniel, Boster 1976) should be mentioned.

The JARK-WAK method is based on the determination of homogeneous areas in terms of shape, cover and historical origin. Depending on the planning scale, architectural and landscape units or architectural and landscape interiors are distinguished, which are then divided into three categories: natural, cultural and natural-cultural landscapes. The next stage is valorization, consisting in assigning appropriate grades to the landscapes: the historic landscape receives a grade from I to III, modern IV, and mixed – grades V-VI. The last step is to indicate the directions of activities and the scope of protection of individual units (Wrochna 2012).

The Wejchert's Impression Curve Method is based on the graphical representation of the emotional experience related to the perception of a place along a specific time-space sequence. Assessments are made at intervals according to the criteria related to the degree of diversity, the degree of devastation, infrastructure saturation and the harmony of the composition. The criteria are assessed on a point scale. The results for the criteria are summed up and presented in the form of a graph - an impression curve (Szopińska et al. 2016). This study presents the observer's feelings when staying in a given place (Gąsowska 2008). Based on this method, it can be concluded which parts of the landscape have higher or lower visual values (Szopińska et al. 2016).

It should be emphasized that the above-mentioned methods are not based on statistical data which can significantly be used to verify the relationship between landscape components and the assessment of its visual values.

The Bajerowski's Method of Value Matrix is based on a mathematical and statistical analysis of information contained in generally available maps. In these studies it was assumed that the aesthetic value of a landscape results from the configuration of spatial features. These features are often analyzed only with the help of cartographic materials. The studied area is divided into basic assessment fields and assigned a numerical measure that determines the visual value of the landscape (Litwin et al. 2009). Due to the nature of the research, this method ignores significant intangible landscape factors (Antolak 2017).

The Scenic Beauty Estimation is a method based on the evaluation of space by a group of recipients who are presented with photos showing various types of landscape. This study was developed by the United States Department of Forestry (Tveit et al. 2018). The respondents evaluate the photos on a 10-point scale, in which the lowest values are assigned to the least attractive areas. Then the arithmetic mean score for each photo is calculated and in the next step the result is normalized by the standard deviation formula (Gąsowska 2008).

The research on the visual quality of rural landscapes, based on the analysis of the beauty of the scenery combined with a statistical study, was carried out by Arriaza et al. (Arriaza et al. 2004). In the work, the authors presented the methodology of direct and indirect landscape evaluation techniques on the example of two Mediterranean rural areas. The direct method was based on the assessment of the beauty of the landscape by studying the preferences of the observers. The indirect technique involves assigning the contributions of individual landscape elements to its overall aesthetics through regression analysis. According to the results, the factors that play a key role in determining the visual quality of rural areas are the degree of naturalness of nature and the presence of historic or typical buildings, traditional for the region. Another factor determining the aesthetic value of a landscape is the presence of water and color contrast. In the above-mentioned studies, the degree of nature's naturalness is understood as the degree of trans-formation of the landscape, including the flora. This proves that vegetation, as one of the components of space to a large extent related to anthropogenic factors, which is particularly visible in rural areas, affects the attractiveness of the region. However, it should be noted that the research results did not show that the variable related to the type of vegetation (low vegetation, shrubs, trees) is statistically significant, which means that there is no reason to reject the null hypothesis that there is no correlation between the type of vegetation and visual assessment of the landscape (Arriaza et al. 2004).

3. The importance of tree stands in the revitalization of rural areas

Revitalization of rural areas is related to the protection of the envi-ronment, which can manifest itself through strengthening and improving the functioning of the existing natural systems, as well as through creating new systems in the form of, for example, trees. The importance of trees in the process of shaping the agricultural production space was known in Poland as early as the 1820s and is associated with the person of General Dezydery Chłapowski. In his estate in Turwia, General Chłapowski created a regular network of banded trees, the purpose of which was, among others the wind protection (Kujawa et al. 2019). Activities related to the reconstruction of the landscape, based on the conditions of the natural environment, resulted in the creation of a space with high aesthetic values and high production value of crops (Raszeja 2010).

Mid-field afforestation increase the yield of crops, except for the strip of land in their immediate vicinity (Koreleski 2006). They counteract the decline in the level of biodiversity caused by the intensification of agriculture (Orzechowski, Trzcianowska 2016). The mid-field tree afforestation ia a refuge environment for numerous species of flora and fauna, including pollinating insects (Ryszkowski 1998). Their presence in rural areas provides a rich food base throughout the growing season and creates suitable places for nesting. In addition to biocenotic functions, tree cover plays the role of ecological structures: patches, nodes, corridors and islands (Bożętka 2017). In addition, they regulate the microclimate, inhibit wind speed, reduce water evaporation from the soil, and affect temperature, which is particularly important in times of current climate changes.

Apart from the mid-field afforestation which is so important for the rural landscape, it is necessary to emphasize the importance of roadside and water-bearing trees, which together with forest complexes and smaller groups of vegetation form the green systems of the rural communes. Properly shaped tree systems constitute an extremely important buffer zone between industrial, agricultural and residential areas. They create a biogeochemical barrier to pollution.

They also distinguish features, elements recognizable in a monotonous agricultural landscape and definitely improve the visual value of the landscape.

4. Research methodology

The subject of the study is the analysis of the landscape of the Puchaczów commune in terms of the influence of medium and high greenery (clusters of shrubs and trees) on the assessment of visual values. Puchaczów is a rural commune in which, due to the presence of hard coal deposits, the mining industry has developed. The largest enterprise operating in the region is the Bogdanka Coal Mine, located in the central part of the commune. Industrial areas, roads with intensive traffic and compact buildings are classified as ecological barriers, i.e. structures that hinder the movement of matter, energy and information in the natural environment. Large forest complexes in the towns of Ciechanki, Ostrówek, Zawadów, Wesołówka, Puchaczów and Nadrybie have the form of ecological patches. The ecological corridors located within the studied area include meadows and pastures of a stripy nature, accompanying the Mogielnica and Świnka valleys (Fig. 1). A properly carried out revitalization process, related to the increase in the number of trees in the commune, may in the future improve the functioning of ecological structures, while inhibiting the development of negative factors. This will significantly improve the quality of life of the commune inhabitants.

A modified method of assessing the beauty of scenery (SBE) was used in the research on the evaluation of visual values of the landscape of the described area. The choice of the method was not accidental. In order to test the research hypothesis, it was necessary to compare the areas that differ from each other by one variable feature (there is or don't exist a differentiated height structure of vegetation). The need to use a modified SBE method was also influenced by the distribution of research units over a large area, which makes it impossible to determine a uniform time-space sequence and the use of, e.g. the Wejchert's Impression Curve Method The first stage of the work was to delimit homogeneous research units. In order to distinguish the research fields, an analysis of land cover and an analysis of the shape of the surface were used. The method used enabled the designation of 13 research units, typical for the landscape of the Puchaczów commune (Table 1), having the character of agricultural land, compact buildings, meadows and pastures and industrial areas. Due to the high degree of diversity of the flora, forest units were omitted in the study of visual landscape values and the impact of medium and high greenery (shrubs and trees) on this assessment.

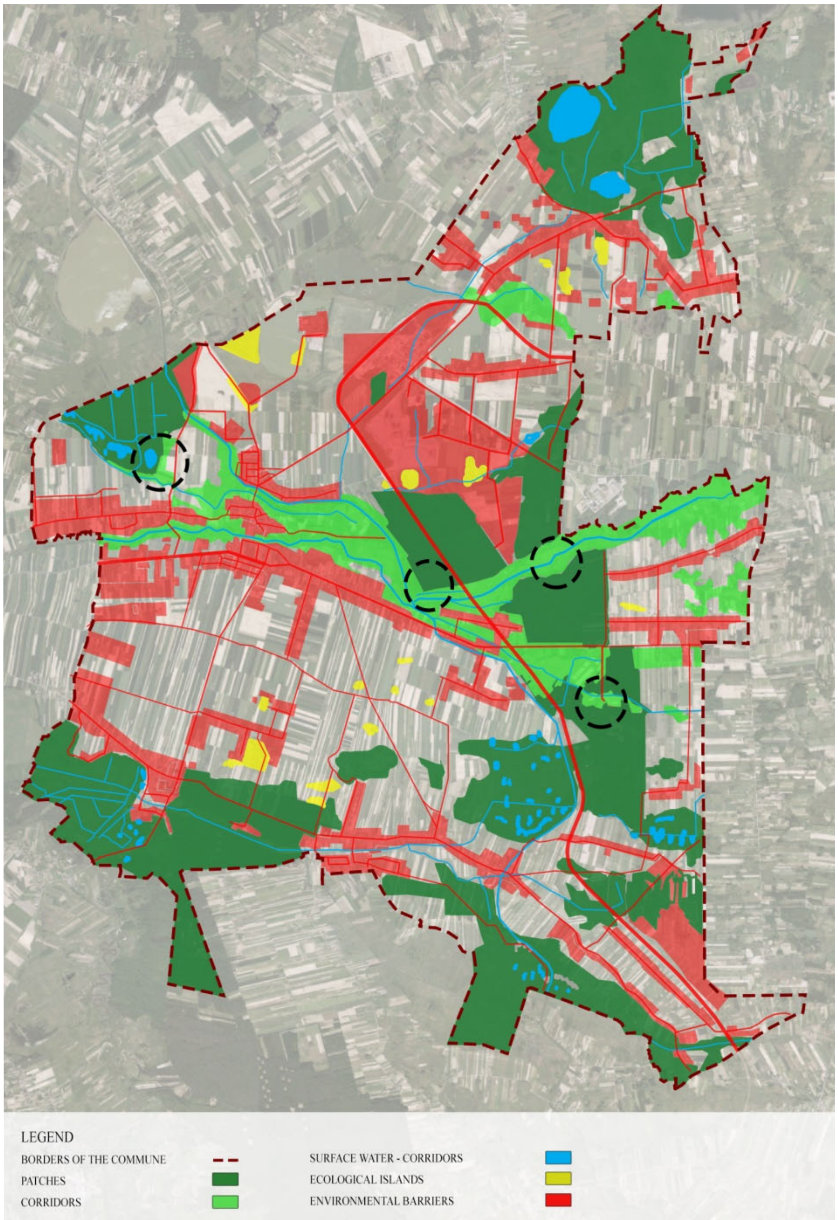

Fig. 1. An analysis of ecological structures in the Puchaczów commune (Own study based on: orthophotomap, https://puchaczow.e-mapa.net/, accessed: 08/01/2018)

Table 1. Featured research units in the Puchaczów commune (Own study 2019)

Research Unit	Unit symbol	The degree of variation in the height of the plant cover	The outline number on the map
Compact settlement on flat areas	ZP	Low	1
Compact settlement on slightly undulating areas	ZL	Low	2
Compact settlement in clearly undulating areas	ZW	Low	3
Agricultural lands in flat areas	RP	Low	4
Agricultural lands in slightly undulating areas	RL	Low	5
Agricultural lands in clearly undulating areas	RW	Low	6
Industrial areas in slightly undulating areas	PL	Low	7
Industrial areas clearly undulating	PW	Low	8
Industrial areas in river valleys	PD	Low	9
Meadows and pastures in flat areas	ŁP	Medium	10
Meadows and pastures in slightly undulating areas	ŁL	Medium	11
Meadows and pastures in clearly undulating areas	ŁW	Medium	12
Meadows and pastures in river valleys	ŁD	Medium	13

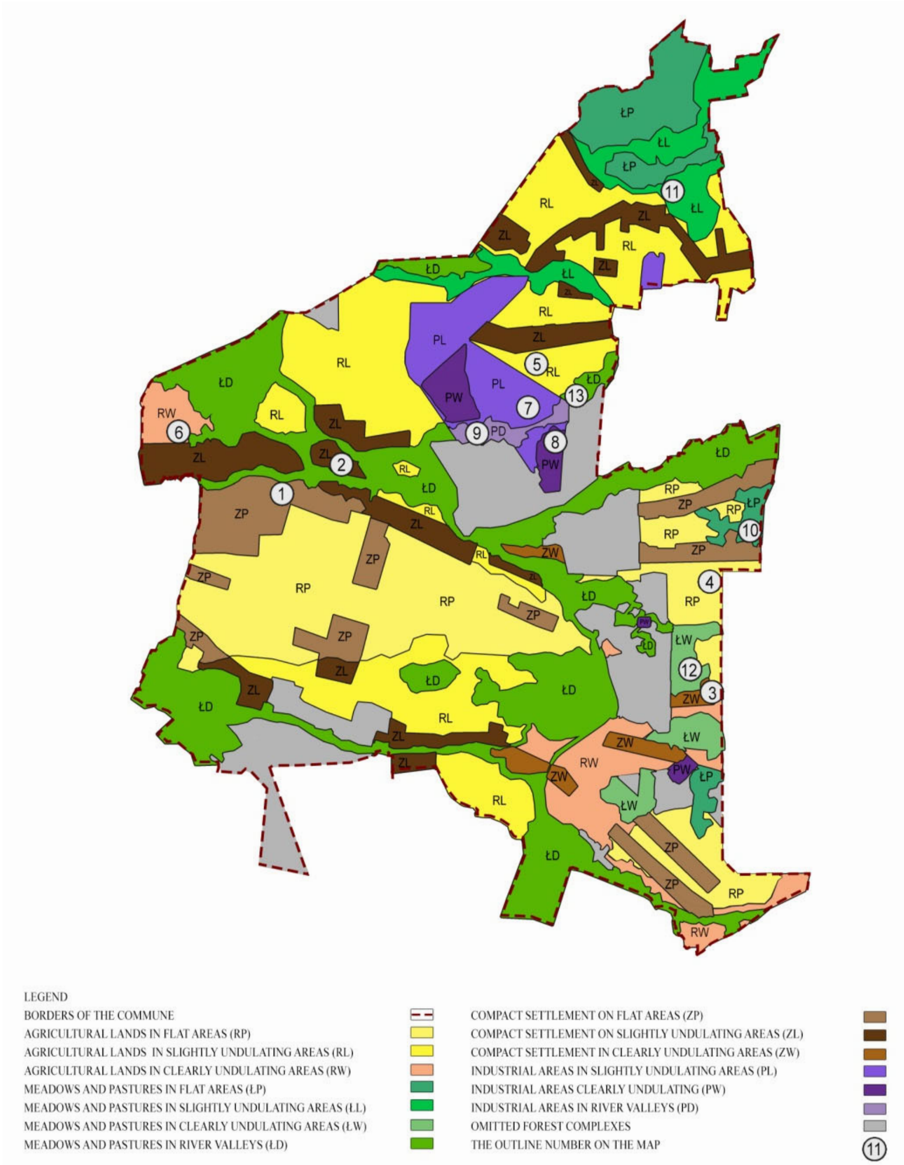

Fig. 2. Map showing the locations of the drafts performed against the background of the distinguished research units in the Puchaczów commune, gray color marks the omitted forest complexes in visual analysis (Own study 2020)

For the selected units, the author indicated representative places (chosen at random), in which she made illustrations showing individual types of landscape (Fig. 2). The figures were then computer-modified by adding bushes and trees. The use of black and white traces in the study is justified by the need to standardize the way individual units are perceived by the respondents.

For SBE reaserch to be credible, standards for group diversity and number of observers must be adhered to. According to Daniel and Boster (1976), a group of just 20 people can provide reliable landscape assessment results. Bearing in mind the above statement and the limited time frame of the experiment itself, the SBE research presented in the article was attended by a group of 20 people diversified in terms of sex, age, education and place of residence. Among the respondents, 50% were men and 50% were women. 15% of the answerers are people under the age of 20, 25% in the 20-30 age group, 20% in the 30-40 age group and 25% in the 40-50 age group. 15% of participants were over 50 years old. More than half of the respondents (60%) were people with higher education, 35% with secondary education, and 5% with primary education. Among the answerers, 45% live in the city, and 55% in rural areas (in order to eliminate the subjective assessment related to the sense of belonging to a given place, they were not, however, inhabitants of the studied region). The respondents were presented with illustrations in a random order, in the form of a multimedia presentation. The people taking part in the study were unaware that the figures represented the actual and computer-modified appearance of the space. A single slide was displayed for 15 seconds. The study participants assessed the aesthetic level of the illustrations on a 10-point scale, in which 10 was assigned to areas of higher visual value, and 1 to the least aesthetic areas. As a result of the study, a total of 260 assessments were obtained, which were then standardized using the formula:

$$Zij = (Rij - Rj) / sj \tag{1}$$

where:
Zij – the standardized result for the i-th assessment of the respondent j,
Rij – the i-th j-observer's assessment,
Rj – the mean of all ratings of respondent j,
sj – the standard deviation of all observer j ratings (Daniel, Boster 1976).

5. Results

The average results of the standardized assessment for individual drafts are shown in Fig. 3. On the axis truncated with symbols, illustrations showing research units are described, where the original figures (without added plant clusters) contain a letter designation (e.g. ZP), and the drawings contain a letter-number designation (e.g. ZP2).

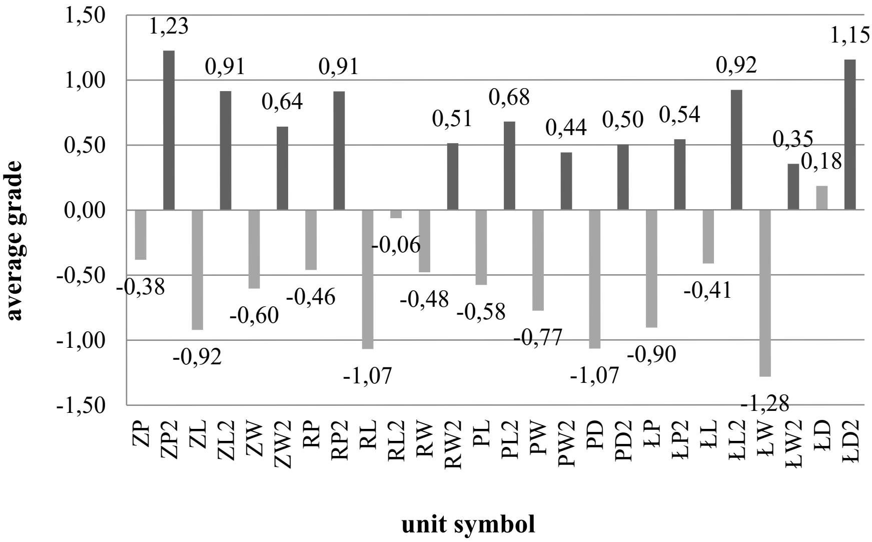

Fig. 3. Average results of standardized assessments for individual sketches (Own study 2020)

As it results from the analysis of Fig. 3, all the drafts with shrubs and trees added were assessed as more attractive compared to the original figures. The lowest scores during the SBE analysis were given to primary illustrations characterizing meadows and pastures in clearly undulating areas (ŁW), production areas in valleys (PD), agricultural lands with a slightly undulating areas (RL), compact settlements in slightly undulating areas (ZL) and meadows and pastures in a flat area (ŁP).

Fig. 4. Real illustration showing meadows and pastures in a clearly undulating area (ŁW) assessed by the respondents as the least attractive (Own study 2019)

Among the presented illustrations, the highest rated were the modified figures, showing: compact settlements on a flat area (ZP2), areas of meadows and pastures in river valleys (ŁD2) and in slightly undulating areas (ŁL2), agricultural lands in flat areas (RP2) and compact settlements in slightly undulating areas (ZL2).

Fig. 5. The highest-rated computer-modified sketch showing compact settlements in a flat area (ZP2) (Own study 2019)

In order to test the research hypothesis that increasing the diversity of the height structure of vegetation significantly influences the differentiation of the visual assessment of the landscape, a one-way analysis of variance was performed. As a result, it turned out that the compared traces differ in a statistically significant maner $p < 0.05$. Tukey's post hoc test was used to check the significance level of the differentiation of the mean scores between the original and the modified drafts for individual units. The test results are presented in tabular form (Table 2). The lowest p value equal to 0.000020 can be observed in four groups: ZP-ZP2, ZL-ZL2, PD-PD2, ŁW-ŁW2 (Fig. 6). In the RW-RW2 group (Fig. 7) the p value is the highest and amounts to 0.010457. However, in all compared groups, the p value is less than 0.05. This means that the differences in the mean visual value assessment between the original and the changed drafts are statistically significant for each research unit. Moreover, in order to show disproportions between the ratings of the primary drawings in relation to the visualization, the author presented the differences between the average ratings in the individual compared groups. It is worth noting that the greatest difference between the average assessment of the primary outline and the modified image is in the ZL-ZL2 group and amounts to 1.83. Another large difference was noted in the ŁW-ŁW2 group (1.63). The smallest difference in mean scores is in the LD-LD2 group (0.91).

Table 2. Tukey's post hoc test results for the average assessment of primary contours and modified (Own study 2020)

Sketches compared with each other	*p* value	Differences between the mean values of standardized assessments
ZP-ZP2	0.000020	1.61
ZL-ZL2	0.000020	1.83
ZW-ZW2	0.000105	1.24
RP- RP2	0.000022	1.37
RL-RL2	0.002167	1.01
RW-RW2	0.010457	0.99
PL-PL2	0.000030	1.26
PW-PW2	0.000246	1.21
PD-PD2	0.000020	1.57
ŁP-ŁP2	0.000021	1.44
ŁL-ŁL2	0.000022	1.33
ŁW-ŁW2	0.000020	1.63
ŁD-ŁD2	0.007161	0.91

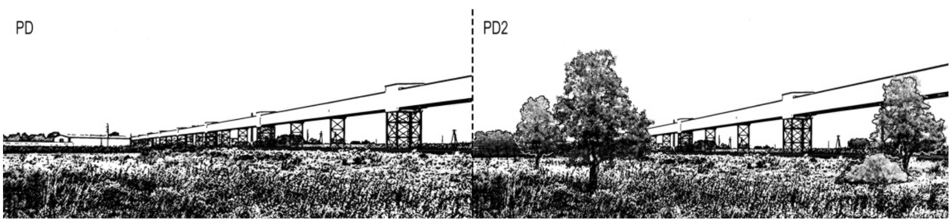

Fig. 6. Primary and modified traces of an industrial area in the valley with a *p* value of 0.000020 (Own study 2020)

Fig. 7. The compared group of the original (RW) and the modified (RW2) draft for an agricultural unit in clearly undulating areas with the highest p value of 0.010457 (Own study 2020)

6. Conclusions

The SBE analysis carried out in the Puchaczów commune showed that, regardless of the form of use and topography, the figures of landscape units on which trees were added had higher visual values. Results of one-way analysis of variance and Tukey's post hoc test showed that there is a statistically significant difference in the mean visual value of the original and modified sketches. This proves the correctness of the research hypothesis presented in the article saying that the existence of differentiation in the height structure of the flora has an impact on increasing the attractiveness of the landscape.

On the basis of the presented research, elementary activities facilitating the revitalization of the Puchaczów commune can be determined. It should be noted that the places requiring improvement of the visual quality of the landscape for the studied area are, in particular, compact settlement on flat areas, slightly undulating areas, industrial units in the river valleys and meadows and pastures in in clearly undulating areas, that is, the units with the lowest visual rating. This quality of landscape aesthetics can be increased by changing the structure of vegetation and introducing groups of trees. In densely built up areas, along the main communication routes, insulating vegetation should be introduced, which will also reduce noise. Between the industrial areas and other units, it is necessary to expand the existing greenery system with a buffer function. In addition, tree plantings should obscure the technical infrastructure related to the existence of the mine, which is unattractive for observers. The landscape of meadows and pastures can be diversified by planting groups of trees and shrubs. In addition to increasing the visual value, they will also improve the functioning of the main ecological structures, and in the future they may become ecological islands of local importance, facilitating the movement of matter in the environment.

It is worth emphasizing that the introduction of new groups of tree stands should always be preceded by actual plant community research and identification of the existing habitat conditions. Only such a research process will make it possible to correctly indicate specific species recommended for planting. For example, in the process of shaping mid-field shelterbelts in dry soils, species such as: *Pyrus communis*, *Prunus spinosa*, *Malus sylvestris*. In humid and shady habitats: *Prunus padus*, *Sambucus nigra*, *Sorbus aucuparia*, *Corylus avellana.*

7. Summary

Visual analyzes of the landscape facilitate the process of identifying rural areas requiring revitalization works. They are an effective tool in identi-fying specific elements disrupting the spatial order and thus, indirectly, they can be used to indicate guidelines aimed at improving the quality of rural life.

Revitalization of rural areas, which consists in deliberately shaping the vegetation by introducing tree coverings of a form appropriately matched to the area, e.g. in the field, along communication routes, has a positive effect on the landscape structure, both at the environmental and functional-spatial level. Proper species selection is also an inseparable issue related to the increase in the number of trees. The general rule is to avoid invasive species in favor of native plants adapted to the prevailing habitat conditions.

References

Antolak, M. (2017). Analiza i waloryzacja krajobrazu gminy wiejskiej Ostróda, in: *Studia Obszarów Wiejskich*, *45*, 141-155 (in Polish).

Arriaza, M. et al. (2004). Assessing the visual quality of rural landscapes, in: *Landscape and Urban Planning*, *69*(1), 115-125.

Bajerowski, T. (1996). *Metodyka wyboru optymalnego użytkowania ziemi na obszarach wiejskich*. Olsztyn: Publishing House of the Agricultural and Technical Academy (in Polish).

Bajerowski, T. et al. (2007). *Ocena i wycena krajobrazu. Wybrane problemy rynkowej oceny i wyceny krajobrazu wiejskiego, miejskiego i stref przejściowych*. Olsztyn: Publ. Educaterra (in Polish).

Bernat, S. (2019). Landscape and Health in Sustainable Development, in: *Problemy ekorozwoju/Problems of sustainable development, 14*(1), 87-96.

Bogdanowski, J. (1994). *Metoda jednostek i wnętrz architektoniczno-krajobrazowych (JARK-WAK) w studiach i projektowaniu*. Kraków: Cracow University of Technology. 1-36 (in Polish).

Bożętka, B. (2007). Wybrane problemy waloryzacji zadrzewień i zakrzewień obszarów rolnych, in: *Waloryzacja środowiska przyrodniczego w planowaniu przestrzennym*, ed. M. Kistowski, B. Korwel-Lejkowska. Problemy Ekologii Krajobrazu XIX, Gdańsk-Warszawa: Fundacja Rozwoju Uniwersytetu Gdańskiego. 117-127 (in Polish).

Daniel, T.C., Boster, R.S. (1976). *Measuring landscape aesthetics: the scenic beauty estimation metho.,* Fort Collins: USDA Forest Service Res. Paper RM-167.

Feltynowski, M. (2009). *Polityka przestrzenna obszarów wiejskich. W kierunku wielofunkcyjnego rozwoju*. Warszawa: Ce-DeWu. PL Wydawnictwa Fachowe (in Polish).

Gąsowska, M. (2008). The SBE and VRM methods as landscape esthetic estimation methods on example of Elbląg Canal, in: *Annals of Warsaw University of Life Sciences – SGGW Horticulture and Landscape Architecture*, 29, 185-192.

Guzal-Dec, D. (2015). Samorząd gminny w kreowaniu zrównoważonego rozwoju obszarów przyrodniczo cennych województwa lubelskiego, in: *Monografie i Rozprawy nr 4*. Biała Podlaska: Wydawnictwo PSW JP II. 255-257 (in Polish).

Herzog, T.R. et al. (2000). Cultural and Developmental Comparisons of Landscape Perceptions and Preferences, in: *Environment and Behavior*, *32*(3), 323-346.

Jakiel, M. (2015). Ocena atrakcyjność wizualnej krajobrazu dolinek krakowskich – możliwości zastosowania w planowaniu przestrzennym, in: *Współczesne problemy i kierunki badawcze w geografii*, 3, ed. J. Liro, M. Liro, P. Krąż. Kraków: IGiGP UJ. 91-107 (in Polish).

Kistowski, M. (2007). Metoda delimitacji i oceny wartości wizualno-estetycznej jednostek krajobrazowych i jej zastosowanie dla obszaru województwa pomorskiego, in: *Znaczenie badań krajobrazowych dla zrównoważonego rozwoju,* ed. K. Ostaszewska, I. Szumacher, S. Kulczyk, E. Malinowska. Warszawa: Publishing House of the University of Warsaw. 677-695 (in Polish).

Koreleski, K. (2006). Wstępna ocena wpływu lasów i zadrzewień na wartość gruntów ornych, in: *Infrastruktura i Ekologia Terenów Wiejskich*, *2*(1), 5-14 (in Polish).

Kożuch, A. (2010). Rewitalizacja a zrównoważony rozwój obszarów wiejskich, in: *Zarządzanie publiczne,* 1-2(9-10), 79 (in Polish).

Kujawa, K. et al. (2019). Nieocenione zadrzewienia śródpolne, in: *Magazyn Polskiej Akademii Nauk,* 3-4(59-60), 28-29 (in Polish).

Litwin, U., Bacior, S., Piech, I. (2009). Metodyka waloryzacji i oceny krajobrazu, in: *Geodezja, Kartografia i Fotogrametria,* 71, 14-25 (in Polish).

Orzechowski, M., Trzcianowska, M. (2016). Zadrzewienia śródpolne w gospodarowaniu przestrzenią, in: *Studia i Materiały Centrum Edukacji Przyrodniczo-Leśnej,* 16(5), 153-163 (in Polish).

Puchaczów - System Informacji Przestrzennej, puchaczow.e-mapa.net (08.01.2018)

Raszeja, E. (2010). Struktura krajobrazu rolniczego w Parku Krajobrazowym im. gen. Dezyderego Chłapowskiego, in: *Acta Scientiarum Polonorum. Administratio Locorum*, *9*(1), 97-110 (in Polish).

Richling, A., Solon, J. (2011). *Ekologia krajobrazu*. Warszawa: PWN (in Polish).

Rizov, M. (2005). Rural development under the European CAP: The role of diversity, in: *The Social Science Journal, 42*, 621.

Rylke, J., Gąsowska, M. (2009). Wartości krajobrazu wiejskiego i przemysłowego dla rozwoju rekreacji na przykładzie wsi warmińskich i kanału elbląskiego, in: *Nauka Przyroda Technologie*, 3(1), #33, 1-10 (in Polish).
Ryszkowski, L. (1998). Nature-friendly farming. Shelterbelts in Polandin: *Naturopa*, *86*, 9.
Sonnenfeld, J. (1967). Environmental perception and adaptation level in the Arctic, in: *Environmental perception and behavior,* ed. D. Lowenthal, University of Chicago, Department of Geography, Research Paper. 109, 42-59.
Szopińska, E. et al. (2016). Evaluation of the Landscape – Review of Selected Methods, in: *Architektura Krajobrazu*, *2*, 54-71 (in Polish).
Tveit, M. S, et al. (2018). Visual Landscape Assessment and Human Landscape Perception, in: *Environmental Psychology: An Introduction, Second Edition,* ed. Steg L., de Groot J. I. M., Great Britain: John Wiley & Sons Ltd. 46-51.
The Act of 27 April 2001. Environmental law. Journal of Laws of 2001, No. 62, item 627 as amended.
The Act of 27 March 2000, on Planning and Spatial Development. Journal of Laws of 2003, No. 80, item 717.
The Revitalization Act of 9 October 2015. Journal of Laws of 2015, item 1777.
Waszak, A. (2002). Drzewa i krzewy na obrzeżach miast, in: *Przegląd Komunalny* *6*(18): 76-77 (in Polish).
Wejchert, K. (1984). *Elementy kompozycji urbanistycznej*. Warszawa: Arkady (in Polish).
Wrochna, A. (2012). System informacji geograficznej o jednostkach architektoniczno-krajobrazowych. Źródła kartograficzne w badaniach krajobrazu kulturowego, in: *Prace Komisji Krajobrazu Kulturowego*, *16*, 95-104 (in Polish).

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Variabilities of Surface Water Quality of Degraded Post-mining Areas in Bytom

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Abstract: In the paper there is presented an evaluation of variability of surface water quality (reservoirs and watercourses), on the area of degraded post-mining area in Bytom. The physicochemical analysis of water and compared with archival data obtained in 2009 and 2014. There were done analysis of following parameters: reaction, total content of substances dissolved in water, water hardness and the content of: Cl^-, SO_4^{2-}, HCO_3^-, Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, NO_3^-, NO_2^-, PO_4^- ions as well as Fe and Mn. The examined surface waters were characterised by high content of solutes. Anions were dominated by chlorides, the sodium proved to be the dominating cation, the examined water samples were characterised by high concentration of sulphates. In all analyzed reservoirs, permissible concentrations of chlorides and sulphates were exceeded. In all sample points there was observed a decrease of pH value in long term period, the concentration of chlorides lowered, however concentrations of sulphates increased in the majority of sampling points.

Keywords: degraded post-mining areas, quality of surface water, reclamation

1. Introduction

Degraded post-mining areas represent complicated, complex genesis as well as different environmental problems. One of the important problem is the issue of surface water protection. A good example of post-mining area is former Rozbark mine site in Bytom, where a surface water monitoring have been conducted for 10 years.

Investigated are is an example of an interesting and natural valuable greenery terrain of Bytom, showing significant influence of anthropogenic pressure. The storage of communal and mining wastes of the land's surface and surface water contamination belong to the most important environmental problems in the described area. Coal, as well as Zn and Pb ores exploitation resulted in subsidence, collapses and construction of dumps, which led to the disturbance of natural water circulation. A particular characteristic of the area is the diversity of different anthropogenic landforms and types of wastes. The main impact of underground mining in study area is presence of subsidences, which caused origin of anthropogenic water reservoirs. Another important factor of post-mining character of the terrain is the vicinity of mining waste dump, which influence of the concentrations of chemical compounds, particularly chlorides and sulphures.

In the area connected with the mining activity, surface and groundwater chemistry was formed as a result of mine drainage, which begins from the intensive weathering of waste dumps. Finally, this process may lead to heavy acidification and increase the concentration of sulphates and metals in the water. Mine drainage is observed especially in ore, coal mine and waste dumps, where waste rocks are exposed to atmospheric factors. In Poland, this problem occurs eg. in coal mines, which are located in the southwestern part of the Upper Silesian Coal Basin (Pluta 2004), in the eastern part of the Arch of Muskau (Labus & Skoczyńska 2013), in the Częstochowa region (Razowska 2001) and in the vicinity of the mine waste dumps (Twardowska et al. 1988, Szczepańska 1990, Gawor & Lutyńska 2015). In the area of former mine Rozbark in Bytom, the influence of acide drainage is also observed.

2. Characterization of study area

2.1. Localization

The post-mining degraded area of the former coal mine Rozbark is situated in the southern part of Bytom, in the neighbourhood of Chorzów and Siemianowice Śląskie (Fig. 1), between the streets Cicha, Łagiewnicka and Krzyżowa, as well as municipal parc (Park Miejski im. A. Mickiewicza) and small stream Rów Graniczny.

As far as physio-geographical classification of J. Kondracki (2000) is concerned, investigated area is situated in the northern part of the Silesian Upland (Wyżyna Śląska), in the meso-region of the Katowice Upland (Wyżyna Katowicka) and in the Bytom-Katowice Plateau (Płaskowyż Bytomsko-Katowicki). These areas represent a terrain with relative elevations of 260-270 m a.s.l. A significant influence on the morphology of the land was derived from the mining exploitation (mining subsidences, coal mining waste dumps), as well as the exploitation of Zn and Pb ores.

The researched area has been used as a place of illegal waste storage for several years. As a result, water table and surface waters were exposed to contact with hazardous effluents from disposed waste. The wastes and effluents were also hazardous for the soil cover. The natural relief was transformed by of the rise of new hills and slopes built of waste. The degradation of the landscape influenced the aesthetics of the naturally rich and attractive area (Fig. 2).

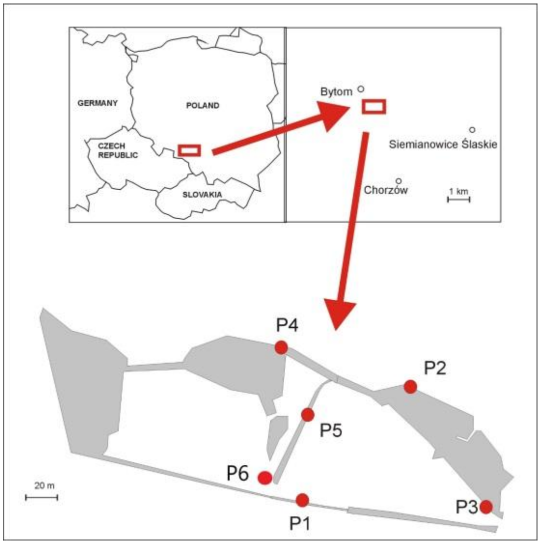

Fig. 1. Location of the study area and sampling points: P1-P6 – sampling points

Fig. 2. Study area in 2009 – illegal waste storage in the neighbourhood of water reservoirs (phot. Ł. Gawor)

2.2. Geological composition

The lithological-stratigraphic description of the study area includes the Carboniferous, Triassic, Jurassic, Paleogene, Neogene and Quaternary layers. The layers older than the Carboniferous were not taken into consideration, because of their low significance for reclamation processes. The oldest stratigraphic cell significant for the conducted work represent Carboniferous coal deposits, as well as accompanying rocks, associated with mining activity, which started more than 100 years ago in the region (Gabzdyl 1999).

The Carboniferous orogeny was recognized in the study area from the coal seam 401 rudzkie beds, until the seam 621 of the porębskie beds. Geological data on these seams are important, because they form the only basis on which the composition of the mining wastes disposed in the area may be concluded. In this site, the following beds are distinguished: rudzkie, siodłowe and porębskie. The rudzkie beds occur in a form of alternating layers of sandstones, mudstones and siltstones with coal seams. The siodłowe beds are the most rich in coal Carboniferous layers and represent a complex of sandstones (sometimes also conglomerates) with an admixture of siltstones. The thickness of the coal seams in this area reaches 9-12 m – coal seam 510). The porębskie beds are characterized by the dominance of siltstones and mudstones over sandstones. The coal seams show large variability in thickness (Mgłosiek 1998).

The Triassic deposits on the whole area reach significant thickness. Particularly sedimentary rocks from Muschelkalk are well developed. They are represented by different types of dolomites with Zn-Pb ores, comprised of ore minerals like sphalerite and galena. The thickness of carbonate rocks reaches 100 m (Gabzdyl 1999). Under the carbonate layers, deposits of the Lower Triassic – Bundsandstein, of which the main part (ret) is represented by limestone, marls and dolomites with an admixture of silts, can be found. Lower and medium Bundsandstein is built of silts, sands, gravels and sandstones.

In the neighbourhood of study area occur small patches of Jurassic deposits, which belong to Liass. Lithologically they represent multi-colour silts and clays with limonite as well as sands.

There is a thick layer of Miocene deposits, represented by marl silts, sands, sandstones, gypsum and tuffite. The Pleistocene layers are represented by ground moraine sediments, shaped as sands, clays and sandy clays with admixture of humus. The Holocene layers are represented by fluvial deposits – sands, clays and sandy clays with an admixture of humus. The thickness of these deposits reach 2.0-6.0 meters.

2.3. Hydrological and hydrogeological conditions

The hydrogeological conditions of the Upper Silesian Coal Basin are shaped by two factors: a natural factor, which is the influence of the geological composition of the region, as well as the mining factor. Groundwater flow occurs in the Neogene, Triassic and Carboniferous deposits.

Water-bearing strata and the quality of groundwater depend on mining exploitation and mine drainage. The study area is situated in the zone of degraded groundwater covering a surface of ca. 177 km^2. The mines located in the neighborhood of the Bytom-Rozbark are characterized by different inflows. Their intensity is connected with the hydraulic contact of the mining works with the water table in Triassic rocks. As a consequence of long-term mine drainage of the Bundsandstein, the water table has been dropping systematically (Kropka et al. 1998). The long-term mining exploitation of Zn-Pb ores and hard coal, in the neighborhood of the study area, has caused changes in the morphology of the ground surface. The mining subsidence and waste dumps leads to disturbances in natural water circulation. Changes in water conditions were caused, for example, by local inundation of the ground surface (Girczys, Sobik-Szołtysek 2002). The study area designated for reclamation belongs to the catchment of the Bytomka River and is situated on the Bytomka's tributary – "Rów Graniczny". In the terrain depressions, three ponds linked together are to be found. There is no natural outflow from water reservoirs. Water which recharges the ponds comes from precipitation and infiltration from the "Rów Graniczny" (Fig. 3-4).

Fig. 3. The stream "Rów Graniczny" (phot. Ł. Gawor)

Fig. 4. The pond in the central part of study area (sampling point P4) – low level aerial photograph (phot. Ł. Gawor)

3. Materials and methods

Surface water samples were collected in May 2018 at 6 measurement points: P1 – control profile of "Rów Graniczny"; P2 – shallow pond overgrown with water plants; P3 – shallow pond overgrown with water plants; P4 – shallow pond; P5 – tributary to the pond; P6 – tributary to the pond. Situation of sampling places referred to the samples taken in 2014 (measurement points P1-P5). Because of variable spatial conditions it was not possible to copy sampling place in P4 point. In the point 6 there was taken a sample only in 2018.

The places of collecting of the samples have been chosen regarding different kinds of surface water occurrence – ponds as stagnant water and streams and tributaries as flowing water. Between sampling points there was observed water flow.

What was measured as part of chemical analysis were: reaction, total content of substances dissolved in water, water hardness and the content of: Cl^-, SO_4^{2-}, HCO_3^-, Ca_2^+, Mg_2^+, K^+, Na^+, NH_4^+, NO_3^-, NO_2^-, PO_4^- ions as well as Fe and Mn. The analyses were carried out in the chemical laboratory of the Department of Applied Geology of the Silesian University of Technology in Gliwice.

PH-value was marked with the use of ELMETRON – CX-742 multifunction meter, dry residue was analysed according to the gravimetric method, water hardness by means of versenate test, while the content of chloride ions by using titration method. HCO_3^- and Na^+ ions concentration was established by concentration method. Remaining ions were tested by means of SLANDI LF – 205 microprocessor photometer.

In 2009 there was done a complex technical and biological reclamation. There was done an inventarization and classification of wastes, which have been removed, what have had a key influence on the improvement of surface water of investigated area. The analysis and evaluation of complex reclamation including surface water quality has been done after 10 years. The study area has been restored, the impact of communal wastes and mining wastes has been diminished, what was one of the reasons that Authors decided to compare quality of surface water in mentioned above periods.

4. Results

Results of the analysis are shown in Table 1.

Table 1. Results of the chemical analysis of surface water

Parameter/Analysis	Units	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
Dry residue	mg/dm^3	3072	2956	1650	4706	4723	4409
pH		7.15	6.87	7.48	7.03	7.08	7.07
Total hardness	°n	54.68	47.67	32.25	72.9	72.9	65.89
Carbonate hardness	°n	23.83	22.71	13.18	31.4	31.97	27.48
Non-carbonate hardness	°n	30.85	24.96	19.07	41.5	40.93	38.41
Chlorides	$mg\ Cl/dm^3$	763.25	869.75	550.25	1331.25	674.5	1278
Sulphates	$mg\ SO_4/dm^3$	1030	875	345	1850	1940	1670
Bicarbonates	$mg\ HCO_3/dm^3$	517.111	492.807	286.006	681.38	693.749	596.32
Calcium	$mg\ Ca/dm^3$	210.42	150.3	110.22	290.58	250.5	250.5
Magnesium	$mg\ Mg/dm^3$	109.44	115.52	72.96	139.84	164.16	133.76
Potassium	$mg\ K/dm^3$	35	32	11	23	40	36
Sodium	$mg\ Na/dm^3$	395.46	416.38	270.48	388.63	958.15	442.38
Ammonium nitrogen	$mg\ NH_4/dm^3$	0.3	0.3	0.2	< 0.1	0.2	0.2
Nitrates	$mg\ NO_3/dm^3$	10.7	3.5	3.4	0.9	1.5	1
Nitrites	$mg\ NO_2/dm^3$	< 0.02	0.02	0.08	0.04	< 0.02	0.03
Phosphates	$mg\ PO_4/dm^3$	< 0.2	< 0.2	0.4	< 0.2	< 0.2	0.4
Manganese	$mg\ Mn/dm^3$	0.12	0.32	< 0.05	0.38	0.24	0.31
Iron	$mg\ Fe/dm^3$	0.2	0.1	< 0.05	< 0.05	< 0.05	0.1

The examined surface waters were characterised by high content of solutes, ranging from 1650 mg/dm^3 in P3 sampling site to 4 723 mg/dm^3 in P4 and by slightly alcaline reaction. The only exception was the sample collected in P2 site, whose reaction was slightly acid.

According to Pazdro (1990) classification, as regards hardness, the tested waters can be considered very hard and with the predominance of non-carbonate type.

Anions were dominated by chlorides, whose concentration ranged from 550.25 mg Cl/dm^3 in water collected in P3 site to 1331.25 mg Cl/dm^3 in P4. Sodium proved to be the dominating cation and its concentration ranged from 270.48 mg Na/dm^3 in P3 site to 958.15 mg Na/dm^3 in P5.

The examined water samples were characterised by high concentration of sulphates; with the highest concentration observed in samples collected in P5 and P4 sites and amounting to 1940 mg SO_4/dm^3 and 1850 mg SO_4/dm^3 respectively. Calcium content ranged from 110.22 mg Ca/dm^3 (P3) to 290.58 mg Ca/dm^3 (P4), while that of magnesium from 72.96 mg Mg/dm^3 (P3) to 164.16 mg Mg/dm^3 (P5).

Water with the lowest level of mineralisation, collected in P3 site, had the highest concentration of nitrites (0.08 mg NO_2/dm^3) and phosphates (0.4 mg PO_4/dm^3). At the same time, it was characterised by the lowest concentration of manganese and iron – below 0.05 mg/dm^3. The highest concentration of these metals could be observed in sites: P4 (0.38 mg Fe/dm^3), P2 (0.32 mg Fe/dm^3) and P1 (0.2 mg Mn/dm^3). Concentration of potassium ranged from 11 mg K/dm^3 in P3 site to 40 mg K/dm^3 in P5 and that of nitrates also varied, amounting to 0.9 mg NO_3/dm^3 in P4 site and 10.7 mg NO_3/dm^3 in P1.

In order to determine how the quality of water changed in the course of time, results of this research were compared to those from 2014 and 2009. The exceptions were water samples taken at the measurement point P6, which were not included in the analysis from previous years. When compared to the analysis from 2014, all the sampling sites proved to have a decreased reaction value of water. Concentration of chlorides in samples collected in sites P1, P4 and P5 was lower in comparison to the samples collected in 2009 and 2014. The most significant decrease was observed in P1 site, where concentration of chlorides decreased by approximately 41% in comparison to 2009 and by 61% when compared to 2014 (Fig. 5).

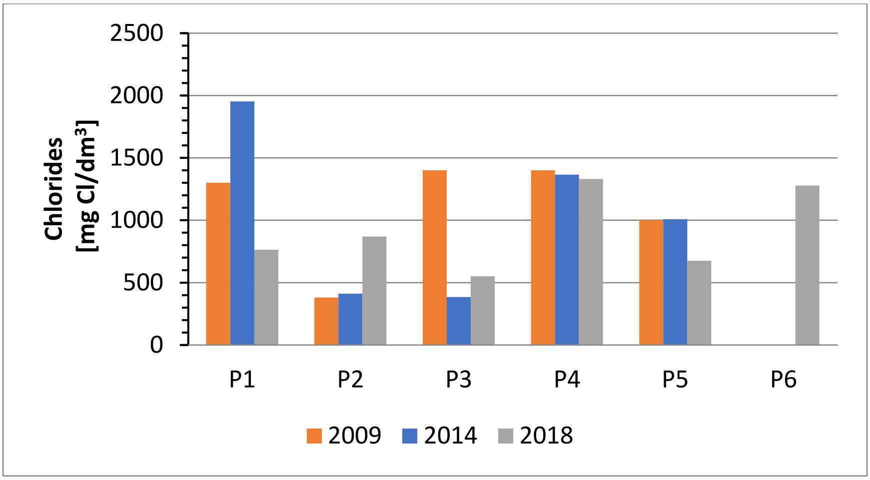

Fig. 5. Concentration of chlorides in the sampling sites

In P2 and P3 sampling sites, concentration of chlorides increased by 111% and 43% respectively in comparison to 2014.

In comparison to 2014, concentration of sulphates increased in water samples collected in all the sampling sites except for P1 (Fig. 6).

The most notable difference as regards concentration was observed in P2 sampling site, where the content of sulphates increased from 428 mg SO_4/dm^3 to 875 mg SO_4/dm^3. In P1 site a decrease was observed in the content of sulphate ions by 33% when compared to 2009 and 38% in comparison to 2014.

A similar tendency can be observed as regards Ca^{2+} and Mg^{2+} ions. In the surface water samples collected in 2018 in P2, P3, P4 and P5 sampling sites, both calcium and magnesium concentration is higher than in the samples which were analysed in 2014 (Fig. 7 and 8).

The most considerable difference was noticed in P3 sampling site, where concentration of calcium increased by 83% in comparison to the results from 2014, as well as in P2 site in which the concentration of magnesium increased by 179% when compared to the samples collected in 2014.

In comparison to the results from 2009 a considerable decrease was noticed in the content of ammonium ion in the examined water samples (Fig. 9). Concentration of that particular ion observed in water in 2018 was lower, by 44% in P2 site and by 91% in P4, when compared to the results from 2009.

In reference to 2014, decreased concentration was observed only in two sampling sites, which are P2 and P3. In P1 site one could observe an increased concentration of ammonium ion in comparison to the two previous measuring series (Fig. 9).

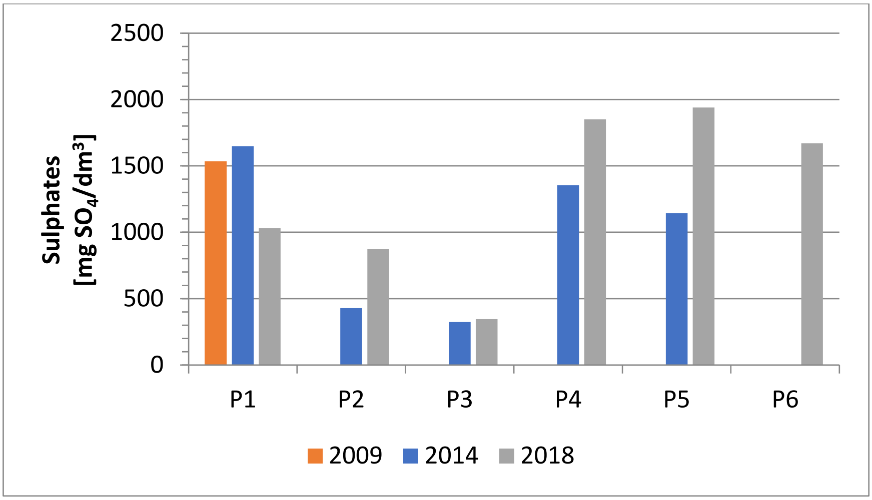

Fig. 6. Concentration of sulphates in the sampling sites

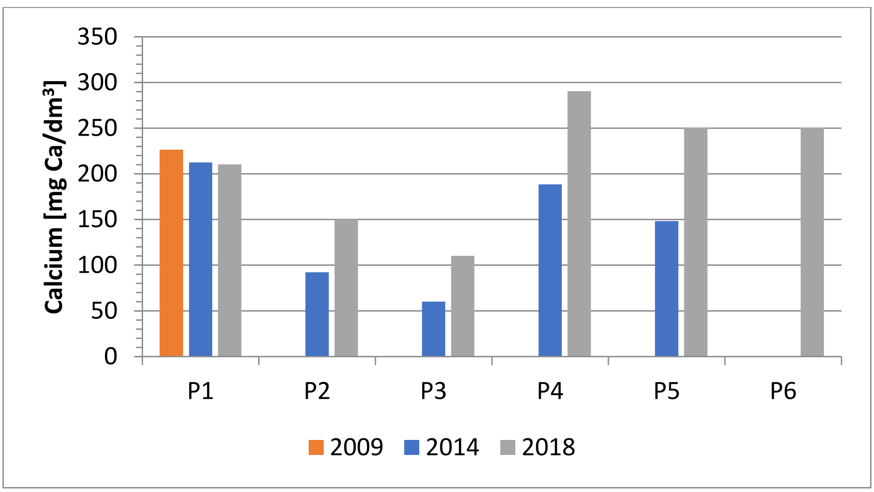

Fig. 7. Concentration of calcium in the sampling sites

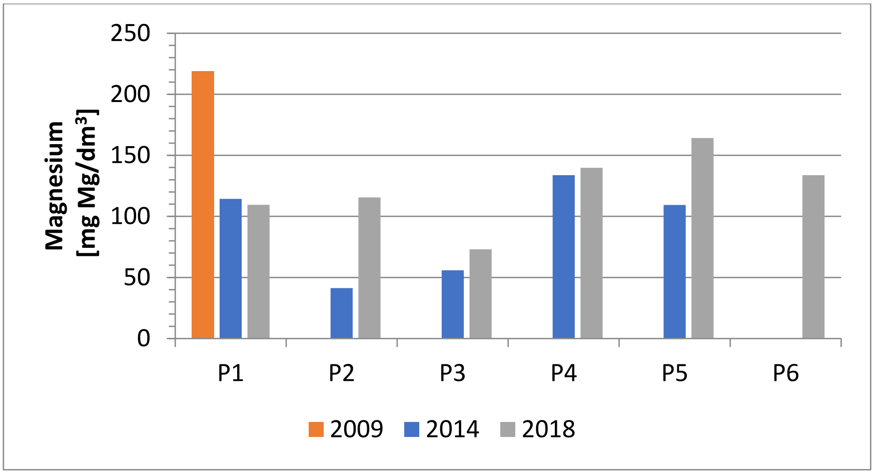

Fig. 8. Concentration of magnesium in the sampling sites

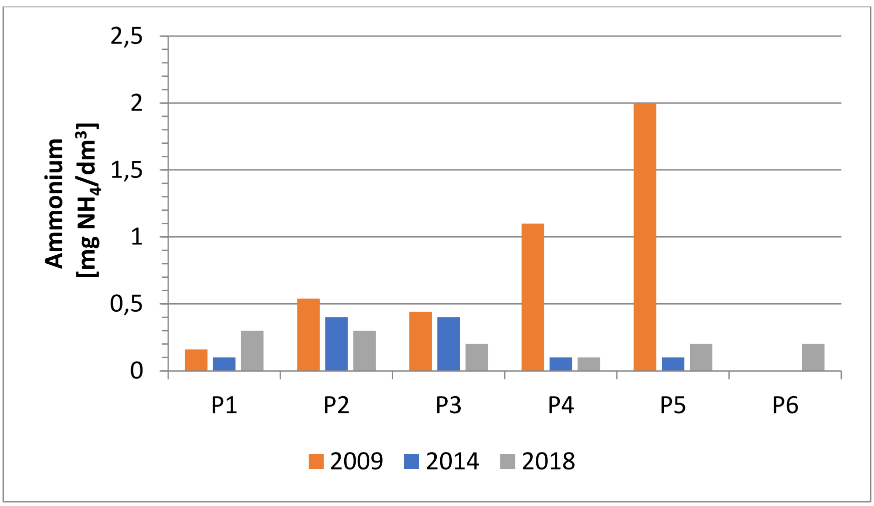

Fig. 9. Concentration of ammonium ion in the sampling sites

Concentration of nitrates was the highest in 2018 in all the sampling sites, except for P4 (Fig. 10). In comparison to the results from 2014, concentration increase was noticed in sites P5 (by 88%) and P1 (by 1683%).

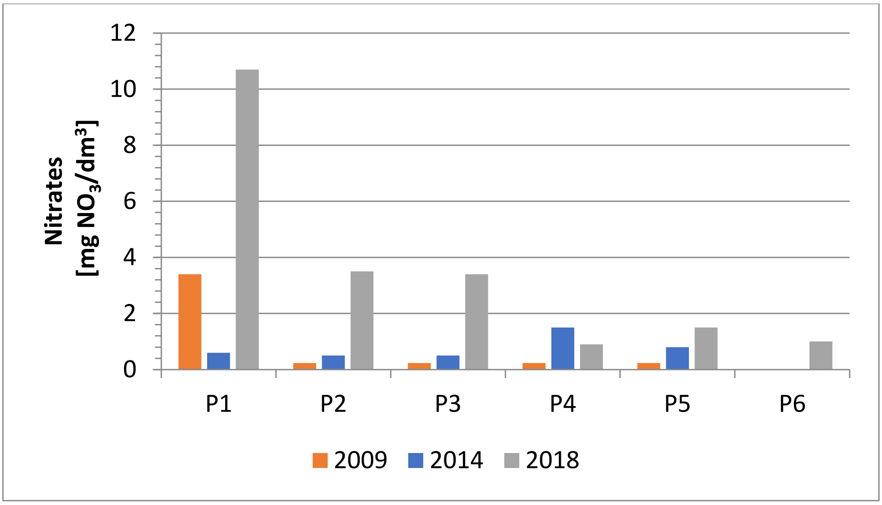

Fig. 10. Concentration of nitrates in the sampling sites

Area of disposed wastes and degraded water reservoirs in Bytom presents interesting, but not typical area, where surface water has been tested. In the literature (Pluta 2004, Labus & Skoczyńska 2013, Twardowska et al. 1988, Szczepańska 1990, Wiggering & Kerth 1991) the problem of contamination of surface water in post mining areas is limited to waste dumps or considers regions of open-pit exploitation (Cała, Bismarck & Illig 2014). Only one position of literature describes similar study area, but in different period of time (Gawor & Lutyńska 2015). A part of results which can be compared is presence of chlorides and sulphates in surface water, what is typical for coal mining wastes and geochemical processes occurring in these wastes. The values of mentioned chemical compounds are higher in similar mining areas like e.g. Ruhr Basin (Wiggering & Kerth 1991, Melchers, Westermann & Reker 2020).

5. Summary and conclusions

Area of disposed wastes and degraded water reservoirs in Bytom represent interesting and valuable terrain having though high degree of anthropogenic pressure and implicating environmental problems. To the most important problems belong negative impact of disposed on the land`s surface wastes and the issue of surface water protection.

In 2009 there was done a complex technical and biological reclamation. There was done an inventarization and classification of wastes (stored on the land`s surface and in the water reservoirs), which have been removed, what have had a key influence on the improvement of surface water of investigated area. The analysis and evaluation of complex reclamation including surface water quality has been done after 10 years. The results are positive and it should be outlined the complexity of environmental issues, which required interdisciplinary knowledge on project and reclamation stages.

In the first five years no significant improvement of water quality has been observed (Gawor & Lutyńska 2015). In the majority of collected samples the permissible concentrations of chlorides and sulphates were high and exceeded. On this basis, it seems that the waste dumps located in the analysed area have not been completely leached yet, which causes additional pollution and the migration of pollutants to the surface water. It can be assumed that the self-purification processes occurring in the aquatic environment are so slow, that they do not lead to perceptibly natural elimination of the pollutants.

After 10 years since finishing the reclamation the anions were dominated by chlorides, the sodium proved to be the dominating cation, the examined water samples were characterised by high concentration of sulphates. In all analysed reservoirs, permissible concentrations of chlorides and sulphates were exceeded. This may be caused by presence of coal mining wastes in the northern part of study area. Although a part of this wastes has been removed (lying in the direct vicinity of the pond), the other part of the dump still exists and precipitation water infiltrates through waste material.

In all sample points there was observed a decrease of pH value in long term period, the concentration of chlorides lowered, however concentrations of sulphates increased in the majority of sampling points.

Comparing analysed project with numerous similar projects in the area of the Upper Silesian Coal Basin it should be outlined that it represents one of the most interesting realizations concerning both the complexity and effective management of the terrain.

References

Cała, M., Bismarck, F. & Illig M. (2014). *Geotechnical and environmental aspects of reclamation and revitalization of post-mining areas*. PH AGH, Kraków (in Polish).

Gabzdyl, W. (1999). *Mineral deposit geology*. Series: Skrypty Uczelniane – Politechnika Śląska im. Wincentego Pstrowskiego, 2163, Publishing House of the Silesian University of Technology (in Polish).

Gawor, Ł. & Lutyńska, S. (2015). Assessment of water quality of degraded anthropogenic reservoirs situated in the area of the former coal mine Rozbark in Bytom. *Geol. Geophys. Environ. 41*(3), 249-256.

Girczys, J. & Sobik-Szołtysek, J. (2002). Waste from zinc-lead industry. Series: Monografie – Politechnika Częstochowska, 87, PH Częstochowa University of Technology (in Polish).

Kondracki, J. (2000). Regional geography of Poland. Warszawa: PWN (in Polish).

Kropka, J., Kowalczyk, A. & Rubin, K. (1998). *Hydrogeological map of Poland in the scale of 1:50 000*. Arkusz Bytom. Warszawa: Państwowy Instytut Geologiczny (in Polish).

Labus, K. & Skoczyńska, S. (2013). Origin of sulphates in the post-mining lakes in the eastern part of Muskau Arch (Polish-German borderland). *Geological Quarterly, 57*(3), 561-566.

Mgłosiek, J. (1998). *The diversity of coal's quality in Niecka Bytomska on the example of deposits 407/1 and 507 in KWK Rozbark's mining area*. Archiwum Instytutu Geologii Stosowanej (in Polish).

Melchers, C., Wastermann, S., Reker, B. (2020). *Evaluation of Mine Water Rebound Processes*. Selbstverlag des Deutschen Bergbau-Museums, Bochum.

Pazdro, Z. & Kozerski, B. (1990). *General hydrogeology*. Warszawa: Wydawnictwa Geologiczne (in Polish).

Pluta, I. (2004). Acid waters in mines on southwest area of Upper Silesian Coal Basin. *Przegląd Górniczy, 2*, 20-23 (in Polish).

Razowska, L. (2001). Changes of groundwater chemistry within the flooded iron mines area in the Czestochowa Region (Southern Poland). *Journal of Hydrology, 244*, 17-32.

Feasibility study, Project's discharge report, technical specification and technical documentation on the need of conclusion relevant to endowment as a matter of subregion development programme of central regional operational programme "Reclamation of degraded waters in Bytom'', 2009, Bytom (in Polish).

Szczepańska, J. (1990). Coal mining dumping grounds as source of the natural water environment pollution. Series: *Zeszyty Naukowe Akademii Górniczo-Hutniczej im. Stanisława Staszica. Geologia, 35*, AGH, Kraków (in Polish).

Twardowska, I., Szczepańska, J. & Witczak, S. (1988). Influence of hard coal's mining waste on water environment: threat assessment, prediction and prevention. Series: *Prace i Studia – Polska Akademia Nauk. Instytut Podstaw Inżynierii Środowiska, 35*, Zakład Narodowy im. Ossolińskich, Wrocław (in Polish).

Wiggering, H., Kerth, M. (1991). Bergehalden des Steinkohlenbergbaus. Vieweg, Braunschweig / Wiesbaden.

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Designing a Small Water Power Plant in Poland in the Aspect of Minimizing the Impact on River Ecosystem

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Abstract: A small hydro-power plant designing in aspect of current legislation is an interdisciplinary problem because of the fact that efficiency priority is not so important as ecological one. In this article the regulations concerning permissions for plant operation are discussed. The small hydro-power plant designing criteria are presented in the aspect of a plant impact on the river ecosystem.

Keywords: hydropower plant multi-criterial designing, fish protection, environmental protection, CFD

1. Introduction

European Union, by implementing directives on the share of renewable energy sources (RES) in the energy balance, such as Directives 2009/28/EC and 2001/77/EC, predicts that in the year 2020, the member states will achieve a twenty percent share of renewable energy sources in final energy consumption. In the case of Poland, this level was set at fifteen percent, which is still a huge technological, political and economic challenge. It should also be noted that ensuring access to energy in accordance with the principle of sustainable development, i.e. in the interest of proper development of civilization while maintaining all environmental resources for future generations, is now a priority of world politics. Therefore, the search for new technological solutions in the field of renewable energy requires taking into account widely understood environmental impact in the design process.

Small Hydroelectric Power Plants (SHPP) are generating units which, due to their lower capacity are most often connected to low voltage lines, less often to medium voltage lines. In the farthest point from the transformer stations, the voltage will be lower than at the station itself (due to voltage drops and the so-called transmission losses). As a result, voltage drops will also be more dangerous and visible. Location at a point in the network between the network and the recipient of the source generating low voltage will limit the possible voltage drop, counted from the source to the recipient. At the point of connection of a small hydropower plant to the network, regardless of the voltage value before it is connected, it will be increased and will aim to the value generated from the power plant.

Additionally, the use of micro sources in low-voltage networks results in a favorable current flow limitation. After switching on the power plant at a point in the network far away from the transformer station, partial demand of the recipients behind the small hydropower plants will be supplied from a micro source. Thanks to this, with the increase in electricity demand the modernization or expansion of the distribution network will not be required or it may be postponed.

Renewable energy sources (including SHPP) are susceptible to changing weather conditions (mainly the amount of rainfall in the catchment area), which forces the electricity market to have power reserves that can compensate for these fluctuations. The replacement by intermittent RES, has two-fold effect on power systems: reduction in inertia and intermittent generation, lead to the degradation of the frequency stability. In modern power system, the frequency regulation (FR) has become one of the most crucial challenges compared to conventional system because the inertia is reduced and both generation and demand are stochastic (Umer et al. 2020). Currently, a number of studies (Pradhan et al. 2021, Hunt et al. 2021, Xin et al. 2021) are being carried out in the field of energy storage solutions (mainly from renewable energy sources) that enable the balancing of the electricity availability profile regardless of weather conditions.

One example is an innovative energy storage solution based on "buoyancy energy storage" in the deep ocean. The ocean has large depths where potential energy can be stored in gravitational based energy storage systems (Hunt et al. 2021). An interesting proposal for storing energy is storage in the form of hydrogen. Hydrogen has a good potential for energy storage because it can tackle the spatial differences in renewable energy supply, but its storage in compressed gas or cryogenic liquid form incurs high investment cost. Liquid organic hydrogen carrier offers a much cheaper and more convenient way of storing hydrogen as compared to conventional means (Xin et al. 2021).

Compared to other renewable energy sources, hydropower is characterized by very high productivity (Malicka 2018). In many countries (e.g. Norway, Switzerland, Brazil) it is the basic source of cheap and ecological energy that almost completely covers the country's electricity demand. Currently, there are 766 hydropower plants in operation in Poland with a total capacity of 988.377 MW, which in recent years, on average, generated approximately two thousand GWh/year of electricity from natural inflow. Of all hydropower plants, 685 are facilities with an installed capacity of no more than one MW. Total capacity of these installations is 103 MW and they generate approximately 320.5 GWh of electricity each year (Malicka 2018). Despite the small number of sites adequate for investments in large hydropower plants, it is estimated that there are nearly 6,000 sites with high potential for building small hydropower plants (Figure 1).

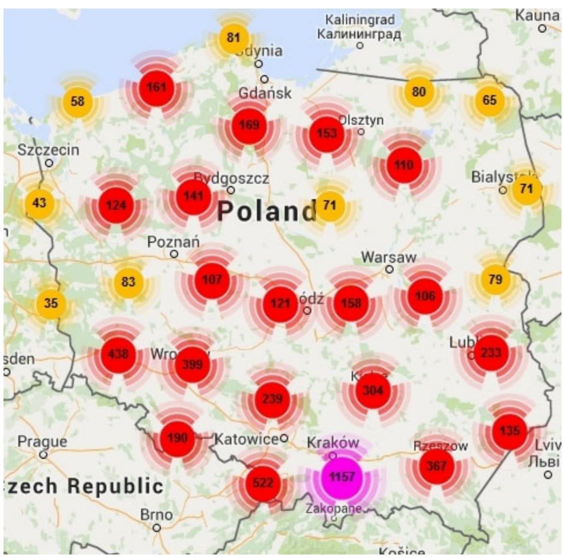

Fig. 1. Potential locations for SHP in Poland, http://www.restor-hydro.eu/restor-hydro-map/

With the exception of piedmont areas, the vast majority of dams that can be developed (or built) in Europe are low-fall (drop below 20 m), with ultra-low-fall objects (drop below 2.5 m) having the largest share (Malicka 2018).

Most European, including Polish, SHP installations are technologically outdated, having low efficiency and do not taking into account the ecological aspects of using water courses (e.g. protecting migrating fish). Moreover, they are not adapted to work on watercourses with low, medium flows and small falls (these conditions prevail in Poland and Europe). It is also important that many currently operated turbines will have to be replaced with new ones within a few years due to expiration of the existing water-legal permits enabling their operation. The amendment to water law shortened the validity of water permits to a maximum of 20 years since obtaining a final decision, and regulations of Regional Water Management Authority (RZGW) on the conditions of using the waters of water regions introduce numerous requirements. Permits cannot be renewed, but new permits must be obtained. Obtaining new permits in the light of the applicable legal regulations poses numerous challenges for designers.

A small hydropower plant is a hydropower facility listed in the Polish Act of July 20, 2017, Water Law, qualified for water facilities. The use of water for energy purposes is a special use of water, referred to in Art. 37 point 5 of Water Law. The execution of SHP and the use of water for energy purposes has not been mentioned in Art. 123a of Water Law, which means that it cannot be implemented on the basis of a water law notification. However, this requires obtaining a water law permit, which will set out the rights and obligations to an appropriate extent, resulting from Art. 128 of the Act, according to the information contained in a water law survey and other documents collected on the matter.

Small hydropower plants operating in Poland are currently struggling with the renewal of water permits due to the applicable legal regulations, but above all because of their different interpretations by administrative authorities issuing permits. The introduced regulations should apply to newly built devices, but many of them impose new obligations on the existing devices (Basiński 2015).

Current law makes it necessary to increase intact flow even on river courses with a highly developed infrastructure, poor in flora and fauna. This situation often determines profitability of further SHP's activity, as it directly translates into limitations in the amount of available water, which determines the efficiency of a power plant (Augustyn 2010, Basiński 2015, Khudhiri et al. 2018).

In addition, damming of watercourses' inland surface waters or their sections in question is unacceptable if the damming structures are not equipped with devices ensuring free migration of fish. There are now known cases of properly functioning fish passes, which although once received positive opinions, do not meet requirements for their operation. Such requirements include larger chambers due to planned restitution of salmon and other migratory fish species in particular streams (Malicka 2018).

2. The impact of small hydropower plants on a river ecosystem

Currently operating small hydropower plants, including micro-power plants with a capacity of less than 300 kW, have a detrimental effect on ichthyofauna. Losses in the natural environment of rivers and streams are very serious and threaten the survival of protected species. Basic problems related to location and operation of small power plants are: isolation of species occurring due to transverse development of rivers, blocking flows during the so-called low waters, causing channels to dry up and killing fish turbines. These threats also concern rivers flowing in protected areas, including Natura 2000 areas. Taking into account marginal energy potential of small hydropower plants, despite their large number (in the Pomorskie Voivodeship 86 power plants generate a total of 6.3 MW only), environmental damage caused by their operation is disproportionately high (Witkowski et al. 2009).

The quality of rivers depends on a catchment area, therefore their condition (especially biological) is the sum of all events taking place in the basin (Waters et al. 2015). Construction and operation of river infrastructure has many negative effects on flowing waters, mainly due to their natural continuity disruption. Division into separate parts of the previously homogeneous whole system causes rapid abiotic and biotic changes in the structure and functioning of a river. Their impact on ichthyofauna in the river below a partition is expressed by (Waters et al. 2015):

- physical changes to habitats,
- modifications to thermal, seasonal and daily water flow regime,
- changes in the availability of food base,
- changes in the composition and structure of fish communities leading to changes in biotic interactions.

An example of hydrotechnical infrastructure impact on biodiversity in the area of ichthyofauna is presented in Table 1.

Table 1. The numbers of fish caught in the Liw and Wierzyca rivers and the number of their species before and after the construction of hydrotechnical structures for the SHP and as a result of its operation (Witkowski et al. 2009)

River/fishing	*Year*	*Fish abundance*	*Number of species*
The number of fish caught on the site in Liw below the Młyniska power plant near Gąty in years 1999, 2004 and 2011	1999	228	11
	2004	116	9
	2011	44	9 (4 left but 1 arrived)
The number of fish caught on the site in Wierzyca below the power plant in Zamek Kiszewski in 1997 and 2012	1997	251	12
	2012	103	9 (4 left but 1 arrived)

As can be seen from the example presented in the table, construction and operation of SHP, despite obtaining water and legal permits for its commissioning, has a significant impact on the ecosystem.

Factors affecting, directly and indirectly, river ecosystem in the case of a small hydropower plant are:

- mechanical damage to fish bodies as a result of turbine rotor blades blows,
- damage to fish bodies as a result of pressure in a device (fish die sometime after leaving a device due to damaged gills),
- introducing lubricants to waters,
- vibrations and oscillations generated by devices,
- interference with a natural water threshold (construction works),
- disturbance of a river course natural continuum.

One of the technical solutions of a small, ecosystem-friendly hydropower plant is the use of a water turbine using an Archimedean screw (Waters et al. 2015, Dedic-Jandrek et al. 2019). By limiting pressure fluctuations and the speed of the flowing medium, aquatic organisms can flow through the power plant without damage. The Archimedes screw is regarded as one of the earliest hydraulic machines. It is built of a helical array of simple blades that are surrounding the central cylinder. The Archimedes screw is supported within a trough. A small gap separates the screw and the trough. It allows the screw to rotate freely. This design allows only a small amount of water to drain over the edges of the blades (Piper et al. 2018).

Another solution, proposed by the authores, is the advantageously selected shape of the blade of a slow-running water turbine. Due to the appropriate shaping of the stream of the flowing medium, the organisms located in the inter-blade space are repelled from the edge of the blades, which limits the possibility of mechanical damage to the organisms.

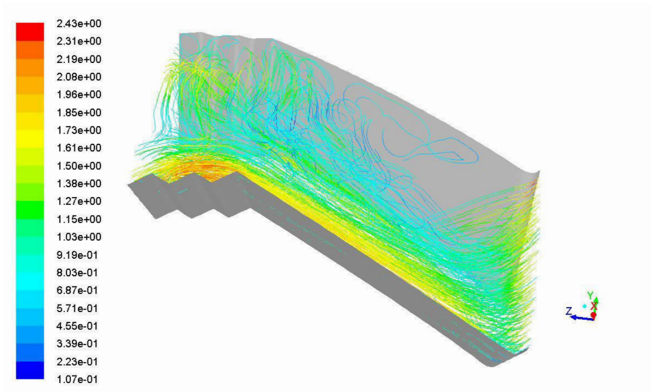

Fig. 2. Stream lines in the interscapular space (own research)

Fish passes can also be an alternative. The specificity of modern ecological fish passes is the variability of their construction parameters, which must be adapted to the biological requirements of the fauna inhabiting the river (fish, invertebrates) and the local conditions of the investment implementation. The biological and environmental conditions that inspire the fish to migrate and the limited ability to overcome obstacles on their way constitute the basis for the design assumptions of these devices. Their common feature is a loose structure, maintaining a system of gaps and gaps. These devices can be constructed in the form of (Wiśniewolski 2003):

- walk around imitating natural streams that avoid the obstacle,
- half-timbered fish passes (a combination of a bypass and a chamber fish pass), where the partitions separating individual chambers are made of loosely positioned boulders, between which a system of different widths of gaps is left,
- rapids (ramps), imitating the gorge sections of the river strewn with boulders and stones.

These design proposals are complemented by slot fish passes, intended for high damming in the terrain conditions preventing the execution of a sufficiently long ecological fish pass.

The diversity of environmental conditions, the degree of transformation of river ecosystems and the hydrotechnical structures existing on them, forces an individual approach to each situation of building a fish pass. Each of them is an individual, unique structure. Using the already developed solutions, the technical parameters of several selected types of fish passes are given in the further part of the paper. They should be treated as examples that, after modification taking into account local conditions, can be used in the development of new designs of fish passes built to restore the ecological permeability of Polish rivers.

3. Obtaining water legal permits

In order to obtain a water permit, an application must be submitted to the State Water Holding of Polish Waters. The most important elements of the set of documents are:

a) application for a water permit,
b) water law survey,
c) description of the intended activity,
d) decision on environmental conditions,
e) an excerpt and a sketch from a local spatial development plan,
f) decision to determine the location of a public purpose investment,
g) decision on development conditions,
h) water law assessment,
i) excerpts from a land register or simplified excerpts from a land register for real estate located within the range of the impact of the intended water use or within the range of the impact of the planned water facilities,
j) draft water management manual,
k) hydrogeological documentation.

The most important and problematic element of the application is the water law survey. The survey is made in writing in a descriptive and graphical form, as well as on IT data carriers as a text document, and the graphic part of the survey in the form of raster-type files (PDF) or files in vector format of spatial data, mapped in one of the applicable geodetic coordinate systems (Radtke et al. 2012).

The descriptive part of the water law survey (adjusted to the type of activity covered by the water law permit) includes, inter alia (https://wody.gov.pl/pozwolenie-wodnoprawne):

- specification of the purpose and scope of the intended use of water, the purpose and type of planned water facilities or works, the type of measuring devices and shipping signs, the type and range of impact of the intended use of water or the planned water facilities, the legal status of real estate located within the range of impact of the intended use of water or water facilities

planned to be constructed, specifying the seats and addresses of their owners – in accordance with the land and building records, obligations of the applicant for a water permit in relation to third parties;
- description of the water device, including basic parameters characterizing this device and the conditions for its implementation, and its location by means of information on the name or number of the cadastral area with the number or numbers of registration plots and coordinates;
- characteristics of the waters covered by the water permit;
- land use plans, river basin management plan, flood risk management plan, drought counteracting plan, marine water protection program, national municipal wastewater treatment program, plan or program for the development of inland waterways of special transport importance;
- determination of the impact of planned water facilities or water use on surface waters and groundwater, in particular on the condition of these waters and the implementation of environmental objectives specified for them;
- the size of the intact flow, the method of its calculation and reading its value at the point of water use;
- the size of the multi-year average low flow (SNQ) or groundwater resources;
- the planned start-up period, the procedure to be followed in the event of start-up, stoppage of operations or failure of devices essential for the implementation of the water permit, as well as the size and conditions of water use and water facilities in these situations, along with their maximum permissible duration;
- information on forms of nature protection created or established pursuant to the Act of 16 April 2004 on nature protection, occurring within the range of the impact of the intended water use or water facilities planned to be constructed.

The graphic part of the water law survey includes, inter alia, (Witkowski et al. 2009):
- the plan of water facilities and the impact range of the intended use of water or water facilities planned to be constructed, along with their surface, marked on the situational and height map of the area, with the property marking;
- basic longitudinal and transverse sections of water devices and flowing water channels within the range of their impact;
- the diagram of the measuring devices’ arrangement and shipping marks;
- functional or technological diagram of water devices.

Another important document, the quality of which has a key impact on obtaining a permit, is the decision on environmental conditions, which specifies, inter alia, (Witkowski et al. 2009):

- conditions of land use at the stage of implementation and operation or use of the project, with particular emphasis on the need to protect valuable natural values, natural resources and monuments, and to reduce nuisance to neighbouring areas;
- environmental protection requirements necessary to be included in the documentation required to issue other decisions listed in Art. 72 sec. 1 of the Act on the provision of information on the environment and its protection, public participation in environmental protection and environmental impact assessments on a building permit, approval of a construction design or a permit to resume construction works. In particular, these requirements must be included in the construction design necessary for the issuance of certain decisions, e.g. a building permit, a permit to resume construction works, or a permit for a road investment.
- requirements for limiting transboundary environmental impact in relation to projects for which the procedure for transboundary environmental impact was carried out.

The most important factor guaranteeing obtaining a water permit for the operation of SHP is undoubtedly its appropriate design in the light of applicable regulations - primarily regarding its impact on the environment.

4. Design guidelines for small hydropower plants in the aspect of obtaining water legal permits

Designing flow devices requires a multi-criteria concept, taking into account phenomena occurring in liquids. Currently, designers are helped by the latest computer-aided design tools. An example of such an approach is the Zawiślak method presented in Figure 3 (Zawiślak 2017).

The application of the method includes the design of a water turbine for SHP, but it is extremely important to correctly formulate the problem to obtain a technical solution that can meet the requirements of a water permit and to be used to prepare the survey. In this case, the efficiency criterion of the device gives way to the priorities related to environmental protection.

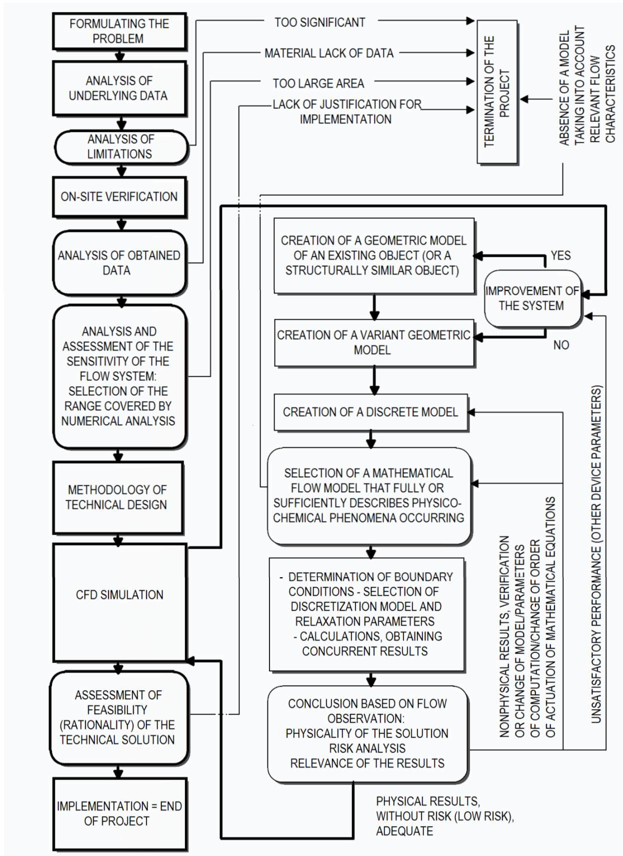

Fig. 3. Scheme for the design and modernisation of machines and flow-through systems using CFD software

For the design of a water turbine, apart from the criterion of its efficiency and the obvious for this type of devices, ensuring the amount of available water appropriate for a given watercourse (which translates into the size of the turbine), the following assumptions should be made:

I. the geometry of turbine cannot cause mechanical damage to fish fauna (the shape of rotor blades and spaces available for fish flow with dimensions characteristic for a given river ecosystem);
II. pressures inside the flow device must not damage the gills of fish (pressures causing cavitation are not allowed);
III. the design of turbine should ensure that the lubricant does not come into contact with river water (bearings are raised above water level);
IV. the noise of device should not exceed 80 dB;

V. the device should be optimized in terms of vibration emission (installing anti-vibration solutions);
VI. installation of the device should have the least possible construction interference with the existing water threshold/natural damming;
VII. the device should enable free fish migration, including upstream (e.g. hydroelevator system);
VIII. ensuring adequate durability of the device (e.g. by applying coatings on the rotor blades);
IX. the device should ensure the use of a water threshold with natural falls (usually low or ultra-low), which will enable the use of existing, natural dams.

Formulation and parameterization of the above criteria and then inference based on the results of numerical calculations concerning their fulfillment will allow to design a device that will enable obtaining a water permit according to new legal regulations.

5. Conclusion

1. The theoretical resources of hydropower in the world are estimated at 40,700 TWh/year (23 TWh/year in Poland), while exploitation resources are estimated at nearly 15,000 TWh/year (12 TWh/year in Poland).
2. Designing small hydropower plants (SHP) with a capacity of < 5MW, including micro (0.1-05 MW) and mini (0.5-2 MW) power plants, in the face of current legal regulations, is an interdisciplinary issue, because efficiency priorities are now not as important as environmental ones.
3. The study analysed current regulations enabling obtaining of water-legal permits and proposed design guidelines in the area of small hydropower plants, taking into account the impact of SHP on the condition of river ecosystem.
4. Taking the formulated criteria into account in the design process will allow obtaining water-legal permits in the light of the current legislative conditions.

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References

Augustyn, L. (2010). The influence of the Czorsztyn-Niedzica and Sromowce Wyżne hydroelectric power station on the ichthyofauna of the Dunajec River in the Pieniny region. *Monografie Pienińskie, 2*, 227-239 (in Polish).

Basiński, K. (2015). Problems with renewing water permits for SHPPs in the light of new legal conditions. *Energetyka Wodna* (in Polish).

Dedić-Jandrek, H., Nižetić, S. (2019). Small scale archimedes hydro power plant test station: Design and experimental investigation. *Journal of Cleaner Production, 231*, 756-771. DOI: 10.1016/j.jclepro.2019.05.234

Hunt, J.D., Zakeri, B., Giulietti, De Barros, A., Filho, W.L., Delavald, Marques, A., Barbosa, P., Smith, Schneider, P., Farenzena, M. (2021). Buoyancy Energy Storage Technology: An energy storage solution for islands, coastal regions, offshore wind power and hydrogen compression. *Journal of Energy Storage, 40.* DOI: 10.1016/j.est.2021.102746

Khudhiri, N., Dol, S., Khan, M. (2018). Design of hydro-power plant for energy generation for a mid-size farm with insufficient water distribution networks. *Advances in Science and Engineering Technology International Conferences (ASET).* DOI: 10.1109/ICASET.2018.8376799

Malicka, E. (2018). Hydro-answer: small hydropower plants – however, not so little will they come into being. *Towarzystwo Rozwoju Małych Elektrowni Wodnych, REO* (in Polish).

Piper, A., Rosewarne, P.J., Wright, R.M., Kemp, P.S. (2018). The impact of an Archimedes screw hydropower turbine on fish migration in a lowland river. *Ecological Engineering, 118,* 31-42. DOI: 10.1016/j.ecoleng.2018.04.009

Pradhan A., Marence M., Franca M.J. (2021). The adoption of Seawater Pump Storage Hydropower Systems increases the share of renewable energy production in Small Island Developing States. *Renewable Energy, 177*, 448-460. DOI: 10.1016/j.renene.2021.05.151

Radtke G., Bernaś R., Skóra M.E. (2012). Small hydropower stations – major ecological problems: some examples from rivers of northern Poland. *Chrońmy Przyr. Ojcz. 68*(6), 424-434 (in Polish).

Umer, A., Mithulananthan, N., Rakibuzzaman, S., Federico, M. (2020). A review on rapid responsive energy storage technologies for frequency regulation in modern power systems. *Renewable and Sustainable Energy Reviews, 120.* DOI: 10.1016/j.rser.2019.109626

Waters, S., Aggidis, G. (2015). Over 2000 years in review: Revival of the Archimedes Screw from Pump to Turbine. *Renewable and Sustainable Energy Reviews, 51,* 497-505. DOI: 10.1016/j.rser.2015.06.028

Wiśniewolski, W. (2002). Factors favorable and harmful to the development and maintenance of fish populations in flowing waters. *Suppl. Acta Hydrobiol., 3*, 1-28 (in Polish).

Wiśniewolski, W. (2003). Possibilities of counteracting the effects of partitioning rivers and recreating fish migration routes. *Supplementa ad Acta Hydrobiologica, 6*, 45-64 (in Polish).

Wiśniewolski, W., Augustyn, L., Bartel, R., Depowski, R., Dębowski, P., Klich, M., Witkowski, A. (2004). Migratory fish restitution and the patency of Polish rivers. *WWF, Warszawa* (in Polish).

Witkowski, A., Kotusz, J., Przybylski, M. (2009). The degree of threat to Poland's freshwater ichthyofauna: Red list of lampreys and fish – as of 2009. *Chrońmy Przyr. Ojcz. 65*(1), 33-52 (in Polish).

Xin, Yee, Mah A., Shin, Ho, W., Hassim, M., Hashim, H., Yen, Liew, P., Ab, Muis, Z. (2021). Targeting and scheduling of standalone renewable energy system with liquid organic hydrogen carrier as energy storage. *Energy, 218.* DOI: 10.1016/j. energy.2020.119475

Zawiślak, M. (2017). Method of designing and modernising machines and flow systems using Computational Fluid Mechanics. *Publishing House of the Poznań University of Technology.*

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Self-preservation Effect of Gas Hydrates

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Abstract: This work was performed to improve the storage and transportation technology of gas hydrates in nonequilibrium conditions. At atmospheric pressure and positive ambient temperature, they gradually dissociate into gas and water. Simulation of the gas hydrate dissociation will determine optimal conditions for their transportation and storage, as well as minimize gas loss. Thermodynamic parameters of adiabatic processes of forced preservation of pre-cooled gas hydrate blocks with ice layer were determined theoretically and experimentally. Physical and mathematical models of these processes were proposed. The scientific novelty is in establishing quantitative characteristics that describe the gas hydrates thermophysical parameters thermophysical characteristics influence on the heat transfer processes intensity on the interphase surface under conditions of gas hydrates dissociation. Based on the results of experimental studies, approximation dependences for determining the temperature in the depths of a dissociating gas hydrate array have been obtained. Gas hydrates dissociation mathematical model is presented.

Keywords: gas hydrates, self-preservation effect, experimental studies, mathematical modeling, dissociation

1. Introduction

It has now been established that the amount of natural, technically recoverable, gas-gas hydrate is ~ 3×10^{14} m^3 (Pavlenko 2020). Different, sometimes contradictory, data on gas hydrate content in the natural environment are specified in literary sources, but it is obvious that natural gas hydrate is a huge energy resource with global distribution in permafrost regions and oceans; its vast volume requires to be estimated as a potential energy source.

In addition to hydrate production technologies, one of the promising areas for the development of gas hydrate technologies is the transportation and storage of gases in the form of gas hydrates. (Boswell & Collett 2011, Zhao et al. 2015). The self-preservation ability at temperatures below 0 degrees Celsius is important for their storage and transportation (Brown et al. 2010, Chong et al. 2016). That is, if the pressure is decreased over the formed hydrate, it dissociates and forms a thin film of ice on its surface, preventing it from further dissociation. Considering the high gas capacity of the hydrate (up to 164 m^3 of gas per 1 m^3 of hydrate), it is possible to store and transport gas under atmospheric pressure in the form of solid pellets.

A characteristic feature of crystalline hydrates is that their formation temperature is much higher than water freezing point. However, as temperature rises to form a gas hydrate, it is necessary to increase the pressure.

Fig. 1 shows a methane-water system P-T phase diagram with stability areas of methane hydrates. As can be seen in Fig. 1a, the hydrate, formed at low pressure values, is stable if thermobaric conditions are located at the bottom right of the three-phase monovariant equilibrium line. Thus, under appropriate conditions, corresponding to the stability area, the hydrate will be formed sooner or later (with sufficient amount of gas and water). At very high pressures, since compression of fluid phases is higher than the solid hydrate, there comes a time when the hydrate phase volume and the phase of dissociation products are equalized and, therefore, hydrate dissociation curve (h_j) passes through a maximum (47.7°C at $5 \cdot 10^5$ kPa, Fig. 1b). Upon reaching point Q_h, a break in the hydrate dissociation curve is observed, resulting from formation of a new hydrate h_x, its composition and structure have not been studied yet. But since it is almost impossible to imagine any other than van der Waals interactions between methane and water, it can be assumed that this compound also has a clathrate origin.

Adding a gas molecule to the clathrate water lattice results in an increase in the packing coefficient compared to ice Ih (k = 0.43) to 0.47-0.52 for KS-II hydrates (with a stoichiometric composition 1: 17), for KS-I hydrates up to 0.53-0.58 and hydrates with completely filled voids up to 0.59-0.60. Hydrate properties under pressure varies from dissociation to different degrees of stabilization. The guest molecule complementarity and structural void is still not enough to form a denser structure with a factor close to 0.74. Therefore, at high pressures, the clathrate structure density becomes less than the gas phase density, resulting in the maxima in hydrate dissociation curves (just like in the case of methane hydrate, Fig. 1b).

It is worth mentioning the following feature: even under required thermodynamic conditions, the reaction of hydrate formation takes a while. Dissociation of hydrocarbon hydrates is usually an easier process than their formation; under metastable equilibrium conditions they can be stored for a long time as a result of their self-preservation effect (Kipyoung et al. 2014, Ke et al. 2019). It consists in the fact that, in the process of dissociation, gas hydrates are covered with ice crust, preventing their further dissociation.

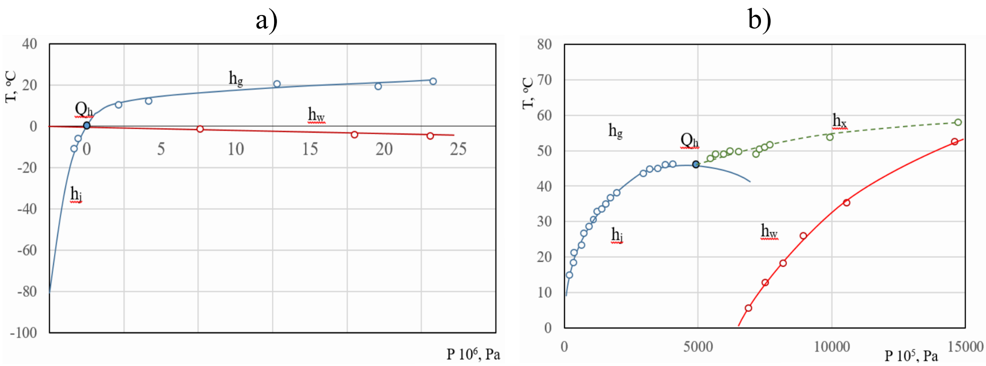

Fig. 1. P, T-phase diagram of a methane-water system; a – within the range from 0 to 250 · 10^5 Pa; b – within the range from 0 to 15 · 10^5 kPa

This property of hydrates allows significant volumes of gas to be transported and stored for a long time in gas hydrate stores (Archer 2007). Therefore, the metastable state of gas hydrate can be maintained due to its self-preservation effect (Vysniauskas & Bishnoi 1983). These issues were studied by (Koshlak & Pavlenko 2019, Pavlenko 2020, Pavlenko & Koshlak 2019, Pavlenko et al. 2014, Pavlenko et al. 2014a). However, thermodynamic parameters of forced preservation of gas hydrate with an ice layer are understudied.

Already in the 1990s, companies in Japan, Norway, England and others began to develop industrial technologies for production, preservation, storage, transportation and use of natural gas hydrates or NGH (Kim et al. 2015). Gas hydrate transportation under nonequilibrium conditions (with atmospheric pressure and temperature not less than 258 K) seems to be the most advantageous. It is based on production of gas hydrate structures, which under these conditions will be highest resistant to dissociation.

In (Veluswamy et al. 2017), a method for gas hydrate production in the form of granules covered with ice crust was proposed. However, given the considerable total surface area of granules, it will result in a significant increase in the ballast water (ice) in a hydrate.

Hence, thermodynamic and technological parameters of phase transitions during forced preservation of gas hydrate with an ice layer shall be determined.

2. Research results

Previous experiments have shown that forced self-preservation of hydrate blocks shall be performed at appropriate pressure and temperature at the boundary of thermodynamic saturation. In Fig. 2 curve 2 limits the area of P-T parameters of natural gas hydrate self-preservation (CH_4 – 92.8%; C_2H_6 – 5.1%; C_3H_8

– 2.1%). According to Fig. 2, the process shall be performed at a pressure higher than equilibrium values of hydrate formation.

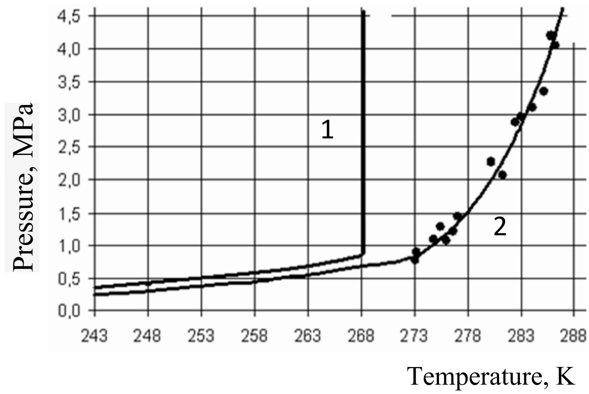

Fig. 2. Conditions of gas hydrate self-preservation: 1 is a gas hydrate equilibrium curve (CH_4 – 92.8%, C_2H_6 – 5.1%, C_3H_8 – 2.1%); 2 is a curve that limits the area of gas hydrate P-T surface parameters for self-preservation

For instance, for the average composition of natural gas, a pressure of not less than 0.85 MPa shall be maintained. However, water crystallization at this temperature will be too slow. Therefore, the initial temperature of a gas hydrate sample shall be lower. In our opinion, the optimal temperature shall be 258K. In this case, the gas hydrate dissociation, according to the equilibrium curve, will be prevented at 0.7 MPa. Therefore, the preservation process can be performed at a pressure higher than the equilibrium for the hydrate of this composition for the appropriate temperature.

However, this process under pressure will significantly complicate the technology.

Depending on heat transfer conditions on the hydrate surface, three main processes are distinguished. We present them in the order of intensification of heat supply to the surface: Self-preservation, ice crust melting and intensive hydrate dissociation. At self-preservation heat supply to the GH surface is relatively small. The gas hydrate surface temperature is one-two degrees below 0°C, and the ice crust does not melt.

To calculate hydrate storage, the dissociation process can be considered long enough to establish a stationary temperature distribution in the hydrate block. But the temperature range for hydrate self-preservation as the first process implementation, shall be determined to prevent its dissociation.

Let us consider a cylindrical gas hydrate block with height *h* and diameter *d*, cooled to a temperature below 273K.

Since a gas hydrate block has a negative temperature, water crystallizes on the block surface during time t_{kr}. The phase transition heat can be considered an internal source of energy of the wetted layer. Under adiabatic conditions, the released heat is dissipated into the middle of a sample to a colder dry gas hydrate. A physical model of the water crystallization process in the pores of the wetted surface layer a gas hydrate is schematically shown in Fig. 3.

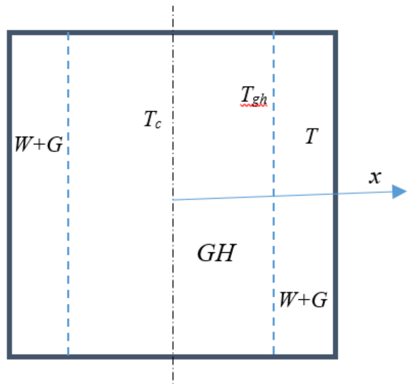

Fig. 3. Gas hydrate self-preservation: GH is gas hydrate; W + G – water and gas hydrate; T_c, T_{gh} is initial temperature of wet and dry gas hydrate, respectively; T_c is temperature in the sample center

For a one-dimensional temperature field, heat propagates in the direction of *OX* axis (Fig. 3). Thermal coefficients are assumed to be independent of coordinates and time.

In dry and wetted gas hydrate zones we will allocate elementary volumes of *dxdydz*. The difference between heat flows is the amount of energy, accumulated by the gas hydrate in this volume:

$$q_x dydz - q_{x+dx} dydz = c_{gg}\rho_{gg}\frac{\partial T_{gg}}{\partial \tau}dxdydz \tag{1}$$

The change in dry gas hydrate temperature over time in cylindrical coordinates is determined by the following equation:

$$\frac{\partial T_{gg}}{\partial \tau} = a_{gg}\left(\frac{\partial^2 T_{gg}}{\partial x^2} + \frac{1}{x}\frac{\partial T_{gg}}{\partial x}\right);\ \tau > 0, 0 < x < R;$$

where T_{gg} is dry gas hydrate temperature, K; a_{gg} is temperature conductivity coefficient of dry gas hydrate, m^2/s; R is a sample radius, m.

Let us consider characteristics of wetted gas hydrate heat transfer. The amount of heat, entering the elementary volume through a right face of *dydz* area per unit time will be $q_x dydz$, and the amount of heat, leaving it through the opposite face will be $q_{x+dx}dydz$. Water crystallization in gas hydrate is accompanied by heat release in an elementary volume:

$$\frac{dw}{d\tau}dxdydz = \rho L\frac{mdV}{Vd\tau}dxdydz.$$

The difference between heat flows of the wetted gas hydrate is the amount of energy, accumulated by the gas hydrate in this volume:

$$q_x dydz = \rho L\frac{mdV}{Vd\tau}dxdydz - q_{x+dx}dydz = c\rho\frac{\partial T}{\partial \tau}dxdydz$$

The equation, describing the change in temperature of the gas hydrate wetted layer during cementation, in cylindrical coordinates has the following form:

$c_k\rho_k\frac{\partial T_k}{\partial \tau} = \lambda\left(\frac{\partial^2 T_k}{\partial x^2} + \frac{1}{x}\frac{\partial T_k}{\partial x}\right) + \rho_w L\frac{dV_w}{V_k d\tau}; V_w = V_k m; A \geq V_w \geq 0; R < x < R + 1;\ \tau > 0;$

where: T_k is the wetted gas hydrate temperature, K; V_w, V_k are volumes of applied water and wetted layer, respectively, m^3; c_k - specific heat of water-wetted gas hydrate, J/(kg·K); ρ_k, ρ_w is density of wetted layer and ice, respectively, kg/m^3;

λ_k is thermal conductivity of the wetted layer, W/(m·K); L is specific heat of water crystallization, J; m is gas hydrate porosity; V is the amount of applied water per sample, m^3.

Initial conditions: $T_k(x,0) = T_0, R < x < R+1, T_{gg}(x,0) = T_1, 0 < x < R.$

Let us set thermal symmetry conditions in the center of a gas hydrate block, and a process of sample heat exchange with the environment is considered adiabatic. The contact is considered perfect at the dry and wet hydrate interface. Let us take up boundary conditions of the fourth kind. They will look as follows:

$$\tau > 0 - \lambda_{gg}\frac{\partial T_{gg}}{\partial x}\bigg|_{x=0} = 0;\ -\lambda_k\frac{\partial T_k}{\partial x}\bigg|_{x=R} = -\lambda_{gg}\frac{\partial T_{gg}}{\partial x}\bigg|_{x=R};\ \ q_k|_{x=R+1} = 0.$$

The problem was solved by the finite difference method (grid approach).

The behaviour the temperature field of a gas hydrate sample during self-preservation of its surface layer is shown in Fig. 4 (temperature distribution at the end of water crystallization in pores, depending on the formed layer thickness for blocks with a base radius of 0.08 and 0.6 m), Fig. 5 (temperature distribution in a hydrate block with a base radius of 0.08 m at the end of water crystallization in surface layer pores, depending on the gas hydrate initial temperature).

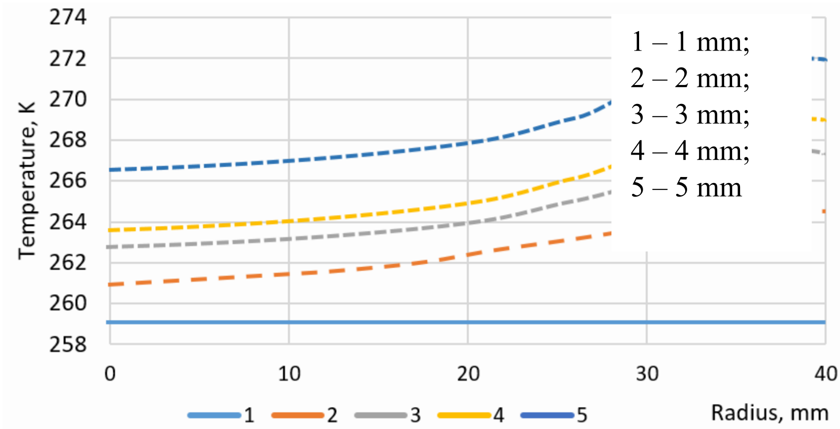

Fig. 4. Temperature distribution in a sample, 0.08 m in diameter, after water crystallization in the surface layer pores, depending on crust thickness (amount of applied water) and its crystallization time: initial temperature: a sample – 259K, water – 273.1K

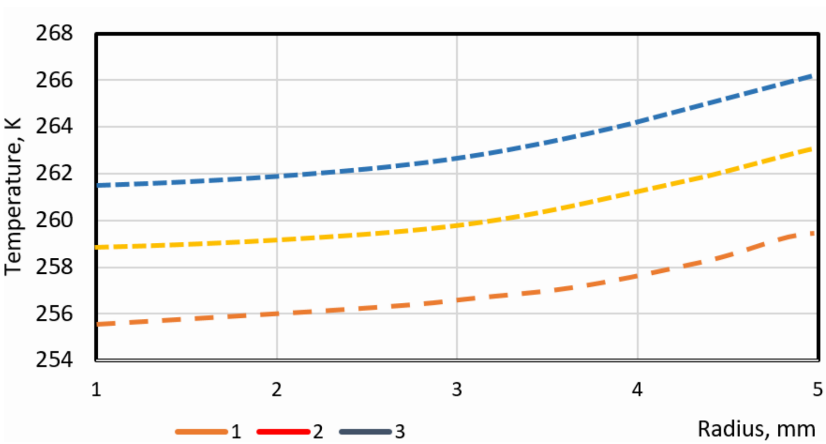

Fig. 5. Temperature distribution in a sample, 0.08 m in diameter, after water crystallization in surface layer pores, 2 mm thick, depending on the initial temperature (T_0) of a gas hydrate (water temperature is 273.1K):1 – T_0 = 259 K; 2 – T_0 = 256K; 3 – T_0 = 253K

Therefore, according to the calculation as a result of water phase transition in wetted layer pores, its temperature rises sharply (for a sample, 0.08 m in diameter to 272 and 268K, respectively, with a layer, 6 and 3 mm thick). However, at atmospheric pressure, the first option is unacceptable, as under these conditions, gas hydrate will intensely dissociate. At the same time, during layer preservation with a water film up to 2 mm thick, its dissociation will be minimal.

Water crystallization time in surface layer pores, 2 mm thick, at the initial temperature of a sample in the range of 253-259K is ≈ 100 s.

To verify the self-preservation process mathematical model, a series of experimental studies were performed. Formed and pre-cooled cylindrical gas hydrate samples, 0.08 m in diameter and 0.11 m high were studied. After formation, samples had an average porosity of 0.06, hydrate lattice filling is 83 mm. The effect of sample initial temperature on water crystallization time and formed protective layer thickness (initial temperature is 259 K) was evaluated. It was determined that in adiabatic conditions water, after partial dissociation at heat supply, completely crystallized in pores, no considerable dissociation is present.

The obtained experimental data on the self-preservation of gas hydrates are in good agreement with the calculated ones. Figures 6 and 7 illustrate this conclusion. The correlation coefficients are in the range of 0.99-0.97 and the coefficients of variation are 0.034-0.1. This testifies to the good accuracy of the proposed mathematical model.

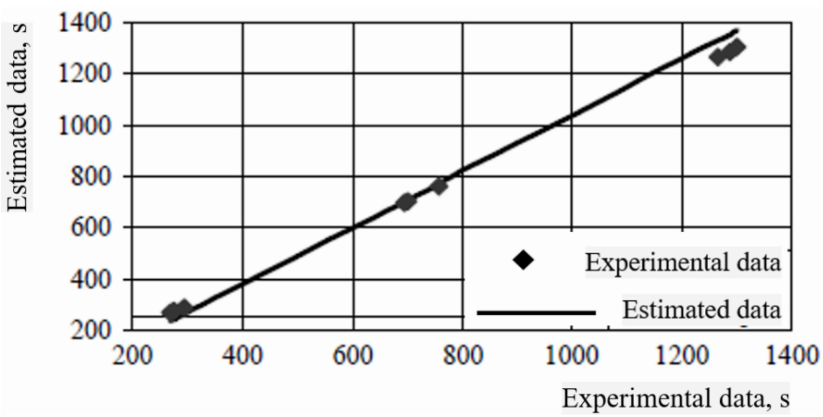

Fig. 6. Comparison of the calculated and experimental data on the crystallization time of water in the pores of the surface layer of gas hydrate, depending on its thickness

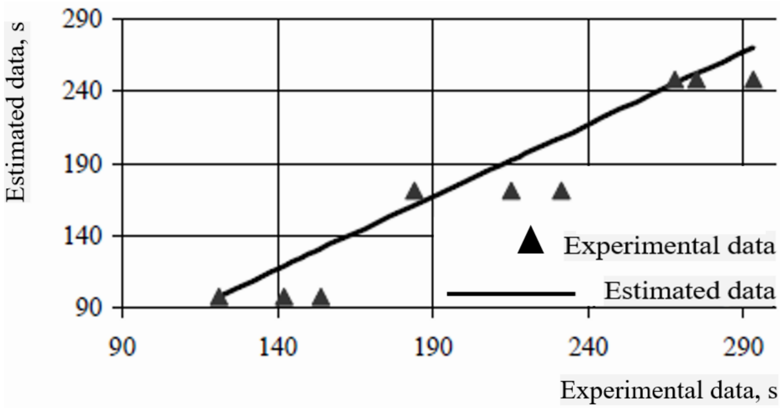

Fig. 7. Comparison of calculated and experimental data on the formation time of the ice crust for different initial temperatures of the gas hydrate block

3. Conclusions

The performed study results show that the main cause of a hydrate self-preservation effect is decrease of temperature in its deep layers as a result of partial dissociation. The ice crust formation on a dissociating GH surface is a consequence, not a cause of the self-preservation effect. Therefore, in the mathematical modelling of thermal processes that occur during hydrate block dissociation, it shall be considered that heat sink is a function of temperature and pressure at this point of the hydrate block.

The conditions under which self-preservation of hydrates of different gases can be achieved are determined. It is determined that the hydrate block size on a self-preservation effect depends on a temperature distribution inside the hydrate block. In a large block, a lower temperature is achieved in hydrate deep layers, contributing to its better storage.

GH concentration effect on distribution of temperatures and heat sink along a dissociating gas hydrate block "depth" is determined. The obtained dependence was confirmed by field experiment results.

References

Archer, D. (2007). Methane hydrate stability and anthropogenic climate change. *Biogeosciences*, *4*, 521-544.

Boswell, R.; Collett, T.S. (2011). Collett Current perspectives on gas hydrate resources. *Energy Environ. Sci.*, *4*, 1045-1528.

Brown, T.D.; Taylor, C.E.; Bernardo, M.P. (2010). Rapid Gas Hydrate Formation Processes: Will They Work? *Energies*, *3*, 1154-1175.

Chong, Z.R.; Yang, S.H.; Babu, P.; Linga, P.; Li, X.S. (2016). Review of natural gas hydrates as an energy resource: Prospects and challenges. *Appl. Energy*, *162*, 1633-1652.

Ke, W.; Svartaas, T.M.; Chen, D. (2019). A review of gas hydrate nucleation theories and growth models. *J. Nat.Gas Sci. Eng.*, *61*, 169-196.
Kim, K.; Kang, H.; Kim, Y. (2015). Risk Assessment for Natural Gas Hydrate Carriers: A Hazard Identification (HAZID) study. *Energies*, *8*, 3124-3164.
Kipyoung, K.; Youtaek, K.; Hokeun, K. (2014). Recent advances in natural gas hydrate carriers for gas transportation. *JKOSME*, *38*, 589-601, DOI: 10.5916/jkosme.2014.38.5.589.
Koshlak, H., Pavlenko, A. (2019). Method of formation of thermophysical properties of porous materials. *Rocznik Ochrona Srodowiska*, *21*(2), 1253-1262.
Pavlenko, A.M. (2020). Thermodynamic features of the intensive formation of hydrocarbon hydrates. *Energies*, *13*, 3396; DOI: 10.3390/en13133396
Pavlenko, A., Koshlak, H. (2019). Heat and mass transfer during phase transitions in liquid mixtures. *Rocznik Ochrona Srodowiska, 21*(1), 234-249.
Pavlenko, A., Szkarowski, A., Janta-Lipińska, S. (2014). Research on burning of water black oil emulsions. *Rocznik Ochrona Srodowiska*, *16*(1), 376-385.
Pavlenko, A., Usenko, B., Koshlak, A. (2014a). Analysis of thermal peculiarities of alloying with special properties. *Metallurgical and Mining Industry*, *6*(2), 15-19.
Veluswamy, H.P.; Kumar, A.; Kumar, R.; Linga, P. (2017). An innovative approach to enhance methane hydrate formation kinetics with leucine for energy storage application. *Appl. Energy*, *188*, 190-199.
Vysniauskas, A.; Bishnoi, P.R. (1983). A kinetic study of methane hydrate formation. *Chem. Eng. Sci.*, *38*, 1061-1072.
Zhao, J.; Zhu, Z.; Song, Y.; Liu, W.; Zhang, Y.; Wang, D. (2015). Analysing the process of gas production for natural gas hydrate using depressurization. *Appl. Energy*, *142*, 125-134, DOI: 10.1016/j.apenergy.2014.12.0714.

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Environmental Awareness and Knowledge of Municipal Waste Management Among Inhabitants of Eastern Mazovia

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Abstract: The problem of municipal waste management is one of the greatest challenges of the 21st century. Its solution requires the integrated involvement of central and local authorities as well as the public. For their actions to be fully effective, they must be accompanied by an increase in environmental awareness. The aim of the study was to assess the environmental awareness and knowledge of inhabitants of eastern Mazovia regarding municipal waste management. A survey study was carried out on a group of 262 individuals using a questionnaire. Analysis of the results showed that the surveyed inhabitants of eastern Mazovia were aware of problems associated with municipal waste management, but some of them were critical of the actions taken by central and municipal authorities to solve them. Their high level of environmental awareness and knowledge was evidenced by the fact that most of those surveyed were familiar with the principles of selective collection of municipal waste, including green and hazardous waste.

Keywords: municipal waste, environmental awareness, survey study

1. Introduction

Waste is an integral part of the daily life and economic activity of human beings. The problem of safe waste management is one of the greatest challenges of the 21st century (Kłoś 2012, Deluga 2018). Waste management is subject to applicable laws, of which the most important in Poland are the Waste Act of 15 April 2021 (consolidated text, Journal of Laws of 2021, item 779) and the Act on maintaining cleanliness and order in municipalities of 13 September 1996, as amended (consolidated text, Journal of Laws of 2020, item 2361).The act on waste defines measures serving to protect the environment and human life and health by preventing and reducing the negative impact of waste production and management on the environment and human health, to limit the overall impact of utilization of resources, and to improve the efficiency of such utilization. The act on maintaining cleanliness and order in municipalities defines the tasks of the municipality and the obligations of property owners concerning the maintenance of cleanliness and order, conditions for carrying out activities associated with the collection of municipal waste from property owners and the management of this waste, and the conditions for granting authorization to entities providing services regulated by the act. The new waste management system and the Waste Act also impose on municipalities the obligation to build, operate and maintain municipal installations (Deluga 2018). According to Statistics Poland (GUS), 114.1 million tonnes of industrial waste was produced in Poland in 2019 (a decrease of 1% from the previous year). Its main sources, as in previous years, were mining and quarrying (63.7 million tonnes), industrial processing (27.2 million tonnes), and the generation and supply of electricity, gas, water vapour, and hot water(14.0 million tonnes). The dominant means of dealing with industrial waste produced in 2019 were recovery (48.9%) and disposal (42.9%). At the same time,12.8 million tonnes of municipal waste was produced in Poland in 2019 (a 2.1% increase from 2018), of which only3.97 million tonnes were collected selectively. The main source of municipal waste was households, which produced 84.5% of the total. An average of 332 kg of waste was collected per inhabitant, which was an increase of 7 kg from the previous year. A total of 7,087,000 tonnes (55.6%) of collected waste in 2019 was directed to recovery processes, including recycling – 3,192,100 tonnes (25%), biological treatment (composting or fermentation) – 1,153,200 tonnes (9%), and thermal treatment with energy recovery – 2,741,800 tonnes (21.5%), while 5,665,700 tonnes (44.4%)was designated for disposal, including thermal treatment without energy recovery – 178,600 tonnes (1.4%) and landfills – 5,487,200 tonnes (43%) (GUS 2019). The amount of waste produced is substantially influenced by demographic factors, standard of living, and environmental awareness (Spigarska 2013, Baran 2017, Przydatek 2020). Antczak (2019) indicated in order from the most influential to the least: population density; average salaries; share of individuals at working age in the general population; and the number of tourists. Kłos (2015), citing Kiełczewski, defines environmental awareness as a person's attitude towards and information and beliefs about the natural environment, as well as the value system guiding the individual's behaviour towards it. Ecological awareness determines the full understanding of the processes and phenomena occurring in the natural environment, which influences its shaping by society (Kobyłko 2007, Sowa 2018). An increase in public environmental awareness, which is closely linked to environmental education, can accelerate efforts to improve the state of our environment (Pawul & Sobczyk 2011, Adamek & Ziernicka-Wojtaszek 2018). In Polish national CE action plan, recommended tasks and actions that should be taken by government and residents themselves are landfill remediation, use of selected municipal waste fractions for economic purposes, sharing products with co-users, waste recovery, remanufacturing products or components, virtual solutions in everyday life to reduce the amount of generated waste, or replacement of household appliances by items with a higher energy class (Smol et al. 2020). Also the actions in municipal waste management were indicated, such as changes in legislation, improvement in the waste management system, prevention of food waste, and education of residents about the importance of CE implementation in everyday life. Polish activity in selective waste collection and recovery should be intensified in the coming years, and the implemented legislation will serve a coherent waste economy policy and will influence selective waste collecting (Lewandowska & Szymańska 2019). These activities will contribute to directing municipal waste management towards the circular economy (Ciechelska 2018). In particular, attention should be paid to the fractions that have been weakly used so far, e.g. biodegradable wastes. The morphology of municipal waste varies depending on factors such as the type of buildings, the living standard of the inhabitants, and their habits (Rosolak & Gworek 2006, Baran 2017). Waste from urban areas contains more packaging and organic substances, while waste from rural areas has a larger proportion of ash and bulky waste. An innovative approach to municipal waste management must take into account economic and environmental aspects as well as local determinants (Baran 2017).

The aim of the study was to assess the environmental awareness and knowledge of inhabitants of eastern Mazovia regarding municipal waste management by analysing responses to a questionnaire.

2. Materials and methods

The environmental awareness and knowledge of inhabitants of eastern Mazovia regarding municipal waste management was assessed by means of a survey study conducted using a questionnaire. The research was conducted from October 2019 to March 2020.

The questionnaire contained five demographic questions and 15 questions testing the respondents' awareness and knowledge. The demographic questions concerned the respondents' gender, age, living conditions, place of residence, and education. The remaining questions were grouped into those assessing the respondents' awareness of the issue and those assessing their knowledge. The survey was carried out on a random sample of 262 inhabitants of eastern Mazovia. Nearly 56% of the respondents were women. Young people up to 25 were represented in the highest numbers (85%), followed by people aged 26-40 (10%), 3% at the age of 40-60, and 2% at the age of over 60. Among those surveyed, 69% lived in single-family housing, and 31% in multi-family housing. 57% of the respondents are rural residents, including 10% of municipal villages, 12% live in cities with a population of up to 50,000, 24% are residents of cities with a population of 50,000 to 10,000, the rest are residents of cities with more than 10,000 inhabitants. Most of those surveyed, 72%, had a secondary level of education, 20% higher education, 7% vocational education and 1% primary education. Statistical analysis of the results was performed using the chi-square test.

The first four questions, aimed at assessing awareness of problems associated with municipal waste management, were as follows: 1) Is waste management a civilization problem? 2) and 3) Do central and local authorities handle waste management well? 4) Is waste sorting at your place of residence sufficiently precise?

3. Results

The research shows that as many as 88% of respondents considered waste management to be a civilization problem (Fig. 1), and 53% believed that central authorities do not handle it well (Fig. 2).

At the same time, 54% of those surveyed stated that the local government in their place of residence handles waste management well.

The statistical analysis showed that the living conditions of the respondents (Fig. 3) were significantly correlated ($p = 0.03$) with the remaining answers to this question ('No' and 'I don't know').

Over 52% of those surveyed stated that waste sorting in their place of residence was sufficiently precise (Fig. 4). The response to this question was significantly correlated with living conditions ($p = 0.02$).

The next group of questions concerned knowledge of proper waste management. As many as 90% of respondents gave a negative response to the question 'Can hazardous waste be mixed with other waste?' (Fig. 5).

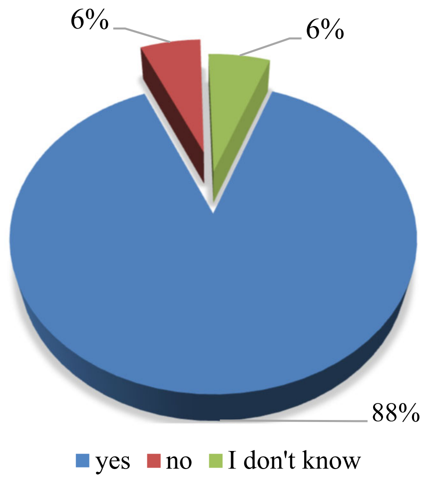

Fig. 1. Responses to the question regarding whether waste management is a civilization problem

Source: our own calculations based on the questionnaires

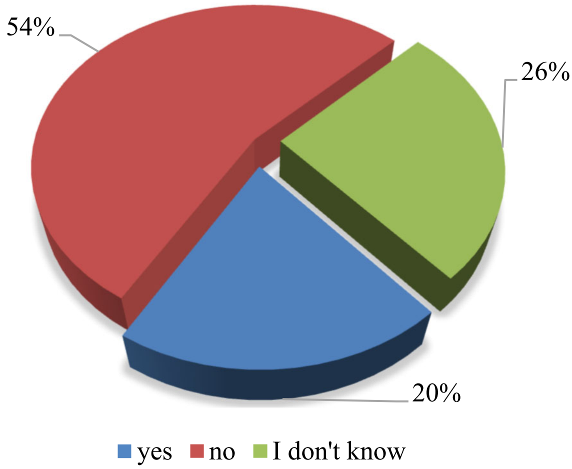

Fig. 2. Responses to the question regarding whether the Polish government handles waste management well

Source: our own calculations based on the questionnaires

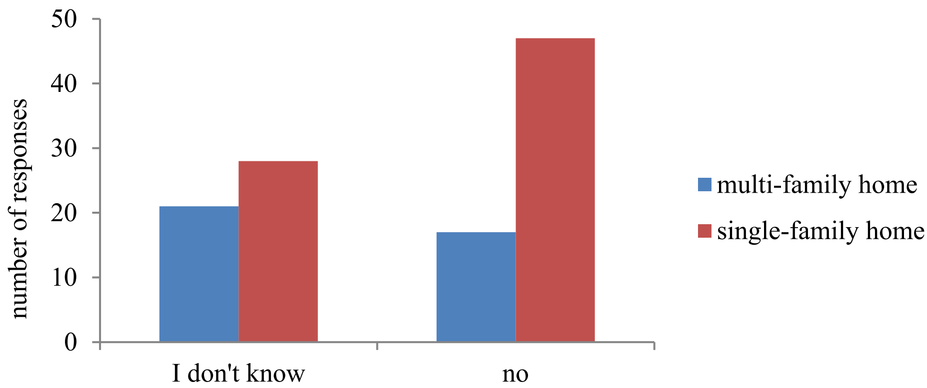

Fig. 3. Responses to the question regarding whether the local government in the respondent's place of residence handles waste management well

Source: our own calculations based on the questionnaires

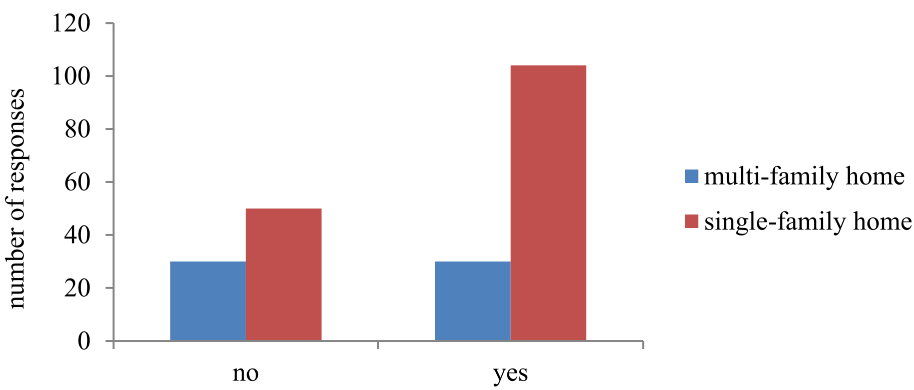

Fig. 4. Responses to the question regarding the precision of waste sorting in the respondents' place of residence

Source: our own calculations based on the questionnaires

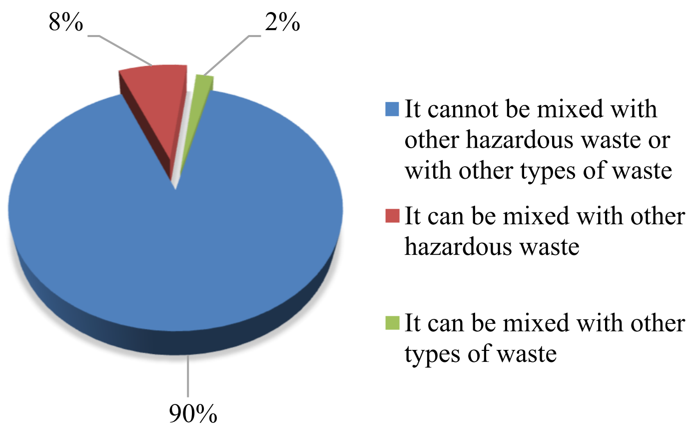

Fig. 5. Responses to the question regarding proper handling of hazardous waste
Source: our own calculations based on the questionnaires

Furthermore, most people (53%) knew that the municipal council can charge lower rates for selective waste collection (Fig. 6). Nearly as many responded that they did not know. The answers were significantly associated with the gender of the respondents (p = 0.04).

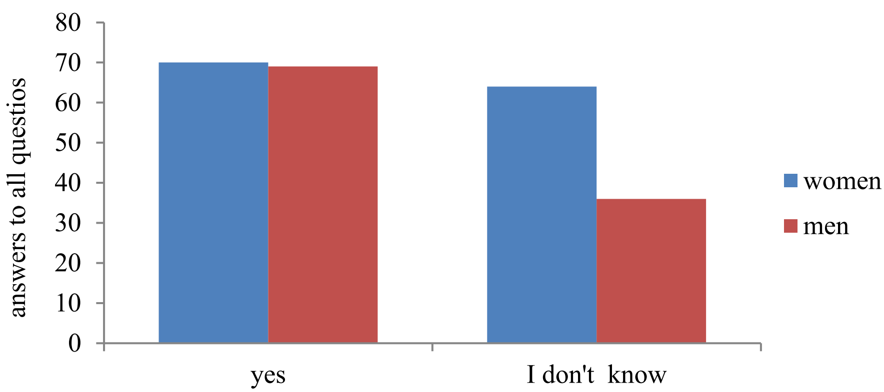

Fig. 6. Responses to the question regarding whether the municipal council can charge lower rates for selective waste collection
Source: our own calculations based on the questionnaires

The next four questions assessed the respondents' knowledge on bins/bags designated for various types of sorted waste. Over 55% of respondents knew the purpose of blue bags, only a few gave an incorrect answer regarding yellow bags, and 24% did not know the purpose of green bags. In the case of white bags, 10% of respondents gave no answer.

In response to the question 'How can green waste be managed?' only 10% of respondents gave no answer, and a few indicated an incorrect answer, such as burning. The most common answers were that it can be composted and used as fertilizer and that it can be placed in a special bag for this type of waste. It is striking, however, that only 56% gave a negative response to the next question, 'Can green waste be burnt?', while as many as 17% stated that it can (Fig. 7).

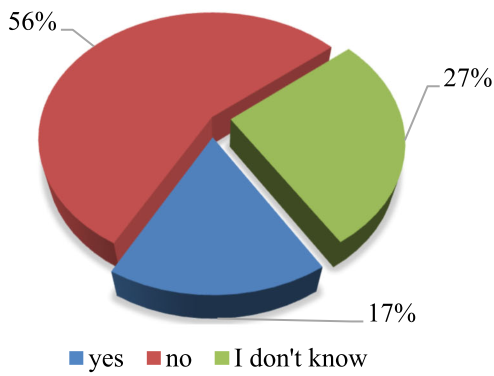

Fig. 7. Responses to the question regarding whether green waste can be burnt

Source: our own calculations based on the questionnaires

The next question dealt with the handling of waste electronics and home appliances. According to the respondents, waste electronics and home appliances (Fig. 8) can mainly be left in a specified place at a specified time (o1), handed over upon delivery of a replacement, or left in the shop when purchasing a replacement (o2). The responses depended significantly on the gender of the respondents ($p = 0.03$). A few individuals suggested that this type of waste can be placed in yellow bags or bins.

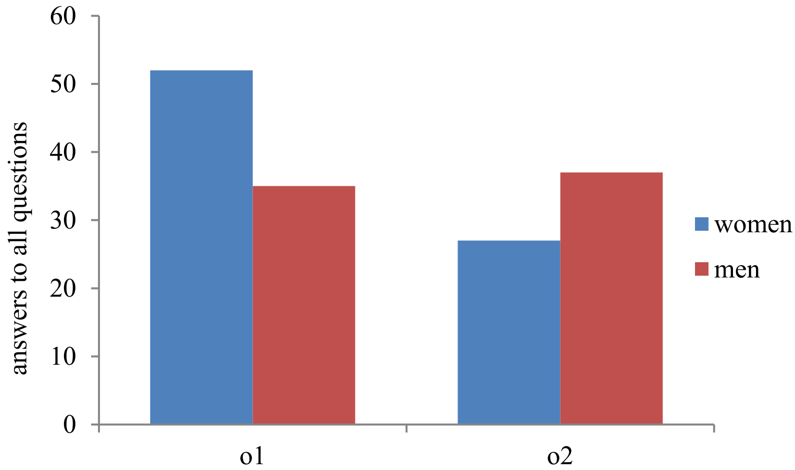

Fig. 8. Responses to the question (%) regarding waste electronics and home appliances
Source: our own calculations based on the questionnaires

In response to the question regarding waste batteries and accumulators, most respondents (236 of 262 surveyed) answered that they can be left free of charge at a collection point, e.g. in a shop. Only 13 people suggested the use of yellow or black bags/bins for this purpose (Fig. 9).

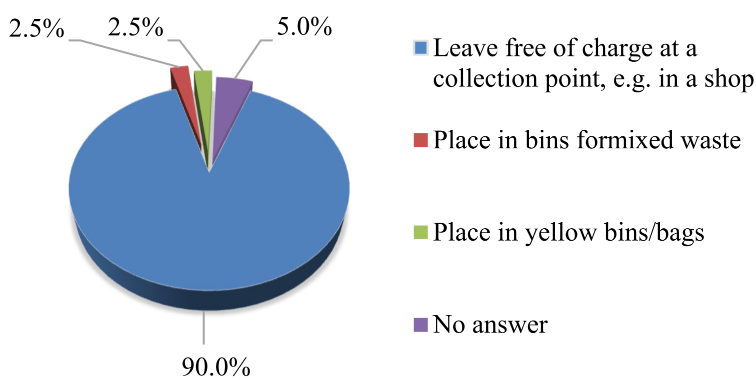

Fig. 9. Responses to the question regarding batteries and accumulators
Source: our own calculations based on the questionnaires

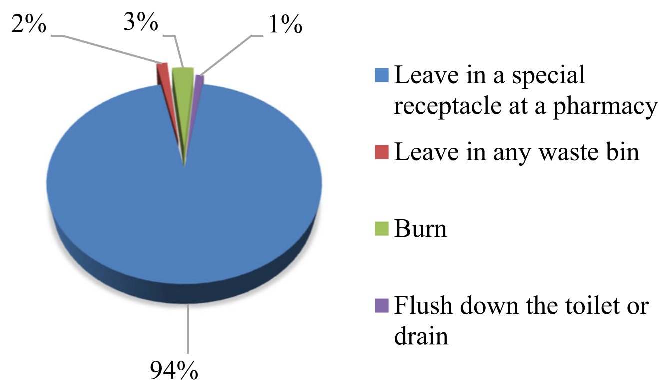

Fig. 10. Responses to the question regarding expired medications
Source: our own calculations based on the questionnaires

The last question in the questionnaire concerned the disposal of expired medicines. In this case, 94% of respondents were aware that they should be left in special containers located at the pharmacy (Fig. 10).

5. Discussion

Municipal waste is a mixture of various components, including packaging, green waste, biodegradable waste, and hazardous waste (Baran 2017). Safe management of municipal waste requires the involvement not only of central and local authorities, but of the public as well (Deluga 2018). For the integrated actions of government and the public to be fully effective, they must be accompanied by an increase in environmental awareness (Pawul & Sobczyk 2011, Alwaeli 2015, Lewandowska & Szymańska 2019). The basic components of ecological awareness are: ecological knowledge, ecological sensitivity and pro-ecological attitudes, i.e. actions taken to protect the natural environment (Kwiatek & Skiba 2017). According to Kłos (2015), the late 1980s and 1990s were a period of development of environmental awareness in Poland; on the one hand, Polish citizens were aware of the need for environmental protection, but on the other hand they were unable to draw practical conclusions from their knowledge and to apply it in practice. Environmental awareness has increased significantly in recent years, which has undoubtedly been influenced by both education and new legal regulations (Adamek & Ziernicka-Wojtaszek 2018, Deluga 2018). An important role in this transformation can be ascribed to an extensive social campaign implemented at every stage of education, concerning issues such as selective collection and management of waste and its impact on the environment. Selective collection of waste is the first step in its reuse and in reducing the exploitation of natural resources.

The survey results indicated that most respondents (88%) were aware that waste management is a civilization problem, but only 25% positively assessed the performance of central authorities, while 54% had a favourable opinion of the performance of their local government. At the same time, 52% respondents stated that waste sorting in their place of residence was adequate. A survey conducted by Deluga (2018) among inhabitants of Koszalin found that only 10.43% of respondents considered the waste sorting system to be run efficiently (10.43%) or rationally (43.8%). Lewandowska & Szymańska (2019) shows that poor-quality collected municipal waste, which must first be sorted into renewable fractions, results from the lack of proper education of inhabitants.

Our study found that most of those surveyed knew which bags/bins were designated for various categories of sorted waste and were aware of methods for dealing with green waste, but few possessed knowledge on the potential exploitation of green waste for energy purposes. Golisz & Boryś (2020) draw attention to the possibility of utilizing waste from urban green areas in this manner. Similar results were obtained by Jakubus et al. (2016), who examined the knowledge of residents of Darłowo and Września in the field of proper municipal waste management.

The high level of environmental awareness and knowledge of inhabitants of eastern Mazovia regarding municipal waste management is also evidenced by the fact that over 90% of those surveyed knew that hazardous waste should not be mixed with other waste and were familiar with the principles governing the disposal of waste electronics and home appliances, waste batteries/accumulators, and expired medications. This is a good basis for implementing the principles of municipal waste management developed under the Polish CE Roadmap (Smol et al. 2020).

5. Conclusions

To conclude, the surveyed inhabitants of eastern Mazovia are aware of problems associated with municipal waste management, but some of them are critical of the actions taken by central and municipal authorities to solve them. Most of those surveyed also possess knowledge of selective waste collection, but it is concerning that some of them did not know which bins/bags are meant for individual waste fractions. Most respondents knew the proper means of disposal of green waste and hazardous waste, including electronics and home appliances, batteries/accumulators, and expired medications.

References

Adamek, A., Ziernicka-Wojtaszek, A. (2018). Ecological Awareness of the Inhabitants of the Upper Silesian Agglomeration. *Rocznik Ochrona Srodowiska, 20,* 1640-1655.

Alwaeli, M. (2015). An overview of municipal solid waste management in Poland. The current situation, problems and challenges. *Environment Protection Engineering, 41*(4), 181-193. DOI: 10.5277/epe150414

Antczak, E. (2019). Municipal waste in Poland: analysis of the spatial dimensions of determinants using geographically weighted regression. *European Spatial Research and Policy, 26*(2), 177-197. DOI: https://doi.org/10.18778/1231-1952.26.2.09

Baran, J. (2017). Municipal Waste Management In Poland Vs. European Union in the Years 2005-2014. *Annals of The Polish Association of Agricultural and Agribusiness Economists, 19*(3), 18-23. DOI: 10.5604/01.3001.0010.3209

Ciechelska, A. (2018). Effectiveness of investments in municipal waste management in poland in the context of goals of the circular economy. *European Journal of Service Management, 27*(2), 85-94. DOI: 10.18276/ejsm.2018.27/2-11

Deluga, W. (2018). Waste Management in Public Awareness. *Rocznik Ochrona Srodowiska, 20,* 1530-1545.

Golisz, E., Bryś, A. (2020). Possibilities of using waste from city green areas for energy. *Materials Management and logistics*, 9, 27-34. DOI: 10.33226/1231-2037.2020.9.3.

GUS (2019). Statistical yearbook. Environmental Protection

Jakubus, M., Jordanowska, J., Tatuśko, N. (2016). Knowledge of inhabitants of Darłowo and Września in the aspect of correct municipal wastes management. *Journal of Agribusiness and Rural Development*, *1*(39), 57-68. DOI: 10.17306/JARD.2016.7

Kiełczewski, D. (2001). *Ekologia społeczna*. Białystok: Ekonomia i Środowisko (in Polish).

Kłos, L. (2012). Municipal Waste Management – the Challenge of the XXI Century. *Scientific Journals of the University of Szczecin, Studies and Works of the Faculty of Economics and Management, 28,* 131-143.

Kłos, L. (2015). Environmental Awareness of Polish People – Overview of Research. *Scientific Journals of the University of Szczecin, Studies and Works of the Faculty of Economics and Management, 42*(2), 35-44. DOI: 10.18276/sip.2015.42/2-03 10.

Kobyłko, G. (red.) (2007). Proekologiczne zarządzanie przedsiębiorstwem, Wyd. II. Wrocław: Wydawnictwo AE, 186 (in Polish).

Kwiatek, A., Skiba, M. (2017). Ecological awareness of young people. *Zeszyty Naukowe Politechniki Częstochowskiej, Zarządzanie, 28*(2), 127-136. DOI: 10.17512/znpcz.2017.4.2.10

Lewandowska, A., Szymańska, D. (2019). Municipal waste recycling in big cities in Poland in the context of ecologisation. *Bulletin of Geography. Socio-economic Series, 43,* 131-141. DOI: http://doi.org/10.2478/bog-2019-0009

Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 15 kwietnia 2021 r. w sprawie ogłoszenia jednolitego tekstu ustawy o odpadach. *Dz.U.2021*, poz. 779.

Przydatek, G. (2020). Assessment of changes in the municipal waste accumulation in Poland. *Environmental Science and Pollution Research, 27*, 25766-25773. DOI: https://doi.org/10.1007/s11356-020-08943-6

Rosolak, M., Gworek, B. (2006). State and assessment of waste management in Poland. *Environmental Protection and Natural Resources*, *29,* 71-84.

Smol, M., Duda, J., Czaplicka-Kotas, A., Szołdrowska, D. (2020). Transformation towards circular economy (CE) in municipal waste management system: model solutions for Poland. *Sustainability, 12,* 4561. DOI: 10.3390/su12114561

Sowa, F. (2018). Ecological awareness and its impact on the greening of society and economy. *Rynek-Społeczeństwo-Kultura, 4*(30), 36-38.

Spigarska, E. (2013). The Citizens' Public Awareness of Waste Management on the Example of Housing Associations. *Scientific works of the University of Economics in Wrocław*, 297, 290-291.

Ustawa o utrzymaniu czystości i porządku w gminach z dnia 13 września 1996r. z późniejszymi zmianami, tekst jednolity z dnia 28 grudnia 2020 roku, *Dz.U. 2020* poz. 2361.

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Distribution of Heavy Metal Fractions in Sewage Sludge from a Selected Municipal Sewage Treatment Plant

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Abstract: Sewage sludge used for reclamation of egraded areas or in agriculture must have a certain total heavy metal content, as required by law. In practice, however, it is important to carry out a fractional analysis of the elements contained in the sludge. This activity allows to determine the chemical form of a given metal, thanks to which it is possible to assess the assimilability of elements by plants. The study proved that the fraction of certain metals in sewage sludge can vary depending on the period studied. The combination of elements with other compounds in sludge from one treatment plant can vary from month to month. Once analysis has been carried out, it should not be the basis for assessing the bioavailability of metals if sludge from a given treatment plant were to be sampled several times a year.

Keywords: sewage sludge, heavy metals, heavy metal fractions

1. Introduction

The number of municipal wastewater treatment plants in Poland is steadily increasing. In the period 2000-2019, their number has increased from 2417 to 3278. The need to serve an increasing population through WWTPs makes it necessary to build more facilities or modernise existing ones in order to increase their capacity and adapt them to new legal conditions (Skorbiłowicz & Ofman, 2015). In Poland, in 2000, the number of cities served by WWTPs was 801, and

19 years later, the number had increased to 938 (Statistical Office, 2020). These aspects determine the inflow of more and more wastewater to municipal treatment plants, and this has an impact on the increase in the amount of generated sludge. In 2010, 895,100 tonnes of sewage sludge were generated and in 2019, 17% more was produced (www.bdl.stat.gov.pl).

Figure 1 shows the quantities of sewage sludge used in agriculture in selected years. Clearly presented statistical data indicate that since 2004 an increasing amount of sludge has been used as a fertiliser for agricultural crops. However, it should be noted that sewage sludge contains heavy metals (Bauman-Kaszubska & Sikorski 2011), as well as other toxic compounds (Ofman & Skoczko 2018, Ofman & Struk-Sokołowska 2019, Struk-Sokołowska et al. 2020). The amount of organic and inorganic pollutants in sewage sludge depends on the chemical characteristics of the wastewater flowing into the facility (WIOŚ 2018). The composition of wastewater is also seasonally variable (Skoczko et al. 2017), so the content of pollutants in sewage sludge may vary depending on the sampling period.

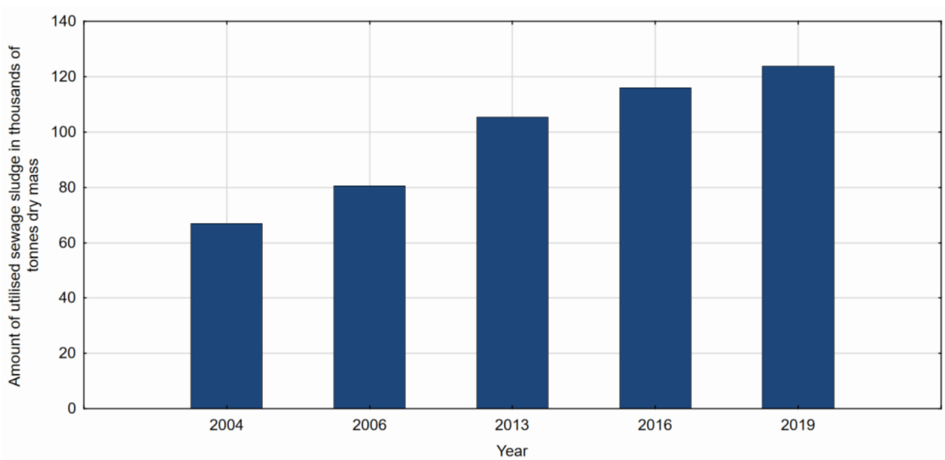

Fig. 1. Use of sewage sludge in agriculture in Poland
Source: Statistical Office: www.bdl.stat.gov.pl

Polish regulations set a limit for the content of heavy metals in sewage sludge used in agriculture and for land reclamation for agricultural purposes (Journal of Laws of 2015, item 257). However, the standards define a general acceptable content of these elements in sludge. Appropriate agricultural practice should include knowing the amount of metals in sludge by fraction (Wikarek-Paluch et al. 2016). Thanks to this, it is possible to determine the mobility of elements. This is important knowledge because mobile metals migrate in the environment, easily find their way into plants and then, when plant consumption takes place, they can enter living organisms, i.e. animals and humans (Boruszko 2013, Amir et al. 2005). Above all, however, performing speciation analysis makes it possible to reduce the occurrence of toxic effects that are caused by an excess of particular metals in the soil (Bozkurt et al. 2006; Dąbrowska & Nowak 2014).

The excess fraction of mobile heavy metals in soil is associated with their penetration through the biological membranes of plants (Matejczyk et al. 2020). Metals are able to completely restrict plant growth and development, as they limit the uptake of important micro- and macroelements by the roots (Wolak et al. 1999, Gruca-Królikowska & Wacławek 2006). Besides, they disrupt photosynthesis, contribute to abnormal transpiration, reduce turgor in leaves, and cause oxidative stress in plants (Kaczyńska et al. 2015, Wolak et al. 1999).

The sequential extraction process of heavy metals was carried out according to the modified BCR method, which gives the same results as the classical four-step BCR extraction method (Leśniewska et al. 2016). Therefore, 4 fractions of heavy metals were distinguished. Fraction I, the exchangeable-carbonate fraction, is the most available to plants. For this reason it is also referred to as the mobile fraction. It is a combination of elements with carbonates. Solubility in acids is a characteristic feature of this form. In an acidified soil environment, metals from this fraction are easily released and then migrate and reach plants (Boruszko 2013). The next fraction, termed reducible, is less mobile. It represents combinations of elements with manganese and iron oxides. The release of metals is determined by changes in the oxidation-reduction potential. Dismutation occurs under anaerobic conditions (Gawdzik 2010; Boruszko 2013). There is also a meta-stable fraction, otherwise known as oxidisable fraction. In this form, elements are bound to sulphides and/or organic matter. Metals are temporarily immobilised but can be released by microorganisms that decompose organic matter, regardless of the degree of oxidation of the environment (Dąbrowska & Nowak 2014). Fraction IV, the residual fraction, consists of metal-silicate combinations. Under natural conditions, elements in this form are completely immobilised (Żelezik & Gawdzik 2015, Wasilkowski & Mrozik 2016).

The aim of this study was to determine the variability of heavy metal fractions (Cu, Zn, Ni, Cd, Pb) in sewage sludge. Sludge was collected for analysis every month for half a year from a sewage treatment plant of 2500 PE. Until now, no research has been conducted in Poland and probably in Europe to determine the variability of heavy metal fractions in sewage sludge from a single plant.

2. Materials and methods

Sludge samples were collected from one wastewater treatment plant with a population equivalent (p.e.) of 2,500, located in the Podlaskie Voivodeship. Wastewater composition is seasonally variable, therefore sludge was sampled monthly for half a year, from October to March. The tested sludge samples were after the dewatering process, but before further treatment, i.e. stabilisation. The finished samples were tested for total heavy metal content and their fractions. The measurement for each sewage sludge sample was performed 3 times and the results were averaged. Figure 2 shows the technological scheme of the sewage treatment plant in Stawiski. The existing treatment plant consists of the following devices: radial sand trap, sludge stabilization chamber, expansion chamber, anaerobic chamber, and two aeration chambers. In addition, there is a catchment point and sludge plots. Sediment samples were collected from the sediment plots.

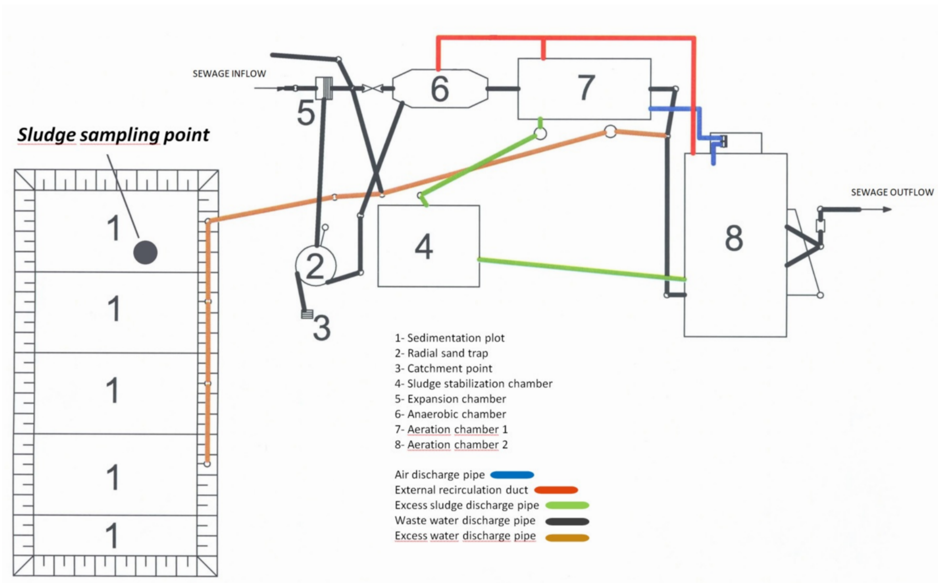

Fig. 2. Technological scheme of the sewage treatment plant in Stawiski

Source: Water permit for wastewater discharge from Stawiski WWTP to Dzierzbia river

Samples were prepared for analysis by drying them at 105°C to constant weight. This was followed by analysis of Cu, Ni, Pb, Cd and Zn using a modified BCR method. Unlike the classical BCR method, this technique uses a sonifier that generates ultrasound to allow mixing of the samples (Łapinski et al.

2019). This is done much faster than with the classical method. According to literature reports (Leśniewska et al. 2016), the modified BCR method, based on the use of ultrasonic waves for the heavy metal extraction process allows to obtain identical results in comparison with the classical four-step BCR extraction method. During the analysis, the probe was immersed to a depth of 4 cm, the amplitude of the probe operation was 70%, and the power was 16W. A 15-second pause after 15 seconds of operation of the device was also established. A sonifier from MIRIS was used for the study.

For BCR extraction, 1 g of dried sample was taken. For the extraction of the first fraction, a 0.11 $mol \cdot dm^{-3}$ solution of CH_3COOH at 40 ml was used. The sample was extracted for 7 minutes. The second fraction was extracted for 10 minutes with 40 ml of 0.5 $mol \cdot dm^{-3}$ $NH_2OH \cdot HCl$ solution. The third fraction was extracted using 50 ml of a 1.0 $mol \cdot dm^{-3}$ solution of CH_3COONH_4, and this took 4 minutes. However, before extracting the heavy metals from the third fraction, the organic matter had to be oxidised. For this purpose, H_2O_2 of 30% concentration was used in an amount of 10 ml, and the operation was performed on a water bath at 80°C. For the determination of the fourth fraction, the sample was incinerated at 470°C and then mineralised in a microwave mineraliser in a mixture of 9 cm^3 HCl and 3 cm^3 HNO_3. The total heavy metal content of the sludge was also determined after mineralisation. The first step was to burn the sample at 470°C, followed by mineralisation in a mixture of 9 cm^3 HNO_3 and 1 cm^3 H_2O_2 (Wojciula et al. 2021). The extracts prepared according to the described methodology were subjected to quantitative analysis on an ICE-3500 Thermo atomic absorption spectrometer using a flame technique operating on an air-acetylene gas mixture. The quantification threshold (LOD) for Cu and Cd was 0.02 mg/L, for Zn and Ni 0.01 mg/L, and for Pb the LOD value was 0.03 mg/L.

In order to indicate significant differences between the contents of all forms of the studied metals in sewage sludge, the results were statistically processed. This was possible by carrying out an analysis of variance, ANOVA using Tukey's test for equal samples (Ofman et al. 2020, Dobrowolska 2016). The total heavy metal content as well as the content of individual elements in the fractions were the dependent variables. In turn, the quality factor was the period (month) of sampling. Saphiro-Wilk's test and Bartlett's test were also performed. This confirmed that the results were characterised by a normal distribution and homogeneity of variance. The level of statistical significance was assumed to be 0.05. Statistical analyses were performed in the Statistica 13.1 software package.

3. Results and disscusion

The examined sewage sludge was characterized by a hydration level of 50% and an organic matter content of 80±5%. These data did not change in the analyzed months. Because of the seasonal variation of the sewage sludge composition, sludge samples were taken monthly for half a year.

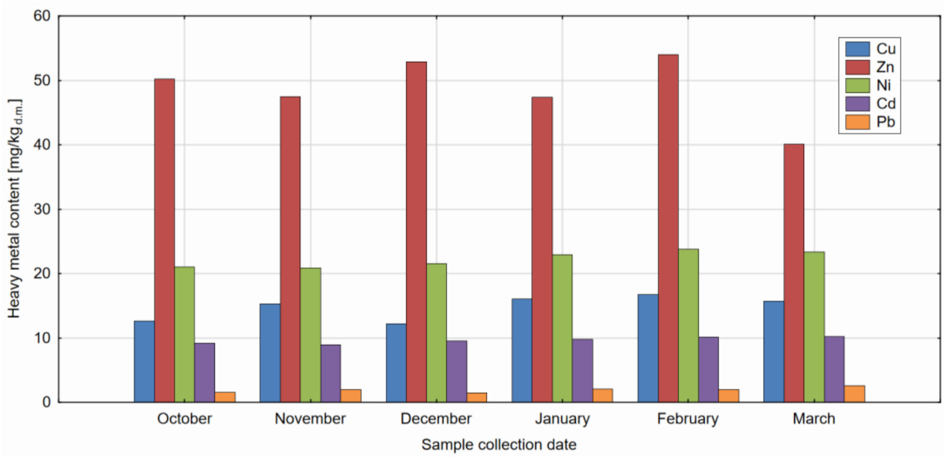

Fig. 3. Total content of heavy metals in sewage sludge according to the study period

Each of the sewage sludge samples, during the 6 months of the study, met the requirements established in the Regulation of the Minister of the Environment of 6 February 2015 on municipal sewage sludge. Sewage sludge from the selected treatment plant can be used for land reclamation for agricultural purposes, as well as in agriculture, but it must meet one condition. It must not be applied to the topsoil (0-25 cm). Figure 3 shows the total content of copper, zinc, nickel, cadmium and lead in the sewage sludge samples taken each month, from October to March. Copper, zinc and nickel occurred in the highest amounts in the sludge collected in February. Cadmium and lead, on the other hand, showed the highest content in the sludge collected in March. Figure 3 clearly shows that the overall metal contents of the samples were, however, very similar to each other, regardless of the season. The only exception was zinc. In February the element was 14 mg/kg d.m. more than in March. The reason for the high amount of zinc in February may have been increased thawing. Górska and Sikorski (2013) proved that zinc and lead are present in the highest concentration in rainwater sewage. In March, with heavy snowfall, zinc concentrations in wastewater were up to 7 times higher than nickel and cadmium concentrations. Lead concentration in that period was twice as high as chromium concentration. This is related to the occurrence of these elements in transport, automotive industry (Górska & Sikorski 2013, Struk-Sokołowska et al. 2020). So far, in Poland and probably in Europe, there have been no studies on periodic changes of heavy metals in dewatered sewage sludge ready for use. Controlled so far are, among others, changes in metal fractions during the composting process, i.e. stabilization of sewage sludge (Ingelmo et al. 2012), as well as differences in metal concentrations in sludge from different locations (Tytła 2019).

Statistically significant differences in Cu and Cd contents between individual periods of environmental sampling were observed over the study period. This phenomenon may indicate variation in the inflow of these elements with raw sewage. On the other hand, the contents of Ni, Zn and Pb did not show statistically significant differences over the study period, which may indicate similar concentrations of these elements in the wastewater flowing into the treatment plant over the study period.

Studies describing changes of heavy metal fractions in sewage sludge depending on the season of sludge intake are very rare. Authors mainly present transformations of metal fractions in sewage sludge during sludge stabilisation, or describe changes in metal forms depending on the size of the treatment plant or the type of sewage inflow. However, it is worth noting that in the same facility, sewage sludge can be characterised by different contents of heavy metal fractions, depending on the time of sludge intake.

According to Figure 4, the distribution of the Cu fraction in the sewage sludge samples varied. In January, the exchange-carbonate fraction, i.e. the fraction most available to plants, occurred at a level of 1.8%, while in November, this fraction occupied almost 12% of the total Cu content. Fraction II, which depends on the oxidation-reduction potential in the environment, occurred in similar amounts in each month (from 29% to 35%). There were more non-mobile fractions than mobile fractions in all samples studied. The highest number of non-mobile Cu fractions (III and IV) occurred in the sludge from January (68%) and the least from December (58%), but this was a 10% difference. Jamali et al (2009) report that Cu is an element very often associated with organic matter. The study carried out also confirmed this. The transformation of Cu fractions can take place under the influence of high temperature. Dąbrowska and Nowak (2014) proved that the incineration of sewage sludge at a temperature of 800°C results in the release of Cu from combinations with organic compounds. In their study, transformations of Cu fractions occurred to a small extent and may have depended on the composition of the influent wastewater.

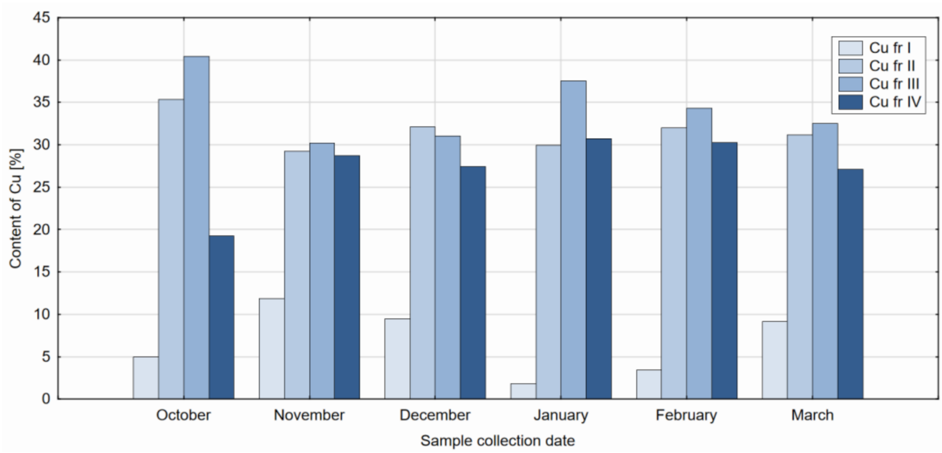

Fig. 4. Average fraction of Cu in sewage sludge samples collected in study period

In the case of Cu statistically significant differences at α = 0.05 level between individual periods of sampling sludge for the study were observed in case of I and IV fraction. On the other hand, the content of this element in the II and III fractions did not show statistically significant differences between individual times of environmental sampling. This observation confirms the observation that the content of Cu in the individual fractions may have been to a larger extent dictated by the form of this element present in the sewage compared to the transformations that may take place in the sludge.

Figures 5 and 6 show the average percentage contribution of Ni and Cd fractions in sewage sludge samples. For both elements, the summed value of the immobile fractions prevailed from October to March. In each month, the contents of individual fractions of both elements were very similar. Changes in the combinations of these metals with other compounds can occur when industrial wastewater is discharged to the treatment plant, or when corrosion of pipes or other elements of the sewage system occurs (Gawdzik 2012, Ilba et al. 2014, Surowska 2002).

In the case of Ni and Cd, no statistically significant differences were observed between the contents of these elements in individual fractions over the study period. This observation may indicate that the chemical forms in which these elements occur in wastewater are not subject to seasonal changes, and the sheer amount of Ni and Cd entering the wastewater treatment plant was equal during the study period.

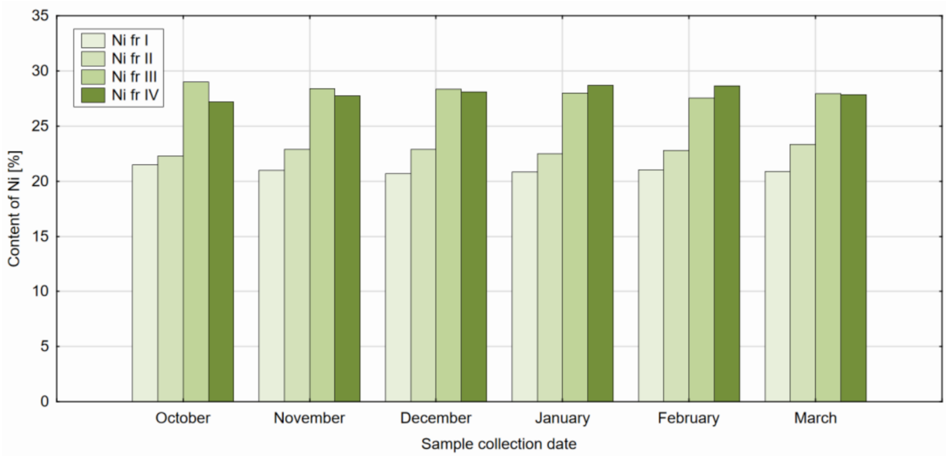

Fig. 5. Average proportion of Ni fractions in sewage sludge samples collected in study period

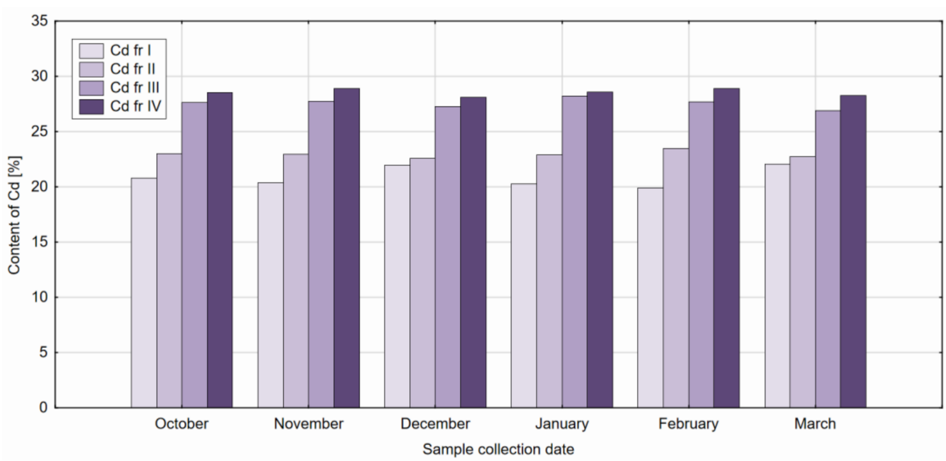

Fig. 6. Average fraction of Cd in sewage sludge samples collected in study period

Associations of Zn with other compounds in the studied sewage sludge differed considerably depending on the period of sludge sampling. It is also worth noting that of all the analysed elements, only Zn was predominantly present in the sludge in the most plant available form. Sludge collected from wastewater treatment plant from the Świętokrzyskie Voivodeship had the highest content of residual zinc fraction (460 mg/kg), but the content of exchangeable fraction (152 mg/kg) was higher than the content of reducible and metastable fraction (Gawdzik 2010). In turn, Gondek (2010) identified zinc as a highly mobile metal in waste materials. Other authors deduced that zinc was mainly bound to iron and manganese oxides, i.e. it occurred in a form where the release of the element is determined by changes in the oxidation-reduction potential (Piotrowska & Dudka 1987).

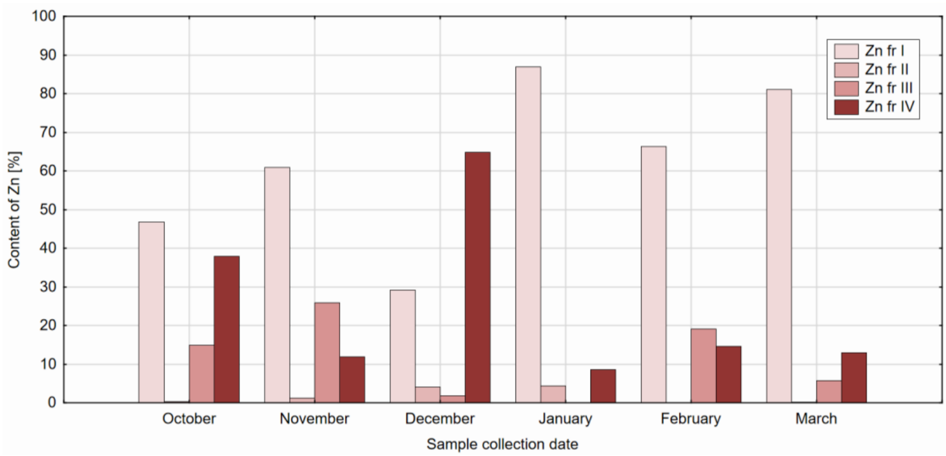

Fig. 7. Average proportion of Zn fraction in sewage sludge samples collected in study period

In almost every month fraction I had the highest share in the total Zn content, as shown in Figure 7. The exception was the sludge collected in December. It contained almost 70% of the immobile fraction. On the other hand, the sludge taken in January showed already less than 10% of these fractions. That is why sequential analysis is so important. Zn is an essential element for plant life, while an excess of it may limit photosynthesis or cause chlorosis and necrosis of leaves (Asati et. al. 2016, Ociepa-Kubicka & Ociepa 2012). The variability of heavy metal forms in sewage sludge largely depends on the composition of the wastewater. In turn, the composition of wastewater can be variable if rainwater enters the combined sewer system. Zn and Pb are the largest contributors to rainwater effluent (Górska & Sikorski 2013). Different rainfall intensity or variable snowmelt frequency can affect the content of zinc forms in the wastewater and, consequently, in the sewage sludge.

In the case of Zn, statistically significant differences were observed between all fractions in individual periods of environmental sampling. This may be due to a change in the chemical form of Zn entering the sewage treatment plant or, in the case of transformations observed in fractions I and III, to the transformation of this element by microorganisms in the sewage sludge.

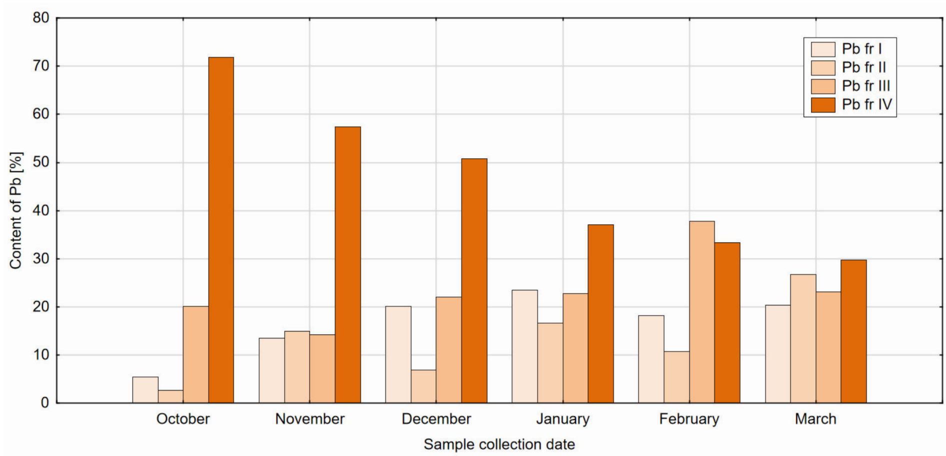

Fig. 8. Average share of Pb fraction in sewage sludge samples collected in study period

The distribution of Pb fractions also varied considerably. Figure 8 clearly shows that from October onwards, Pb was present in increasingly smaller amounts month by month in the form of combinations with silicates. The mobile fractions are also worth noting, as their amount was much higher in March than in October. Variable amounts of Pb fractions may be caused by higher or lower inflow of industrial wastewater, but also by snowmelt or heavy rainfall. Rainwater entering sewerage systems, flushes pollutants from street areas or from green areas (Górska & Sikorski 2013). Depending on the location of the runoff, Pb can form combinations with other compounds. The transformation of Pb fractions in sewage sludge can be influenced by the composting process. Ingelmo et al. (2011) demonstrated that composting contributed to the formation of more immobile fractions. Dąbrowska and Nowak (2014), on the other hand, proved that incineration at 800°C resulted in an almost complete loss of Pb fractions I, II and III, in favour of fraction IV. Sludge stabilisation processes can also have a significant impact on the transformation of heavy metal fractions in sewage sludge (Obarska-Pempkowiak & Gajewska 2008).

The Pb content in fractions I, II and III showed statistically significant differences at the $\alpha = 0.05$ level over the study period, between individual dates of sludge sampling, while for fraction IV statistically significant differences were observed only in the months of October to January. In the rest of the study period no statistically significant differences in Pb content were observed in fraction IV. Taking into account the chemical specificity of Pb and its potentially toxic effect on living organisms, the observed changes in the content of this element in individual fractions may be caused by changes in the form of its occurrence in raw sewage or by additional inflow of rainwater associated with seasonality. On the other hand, to a lesser extent, this element could be subject to transformations connected with the activity of microorganisms present in the sludge.

The total content of heavy metals determined after digestion of the studied sewage sludge was consistent with the total content of metals in particular fractions. The scientific aspect of the study was to determine whether seasonal variation of heavy metal fractions in sewage sludge occurs on the same object. The study confirmed that such changes do occur. In polish and foreign literature there were no references on the subject.

4. Conclusions

1. The proportion of lead, zinc and copper fractions in the sewage sludge varied according to the period studied.
2. The greatest differences in the contents of fractions in the half-year period were found for zinc and lead. These are the elements which have the largest share in rainwater effluents.
3. The distribution of nickel fractions in sewage sludge was very similar in every sample, irrespective of the period of sampling. A similar relationship was observed for cadmium.
4. In almost every analysed sludge sample the highest amount of fraction I of zinc was found. This means that in each month the sediment contained a considerable amount of this element in the form most available, assimilable for plants.
5. In the absence of industrial wastewater inflow to the treatment plant, rainwater, or more precisely the amount of precipitation or frequency of snowmelt, has a decisive influence on the transformation of the fraction.
6. The sum of immobile fractions of all metals (except zinc) was predominant in the studied samples.

References

Amir, S., Hafidi, M., Marlina, G., Revel, J. C. (2005). Sequential extraction of heavy metals during composting of sewage sludge. *Chemosphere, 59*, 801-810.

Asati, A., Pichhode, M., Nikhil, K. (2016). Effect of Heavy Metals on Plants: An Overview. *International Journal of Application or Innovation in Engineering & Management, 5*(3), 56-66.

Bauman-Kaszubska, H., Sikorski, M. (2011). The quality and quantity characteristic of sewage sludge coming from small sewage treatment plants on the area of Plock county. *Journal of Ecological Engineering, 25*, 20-29.

Boruszko, D. (2013). Fractionation of Heavy Metals in Sewage Sludge Processed by Low-input Methods. *Rocznik Ochrona Srodowiska, 15*, 1787-1803 (in Polish).

Bozkurt, M.A., Akdeniz, H., Keskin, B., Yilmaz, I.H. (2006). Possibilities of using sewage sludge as nitrogen fertilizer for maize. *Acta Agriculturae Seandinavica Section B-Soil and Plant Science, 56,* 143-149.

Dąbrowska, L., Nowak, R. (2014). Chemical fractions of heavy metals in sewage sludge and in residue after incineration of sewage sludge. *Engineering and Protection of Environment, 17*(3), 403-414 (in Polish).

Dobrowolska, B.M. (2016). The Analysis of Variance – a Took Used for the Research on Taxing Consumption. *Acta Scientiarum Polonorum. Oeconomia, 4*, 69-78.

EKO-PNC Kacprzyk, M. (2013). Water supply permit for the discharge of sewage from the municipal sewage treatment plant in Stawiski into the Dierzbia river, the municipality of Stawiski, county Kolno, Podlaskie Voivodeship, Łomża, december 2013.

Gawdzik, J.I. (2010). Speciation of heavy metals in sewage sludge: A case study. *Environmental Pollution Control, 32*(4), 15-19 (in Polish).

Gawdzik, J. (2012). Mobility of heavy metals in sewage sludge for example wastewater treatment plant. *Engineering and Protection of Environment, 15*(1), 5-15 (in Polish).

Gondek, K. (2006). The content of different forms of heavy metals in sewage sludge and composts. *Acta Agrophysica, 8*(4), 825-838 (in Polish).

Górska, K., Sikorski, M. (2013). Occurrence of heavy metals in rain wastewater on example of catchment in Kielce. *Proceedings of ECOpole, 7*(1), 333-341.

Gruca-Królikowska, S., Wacławek, W., (2006). Metals in the environment Part II. Effect of heavy metals on plants. *Chemistry-Didactics-Ecology-Metrology, 11*(1-2), 41-54 (in Polish).

Ilba, E., Masłoń, A., Tomaszek, J.A., Kutwicka, A. (2014). Evaluation of heavy metals content in sewage sludge from municipal treatment plant in Przemyśl in the aspect of its use in agriculture. *Journal of Civil Engineering, Environment and Architecture, XXXI, 61*(1/14), 55-65 (in Polish).

Ingelmo, F., Molina, M.J., Soriano, M.D., Gallardo, A., Lapena, L. (2011). Influence of organic matter transformations on the bioavailability of heavy metals in a sludge based compost. *Journal of Environmental Management, 95*, 104-109.

Jamali, M.K., Kazi, T.G., Arain, M.B., Afridi, H., Jalbani, N., Kandhro, G.A., Shah, A.Q., Baig, J.A. (2009). Speciation of heavy metals in untreated sewage sludge by using microwave assisted sequential extraction procedure. *Journal of Hazardous Materials, 163*, 1157-1164.

Kaczyńska, A., Zajączkowski, M., Grzybiak, M. (2015). Cadmium toxicity in plants and humans. Department of Clinical Anatomy, Department of Anatomy, Medical University of Gdansk, Gdansk, Poland, 45, 65-70 (in Polish).

Leśniewska, B., Krymska, M., Swierad, E., Wiater, J., Godlewska-Żyłkiewicz, B. (2016). An ultrasound-assisted procedure for fast screening of mobile fractions of Cd, Pb and Ni in soil. Insight into method optimization and validation. *Environmental Science and Pollution Research, 23*(24), 25093-25104.

Łapiński, D., Wiater, J., Szatyłowicz, E. (2019). The Content of Heavy Metals in Waste as an Indicator Determining the Possibilities of Their Agricultural Use. *Journal of Ecological Engineering, 20*(4), 225-230.

Matejczyk, M., Ofman, P., Dąbrowska, K., Świsłocka, R., Lewandowski, W. (2020). The study of biological activity of transformation products of diclofenac and its interaction with chlorogenic acid. *Journal of Environmental Sciences, 91*, 128-141.

Obarska-Pempkowiak, H., Gajewska, M. (2008). Circulation of heavy metals in wastewater treatment process in MUCT system reactors. Municipal waste management: a collective work. Volume 4/ed. edited by K. Szymański, Koszalin: Committee of Analytical Chemistry of the Polish Academy of Sciences, 225-237 (in Polish).
Ociepa-Kubicka, A., Ociepa, E. (2012). Toxic effects of heavy metals on plants, animals and humans. *Engineering and Protection of Environment, 15*(2), 169-180 (in Polish).
Ofman, P., Skoczko, I. (2018). PAH removal effectiveness comparison from hydraulic fracturing model wastewater in SBR reactors with granular and flocked activated sludge. *Desalination and Water Treatment, 134*, 41-51.
Ofman, P., Struk-Sokołowska, J. (2019). Artificial Neural Network (ANN) approach to modeling of selected nitrogen forms removal from oily wastewater in anaerobic and aerobic GSBR nprocess phases. *Water, 11*(8), article no 1594.
Ofman, P., Struk-Sokołowska, J., Skoczko, I., Wiater, J. (2020). Alterned biodegradation of naphtalene (NAP), acenaphthylene (ACY) and ace naphthene (ACE) in an aerobic granular sludge reactor (GSBR). *Journal of Hazardous Materials, 383*, article No. 121184.
Piotrowska, M., Dudka, S. (1987). Trace metal fractions in sewage sludge as a criterion for its usefulness in agriculture. *Archives of Environmental Protection, 1*(2), 67-72 (in Polish).
Regulation of the Minister of Environment of 6 February 2015 on municipal sewage sludge.
Skoczko, I., Struk-Sokołowska, J., Ofman, P. (2017). Sesonal changes in nitrogen, phosphorus, BOD and COD removal in Bystre wastewater treatment plant. *Journal of Ecological Engineering, 18*(4), 185-191.
Skorbiłowicz, M., Ofman, P. (2015). Changes in specific loads of mineral components outflowing from catchment area of river Supraśl. *Journal of Ecological Engineering, 16*(1), 135-140.
Statistics Poland. (2020). Environment. Statistical analyses, Warsaw, 190 (in Polish).
Surowska, B. (2002). Selected issues of corrosion and protection against corrosion. Textbook for students of Mechanical Engineering, specialties: Engineering of Structural Materials and Food Industry Machines and Equipment. Lublin University of Technology, 145. (in Polish)
Tytła, M. (2019). Assessment of Heavy Metal Pollution and Potential Ecological Risk in Sewage Sludge from Municipal Wastewater Treatment Plant Located in the Most Industrialized Region in Poland-Case Study. *International Journal of Environmental Research and Public Health, 9*, 16(13), 2430, 16.
Wasilkowski, D., Mrozik, A. (2016). Recultivation of heavy metal-contaminated soils using aided phytostabilization. *Advancements of Microbiology, 55*(4), 413-423 (in Polish).
Wikarek-Paluch, E., Rosik-Dulewska, C., Karwaczyńska, U. (2016). Mobility of Selected Heavy Metals in Municipal Sewage Sludge. *Rocznik Ochrona Srodowiska, 18*, 181-192 (in Polish).

Wojciula, A., Boruszko, D., Pajewska, G. (2021). Analysis of Heavy Metal Fraction Content in Sewage Sludge from Selected Wastewater Treatment Plants. *Journal of Ecological Engineering, 22*(4), 98-105.

Provincial Environmental Protection Inspectorate, Opole. Announcement 2/0/2018. Management of municipal sewage sludge in Opolskie Province in 2017, Opole, 1-25 (in Polish).

Wolak, W., Leboda, R., Hudicki, Z. (1999). *Heavy metals in the environment and their analysis*. State Inspection of Environmental Protection, Chełm (in Polish).

Żelezik, M., Gawdzik, J. (2015). The content of heavy metals species in sewage sludge from wastewater treatment plants in Mniów. *Archives of Waste Management and Environmental Protection, 17*(1), 119-126.

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Management Model Improving Environmental Protection

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Abstract: The work concerns a detailed analysis of the possibilities of increasing environmental protection by increasing the efficiency of selective collection of municipal waste in the city of Wroclaw and the economic conditions of this activity. The study includes a short introduction and an overview of waste morphology indicators. Then, a research model for the study of the morphology of municipal waste is discussed, based on the example of Wroclaw (Poland). Finally, 3 variant cost models of measures supporting the segregation of municipal waste were described and discussed. The article ends with a numerical example for Wroclaw along with a verification of the applicable rates for municipal waste collection fees, whether sorted or not.

Keywords: environmental protection, waste morphology, ecologistics, modeling

1. Introduction

The problem of waste management in the aspect of environmental protection is the subject of interest of the society, local governments, state authorities and scientists. It was noted that the problem of waste management is an important element of activities of modern societies. Thus, broad-spectrum activities and studies have been undertaken identifying key elements of waste management. In order to analyze the issues concerning the state and development trends of the waste management problem, selected publications in this area have been reviewed. On this basis, areas relevant to waste management issues were selected, i.e. handling of waste on the example of a motor vehicle, recycling process, transport, organization of waste management (Bendkowski & Wengierek 2002, Bendkowski & Wengierek 2004, Bujak & Zając 2013).

The issue of dealing with waste which is a used motor vehicle. In this area, product recycling is an important issue (Schaik & Reuter 2004, Chamier-Gliszczynski & Krzyzynski 2004), identification of the end-of-life stage of transport vehicles in the product life cycle (Chamier-Gliszczyński 2011), organization of a collection network for end-of-life vehicles (Merkisz-Guranowska 2010, Merkisz-Guranowska 2012), the issue of reuse, recovery and recycling system of end-of-life vehicles (Chamier-Gliszczyński 2010, Chamier-Gliszczyński 2011a, Chamier-Gliszczyński 2011b, Ohno et al. 2015, Merkisz-Guranowska 2018, Czwajda et al. 2019).

The transport task takes into account research in the area of environmentally friendly transport (Jacyna et al. 2018, Izdebski & Jacyna 2021) and organization of waste transport and collection of individual waste (Woźniak et al. 2016, Stryjski et al. 2020, Jacyna-Gołda et al. 2017, Izdebski & Jacyna 2018, Izdebski 2014, Kosobudzki et al. 2018). One of the examples of the organization of waste transport is phosphoric acid transported by barges to the heap in Poland (Wędrychowicz et al. 2019).

Issue of waste management organization. In this area, the Waste Law (Dz. U. 1997 nr 96, poz. 592, Dz. U. 2001 nr 62, poz. 628, Dz. U. 2007 nr 39, poz. 251, Dz. U. 2008 nr 111, poz. 708, Dz. U. 2008 nr 25, poz. 150), which first of all imposes the requirement to sort municipal waste, was introduced in Poland with the aim to increase the quantity of selectively collected waste and, consequently, to reduce the quantity of landfilled waste, to get rid of hazardous substances from the waste stream and, in particular, to save energy and recover valuable recyclables (Jajczyk et al. 2020, Gabryelewicz at el. 2020).

However, implementing this system, raising public awareness and taking the appropriate logistical measures is problematic and very costly. It might seem that the sale of selected recyclables and their reuse as materials in production processes should cover the costs related to waste management and additionally bring profits. Unfortunately, that's not the case. Therefore, citizens are obliged to pay a municipal waste management fee. Despite this, sorted waste is still only marginally cheaper than mixed waste; landfill fees are getting higher every year, waste treatment facilities are being built very slowly, mostly by private companies, and low commodity prices are making waste sorting and recycling less and less profitable. Further on, an analysis has been made of the possibilities of increasing the above-mentioned selective collection of municipal waste in Wroclaw and of the economic conditions of this activity. The directions of organizational and technical measures have been presented in terms of the possibilities of increasing the selective collection of waste as well as an economic analysis of the potential profits connected with the collection of sorted waste.

2. Research method

Information on the morphology of waste makes it possible to reliably formulate a waste management plan, the selection of the best methods for its disposal is conducive to designing an effective selective collection process. For this purpose, quantitative and qualitative tests shall be carried out in accordance with standards on how the samples are prepared and taken, and how the composition and individual components are determined. In addition, knowledge of the quantity, properties and morphology of waste allows for a reliable valuation of waste management services. Such studies also make it possible to develop reliable, long-term forecasts of the amount and type of waste generated in a given area. Forecasting is a very important factor when it comes to city development projects or implementing an efficient waste disposal system.

2.1. Quantitative studies

In the literature (Robak 2015) one can find quantitative studies carried out to determine the number of transport means needed, the frequency of export and to determine the size of landfills or waste treatment facilities. The tests shall be carried out on samples of at least the weekly amount of waste collected, as the daily amount could be unreliable due to large inter-day variation. Studies are carried out in selected regions, i.e. in areas with similar characteristics, e.g. in places with similar building development systems or in places with commercial and service facilities. The mass of waste is calculated on the basis of the weight of the transport vehicles before and after emptying them of the collected waste. The volume, on the other hand, is determined by the number of containers emptied and their volume. Assuming that there are 4.33 weeks in a month, the annual Q_a accumulation can be estimated (Equation 1).

$$Q_a = \left(\sum_1^{12} Q_{week}\right) \cdot 4{,}33 \quad \text{[Mg/year]} \tag{1}$$

The amount of waste generated is variable over time, it can be determined by a random distribution; comparing the amount generated over a short period of time, significant fluctuations can be observed. When looking at it over a longer period of time, one can see that this condition can be described quantitatively and qualitatively. The aforementioned coefficient of waste accumulation irregularity, expressed as the ratio of the monthly value of the waste mass to the monthly average value calculated over the year, is used for this purpose.

The volumetric municipal waste accumulation rate is defined (Zajac 2015) as the volume of waste collected per unit time in a container. The waste is loosely thrown in, i.e. without mechanical compaction such as in garbage trucks, for example. This indicator is expressed in unit volume per capita.

The bulk density of waste (Wolny 2010) [kg/m^3] determines the weight of 1 [m^3] of waste and is an important parameter in planning the collection fleet and the number of waste collection containers.

2.2. Qualitative studies

This type of studies is done to determine the nature of the waste and to the possibility of disposal by an appropriate method. We distinguish 3 types of such analyses:

1. Fractional analysis (sieve analysis) is used for preliminary division of waste into 4 grain fractions according to their size. Performing fraction analysis is necessary to initially determine the possibility of their separation and use of some of its components, and to move on to the next step which is preliminary treatment of waste, i.e. sorting, separation, shredding. An additional advantage of subjecting waste to this procedure is the separation of the fine fraction, e.g. ash, which is a ballast substance that deteriorates its fertilizing properties, for instance. On the other hand, the ash, once separated, can be used for concrete, roads, etc. (Sieja 2006, Siemiątkowski 2011, Wolny 2010).
2. Physico-chemical analysis is carried out by testing susceptibility to biochemical and thermal processes. Based on this analysis, the fertilizer and fuel properties of the waste are determined. Based on the results of these tests, it is determined whether the waste from a given site is susceptible to biochemical transformation, which will determine the validity of the rationale for establishing a treatment facility at a given site. From the technological point of view, the best solution is to dispose of properly selected fractions, i.e. combustible parts should be burnt, organic parts should be composted, and usable parts should be utilized (Styś 2014, Styś et al. 2016, Styś 2013, Zajac et al. 2020).
3. Morphological analysis separates waste into individual streams, i.e. waste types with averaged composition. It is important to extract as many components as possible. Such testing is very important because it carries information about the possibility of recycling, about the suitability for particular processing methods and about returning raw materials to production. These tests are performed manually on a sorting table.

The following morphological components or fractions of waste are distinguished: paper and cardboard, plastics, textiles, glass, organic waste, metals, hazardous waste, wood, composite, waste.

In this paper, waste tests were carried out in Wroclaw according to the PN-93/Z-15006 standard: Determination of morphological composition. In spite of growing demand for municipal waste research at local, regional and national as well as international level, no official, uniform and universal waste research methodology has been introduced so far in the European Union (Zajac & Kwasniowski 2017, Zajac et al. 2019).

3. Studies on morphology of municipal waste from Wrocław

The waste studies conducted in large cities most often take place in three different residential environments, with the following type of development:

- multi-family, multi-storey buildings with central heating, so called environment I,
- in the city centre, with a different heating system and many nearby shops and catering establishments, the so-called environment II,
- single-family, low-rise buildings with gardens and predominantly individual heating systems, so-called environment III.

From 1992 to 2005, the composition of municipal waste was measured three times in the city of Wrocław. The study was performed in the three residential environments indicated above at different times of the year – Fig. 1. Comparison of the results of the tests conducted showed significant changes in the morphology of the waste:

- the fine fraction (<10 mm) decreased significantly; in 1992/93 it amounted to 50-60%, and already in 2004/05 it was 30-40%,
- the glass fraction increased from 4.5% in 1992 to 11% in 2004. The reason for this was an increase in the amount of produced glass packaging,
- observed slight variations in the content of the paper and waste paper fractions,
- a significant increase was observed in the content of waste intended for biodegradation.

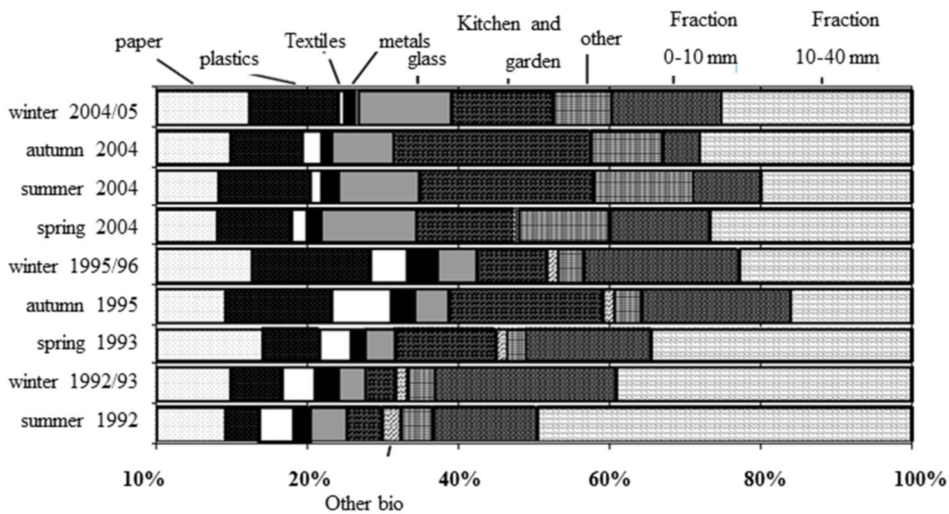

Fig. 1. Composition of municipal waste in 1992-2005 in Wrocław

The composition of municipal waste is greatly affected by the time of year. Figure 1 shows the predominance of the kitchen and garden waste fraction in summer and autumn. The increase in the content of fraction <10 mm in the winter period was influenced by the method of heating residential buildings.

Analysis of conducted studies on the composition of waste in rural areas. Studies on the morphology of waste generated in rural areas were carried out from Autumn 2011 to December 2012. The study included residents of different ages and number of persons in the family. From Figure 2, it can be seen that the most waste is generated in families of 2-3 people, especially in winter. The amount and composition of generated municipal waste depends on the season of the year (Table 1). In rural areas, the largest increase in the fraction of furnace waste is observed in winter, which is largely due to the heating of buildings with solid fuel. In spring and summer, the content of plastics in waste increases, which is related to the increase in consumption of cooling drinks.

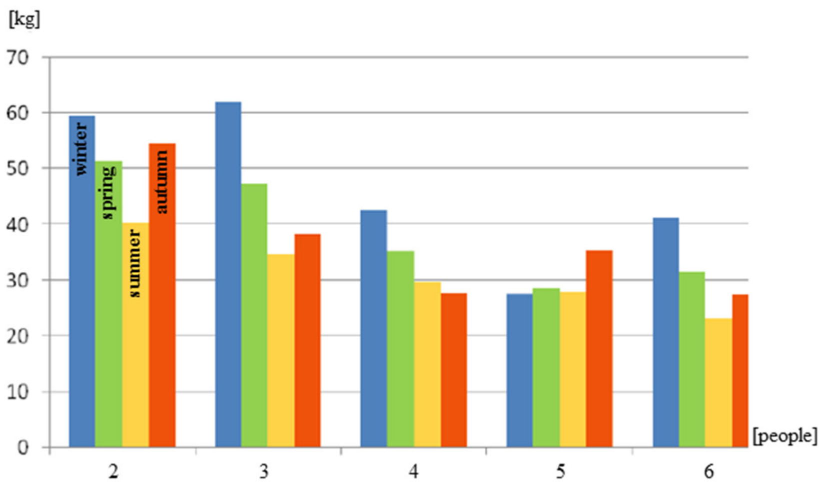

Fig. 2. Seasonal household waste accumulation rates in rural areas [kg/M]

Table 1. Morphological composition of selected waste fractions in rural areas [kg/M]

	Type of fraction	Spring	Summer	Autumn	Winter
1.	Glass	3.82	4.44	4.05	3.61
2.	Plastics	3.03	3.35	2.63	2.74
3.	Biodegradable	19.1	18.71	18.9	19.97
4.	Paper and cardboard	1.85	2.5	1.79	2.05
5.	Metals	0.57	0.66	0.79	0.71

Table 2. cont.

	Type of fraction	Spring	Summer	Autumn	Winter
6.	Textiles	0.46	0.46	0.32	0.35
7.	Wood	0.01	0.02	0.01	0.01
8.	Burning residues	6.31	1.51	2.79	13.19
	Total	**33.15**	**31.65**	**31.28**	**42.63**

Figure 3 illustrates the composition of each waste fraction in rural areas in spring. The dominant waste content is biodegradable waste, which includes kitchen and garden waste. In rural households, it is perfectly possible to use this type of waste by creating a home composter.

4. Models of municipal waste collection and treatment

Each model has a different direct and indirect cost path, which ultimately translates into the total cost of waste disposal. The goal is to analyse each path to get the clearest picture of all cost components. The cost balance for each model analyzed will also be recorded. On its basis it will be possible, with all the company's data, to calculate how much the residents should pay to balance all the costs and profits resulting from the collection and treatment of waste. It will also be possible to see the trend, i.e. which components have the greatest impact on the total cost of disposal, which will clearly indicate which elements subjected to optimization will significantly reduce the cost of waste collection (Jajczyk 2016).

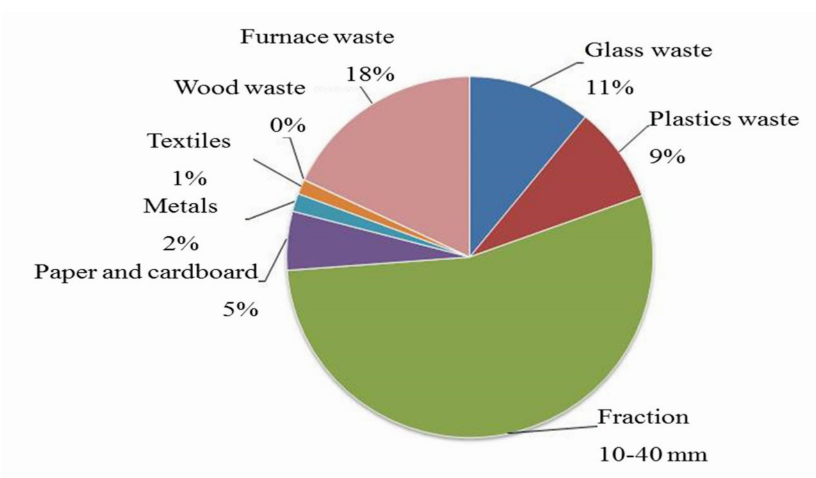

Fig. 3. Waste composition in rural areas during winter

Three cost model variants for municipal waste collection and treatment are presented below: Cost model – variant I-III, which allow to determine the amounts of residents' fees for municipal waste depending on the variant of waste management after its collection in [PLN/person/month]. In each model, several basic processes can be distinguished. These are mainly: transport of waste between Recipient – Regional Municipal Waste Processing Facility, waste sorting at Regional Municipal Waste Processing Facility (mixed waste separately, pre-sorted waste separately), transport between Regional Municipal Waste Processing Facility – PROCESSING PLANT (for recovered raw materials), transport between Regional Municipal Waste Processing Facility – LANDFILL (for both waste not suitable for processing separated as a result of selection and waste transported directly to landfill).

The basis for rate considerations is the cost balance equation (2 and next). The costs of operation K of the municipal waste management system should be covered in full by fees paid for collection of waste from residents and profits from sales of recyclables over a specified period of time (month, year). The relationship below shows the balance of the municipal waste management system functioning on a monthly basis.

$$K = O_m + Z_{ss} \tag{2}$$

where:
O_m – fees from residents for municipal waste collection [PLN/month],
Z_{ss} – profits from sales of sorted waste [PLN/month].

Fulfillment of the above equation indicates full utilization of all funds received. Service providers do not suffer a loss and residents do not overpay for the service. The essence is to find a rate for waste collection (O_m) such that companies are able to generate profit while optimizing their own costs. Too high a value of the O_m indicator results in excessive subsidies for companies, which manifests itself in the growth of administration and the lack of their own activity in innovation. Too low a value precludes a viable business.

The total cost of operating the K waste management system consists of the costs incurred by the transport company, the costs of the waste sorting plant (Regional Municipal Waste Processing Facility) and the costs related to waste disposal. Using equationbelow, the total cost of operating the municipal waste collection and management system can be calculated.

$$K = K_{ft} + K_{fs} + K_{ft} \tag{3}$$

where:
K_{ft} – operating cost of transport company [PLN/month],
K_{fs} – operating cost of sorting plant [PLN/month],
K_{ft} – cost of depositing waste at the landfill [PLN/month].

It is possible to determine the monthly O_M fee that each resident should pay for the collection and management of the generated municipal waste. This rate can be calculated using the following formula.

$$O_M = \frac{K - K_{ss}}{M_o} \tag{4}$$

where:
M_o – number of residents generating collected municipal waste.

Pursuant to the current legal regulations, the municipality establishes the rate for municipal waste collection and management. The entire amount collected from all N residents is transferred to the Regional Municipal Waste Processing Facility. To calculate the total amount collected from residents, the following equation 5 should be used.

$$N = M_o \cdot O_G \tag{5}$$

where:
O_G – monthly rate for residents set by the municipality [PLN/person/month].

It should be noted that the rate O_M may be different from the rate O_G despite the fact that they refer to the same thing. This is due to a different way of calculating the rate in question.

The transport company that collects municipal waste incurs various costs. The total K_{ft} costs of operating a transport company are expressed in relation 6.

$$K_{ft} = \sum K_t \tag{6}$$

where:
$\sum K_t$ – sum of individual costs of waste transport [PLN/month].

The costs of the transport process can be divided in terms of volume and level of activity into: variable (which include: energy and operating materials, fuel, tyres) and fixed (which include: repairs and maintenance services, taxes on transport, real estate and land, loans and lease, depreciation, staff wages and surcharges, insurance, external services, road and environmental charges, other transport activity costs).

The costs incurred by transport companies depend on the number of kilometres travelled by means of transport in a certain period of time. Each transport company also adds a margin to the costs incurred. Transport companies often use the term “run". The number of runs n_k is calculated from relation 7.

$$n_k = \frac{I_o}{Q_t} \tag{7}$$

where:
I_o – amount of generated waste [kg/month],
Q_t – average load capacity of the waste transporting unit [kg].

The amount of waste generated per month (I_o) is the amount of waste generated by each resident for a given number of residents. According to Chief Statistical Office data, a Pole produces about 26 kg of municipal waste per month.

The number of runs made is not always determined by the average payload of the vehicle. For waste with low bulk density (e.g. PET packaging), the number of runs to be made results from the volume of waste the given vehicle type is able to accept.

Therefore, in order to minimize the number of runs that do not fully utilize the permissible vehicle payload, vehicles with an integrated compaction system are used to transport waste with low bulk density. Depending on the type of waste collected, the degree of compaction is: (1:3)-(1:5).

The magnitude of variable transport costs (fuel, consumables, tyres) depends on the total distance covered by the vehicles. The longer the distance travelled, the greater the significance of variable costs in the total costs.

The calculated route length should include both the distances to be covered in order to transport the raw material to the place of processing and disposal. The type of vehicles used depends on the distance. For short-distance transport, it is recommended to use the same vehicles that collect waste from residents. For long-distance transports, this is uneconomical, as these vehicles have a lower capacity and require additional personnel to operate them.

The measure that combines fixed and variable costs is the truck-kilometre (W_{km}). It is a value that characterizes the sum of fixed and variable costs per unit time, per unit distance. The cost per truck-kilometre is expressed in equation 8.

$$W_{km} = \frac{K_{ft}}{S} \tag{8}$$

where:
K_{ft} – transport company operating costs per month including variable and fixed costs [PLN/month],
S – distance for which variable costs were assumed [km].

In the overall costs of the municipal waste management system, transport has a significant share. The costs are highest in areas with low population density and in areas with varied relief. The highest costs associated with municipal waste collection occur in rural areas. The organization of transport is significantly influenced by: containers (their quantity and capacity), location of containers, distances between collection points and installations, vehicle loading capacity and their technical condition.

The Regional Municipal Waste Processing Facility's waste sorting plant carries out sorting of mixed waste and secondary sorting of municipal waste. The total cost of operation K_{fs} of the sorting plant is made up of its individual cost components. The cost of operating the sorting plant is the equation 9.

$$K_{fs} = \sum K_s \tag{9}$$

The waste sorting plant is burdened with the following costs: energy and materials (including maintenance costs), repairs and renovation services, taxes, credits and leases (service, instalments), machine and equipment depreciation (depreciation write-offs), insurance, employee salaries, external services, investment costs, costs related to the production of sold materials (loading, unloading), other costs. The sorting plant's operating costs are strictly related with the quantity and quality of accepted waste. The company's profit should be included in the cost calculations.

It is possible to calculate the operating costs of the sorting plant K_{fsm}per resident. This can be done by dividing the cost of operating the sorting plant by the number of residents it serves. This will give a picture of how much it costs per resident to operate and maintain a waste sorting plant over a given period of time (on a monthly basis in this case). The relationship discussed can be written as follows:

$$K_{fsm} = \frac{K_{fs}}{M_o} \tag{10}$$

A landfill is a place where only waste from which recyclable waste has been recovered after previous selection should be disposed of. The sum of the individual costs of the landfill K_{fw} affects the total cost of operating the landfill over a specific time period (month, year). Using equation 11, the monthly operatingcosts of the landfill can be calculated.

$$K_{fw} = \sum K_w \tag{11}$$

where:
$\sum K_w$ – sum of individual costs of municipal waste landfilling [PLN/month].

The landfill incurs the following costs: consumption of materials and energy, external services, taxes and fees, remuneration of landfill personnel, social benefits and insurance, depreciation, fees to the Environmental Protection Fund for waste disposal, determined by the Ministry of Environmental Protection [PLN/Mg], fees for gas and dust emissions to air, other costs.

These costs depend on the landfill equipment. The costs of environmental fees are closely related to the amount and type of waste disposed of.

Both expenditures and income are included in the economic balance sheet. Companies that manage municipal waste derive revenue from the sale of recyclables. The amount of these revenues depends on the current market prices of raw materials and the morphology of waste in a given period. The total profit Z_{ss} results from the sum of the sales of individual fractions that the plant has at its disposal in a given time. A waste management company is able to estimate the (monthly, in this case) approximate profit from its operations using Equation 12.

$$Z_{ss} = I_0 \sum \frac{P_i \cdot F_i}{100\%} \tag{12}$$

where:
P_i – rate for recyclable deposited in the collection point [PLN/kg],
F_i – composition of a given recyclable in the generated waste [%].

The individual morphological composition of municipal waste in Poland is (Robak 2015) paper 13%, metals2%, glass 10%, plastics 13%, kitchen and garden waste 32%. The remaining fractions: wood, bulky waste, textiles, hazardous waste, multi-material waste, green waste are most often sent to landfills or utilized through composting and occasionally incinerated. Based on (Robak 2015), a citizen in Poland generates about 26 [kg] of waste on average per month.From the telephone survey carried out, information on the rate for sale of particular waste fractions was adopted, which has been used later in this paper.

4.1. Cost variant – variant I

The following cost model of Figure 4a occurs when all the mixed municipal waste collected goes directly to the landfill. The presented variant is unacceptable, because the legal regulations introduced in connection with Poland's accession to the European Union impose the reduction of waste intended for landfilling to a minimum.

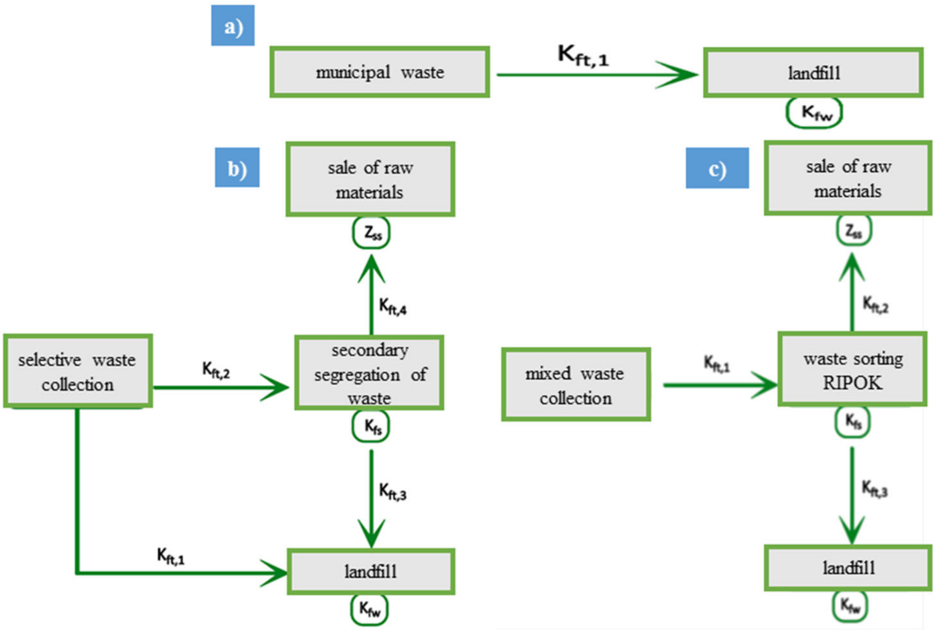

Fig. 4. Model in total landfilled waste, where: K_{ft}means the cost of operation of the transport company, while K_{fs} means the cost of operation of the RIPOK: Polish acronym: Regional Municipal Waste Processing Facility, and K_{fw} means the cost of landfilling waste, while Z_{ss} means profit from sales of raw materials

In the variant I model, the total operating costs of the $\sum K_{I,fi}$ system are affected by the operating costs of the trucking company and the operating costs of the landfill, as shown in equation 13.

$$\sum_{i\in(t,w,s)} K_{I,fi} = K_{ft,1} + K_{fw} \tag{13}$$

where:
$K_{ft,1}$ – operating cost of transport company [PLN/month],
K_{fw} – operating cost of landfill [PLN/month].

The operating cost of the transport company $K_{ft,1}$ depends on the total distance travelled S_1 (in a given time; for a monthly period in this case). It applies both to runs with cargo to the landfill and returns to the base.

Knowing the value of the sum of all distances travelled on a given route on a monthly basis S_1 and the rate per truck-kilometre W_{km} [PLN/km], the cost $K_{ft,1}$is presented in equation 14.

$$K_{ft,1} = W_{km} \cdot S_1 \tag{14}$$

In order to calculate the monthly fee rate per capita in the discussed model, the formula W_I should be used. It is the quotient of all costs (collection, transport and storing) to be borne by the number of residents from whom waste is collected. The whole is defined in the same time frame; here it refers to a month. This relationship is captured by equation 15.

$$W_I = \frac{\sum K_{I\,fi}}{M_o} \tag{15}$$

where:
$\sum K_{I\,fi}$ – sum of all partial costs in the variant in question,
M_o – number of residents from whom waste is collected in the above variant.

This variant has the lowest economic benefits while having the highest negative impact on the environment.

The pro-ecological policy of the European Union forces its members to abandon this model. According to Directive 2008/98/EC, each State is obliged to reduce the amount of waste to be landfilled. For this reason, amendments to the Polish Waste Act require the creation of waste management plans, the implementation of which is to enable the assumed levels of recyclable utilisation to be achieved. It is to be welcomed that Poland is on the way to improving its use of recyclables, although it is a pity that this is the result of European Union pressure rather than its own initiative.

4.2. Cost model – variant II

The cost model variant II, Figure 4b, occurs when selectively collected waste is taken to secondary sorting and mixed municipal waste is directly deposited at a landfill. The scheme described above illustrates the situation currently prevailing on the Polish market, as only 15% of the generated waste is sent to sorting plants, where it is subject to secondary sorting. The cleaned waste is sent for further processing, which enables some profit to be made.

Similarly as in the previous model, the operating cost of the transport company $K_{ft,i}$ depends on the total route covered S_i (in a given time, here for the period of a month). It applies both to runs with cargo and returns to the base. In the model in Figure 4b, the distance S_1 defines the sum of all distances travelled on the route "selective collection – landfill". S_2 refers to the route "selective collection – secondary sorting (Regional Municipal Waste Processing Facility)", etc.

In the case of distances S_3 and S_4, the sum of the route lengths is the product of a single route l_3 (arrival and return) and the number of necessary runs n_k to perform; see equation 16.

$$S_3 = l_3 \cdot n_k \tag{16}$$

It should be noted here that for the route "Regional Municipal Waste Processing Facility - sale of raw materials" the length of the route (l_i) for each raw material will be different, so in the calculations each raw material should be treated individually. Knowing the value of S_1, S_2, S_3, S_4 [km/month] and the rate per truck-kilometre W_{km} [PLN/km] the cost K_{ft} is presented in equation 17. The sum of costs in the variant II model is expressed by formula 18.

$$K_{ft} = \sum_{i\in(1,2,3,4)} K_{ft,i} = W_{km}\,(S_1 + S_2 + S_3 + S_4) \tag{17}$$

$$\sum_{i\in(t,w,s)} K_{II,fi} = K_{ft} + K_{fw} + K_{fs} \tag{18}$$

The calculation of the W_{II} rate that residents must pay to cover the costs of operating model II is expressed in equation 19. It also takes into account profits from the sale of recyclables, the calculation of which is shown.

$$W_{II} = \frac{\sum K_{II\,fi} - Z_{ss}}{M_o} \tag{19}$$

where:
$\sum K_{II\,fi}$ – sum of all costs of variant II,
Z_{ss} – profits from the sale of recyclables,
M_o – number of residents from whom waste is collected in the above variant.

The rate should be calculated for the expected time frame. If it is to refer to a monthly period, $\sum K_{II\,fi}$ and Z_{ss} should be included in the monthly period. The practice of western countries shows that a system based on the selective collection of waste is more cost-effective than the costs of operation of a Regional Municipal Waste Processing Facility. In highly developed countries, Regional Municipal Waste Processing Facilities are replaced by people who take care of improving the quality of collected waste already at source. Increasing selective collection translates into higher profits from their sale, which affects the final rate for their disposal. A very important activity is the creation of conditions enabling proper sorting of waste along with raising the ecological awareness of residents.

4.3. Cost model – variant III

All the mixed municipal waste collected is sent to sorting plants, as shown in Fig. 4c, where it is subsequently sent to Regional Municipal Waste Processing Facilities where it is mechanically sorted. The cost of sorting mixed waste is more than 3.5 times higher than the cost of secondary treatment of selectively collected waste - according to information from Wroclaw City Hall.

Again, the operating cost of the transport company $K_{ft,i}$ depends on the total distance covered S_i (in a given time; a monthly period was assumed here). It should be understood as all the distances that have to be covered in order to pick up and transport waste, as well as to return to the base. The route S_1 refers to the sum of distances along the route "mixed waste collection – sorting plant (Regional Municipal Waste Processing Facility)", S_2 refers to the sum of distances along the route "sorting plant (Regional Municipal Waste Processing Facility) – sale of raw materials", etc.

Analogically to model II (Figure 4), in the case of distances S_3 and S_4, the sum of route lengths is the product of a single route l_3 (arrival and return) and the number of necessary runs n_k to be made, which is expressed in equation 20.

$$S_3 = l_3 \cdot n_k \tag{20}$$

It should be noted that for the route "Regional Municipal Waste Processing Facility - sale of raw materials" the length of the route (l_i) for each raw material will be different, so in the calculations each raw material should be treated individually. Knowing the value of S_1, S_2, S_3 and the rate per truck-kilometre W_{km}, the cost K_{ft} is shown in equation 21.

$$K_{ft} = \sum_{i\in(1,2,3)} K_{ft,i} = W_{km}\,(S_1 + S_2 + S_3) \tag{21}$$

The sum of all costs in the described model (variant III) is expressed in equation 22.

$$\sum_{i\in(t,w,s)} K_{III,fi} = K_{ft} + K_{fw} + K_{fs} \tag{22}$$

The calculation of the rate that residents must pay to cover the cost of operating Model III is described in Equation 23. It takes into account profits from the sale of raw materials that reduce the fee.

$$W_{III} = \frac{\sum K_{III\,fi} - Z_{ss}}{M_o} \tag{23}$$

where:
$\sum K_{III\,fi}$ – sum of all costs of variant III,
Z_{ss} – profits from the sale of recyclables,
M_o – number of residents from whom waste is collected in the above variant.

The largest share of municipal management costs is accounted for by "Landfills" and "Sorting plants for non-separate waste" (Regional Municipal Waste Processing Facility). Transport costs play a secondary role in the global balance sheet.

Looking at the above model, one can see a trend. The cost burden on landfills is already decreasing with the use of sorting plants. The whole balance is strongly affected by costs of sorting the mixed fraction, which are 3.5 times larger than secondary selection. Profits from the sale of raw materials must not be overlooked; these also benefit the financial balance of the process. This is certainly a better solution than no selection at all and transporting all waste to landfills.

For selective collection, as its efficiency increases, returns on sales increase and the cost of collecting waste at landfills decreases. On the other hand, the operating costs for secondary selection are much lower than for sorting plants.Based on this, a trend is emerging that is also noticeable in European politics. Taking into account the presented models of variant 2 and variant 3, calculations were made to verify the amount of waste charges. Table 2 presents the total cost of transporting the monthly quantity of mixed municipal waste accumulated in Sector I, Variant 2.

Table 3. Total cost of transport of the monthly quantity of mixed municipal waste accumulated in Sector I

Transport cost	
Number of runs	833.00
Average distance to Regional Municipal Waste Processing Facility in km	55.00
Number of km to be covered per month	91630.00
Amount of fuel required in litres	4134.00
Cost of fuel in PLN	206168.00
Depreciation and insurance cost in PLN	439824.00
Total transportation cost excluding staff PLN	645992.00
Number of trucks	25.00
Number of employees	75.00
Total remuneration of employees in PLN	225000.00
Costs of intervention collections in PLN	100000.00
Total in PLN	970992.00

Other costs to be taken into account are shown in Table 3.

Table 4. Other costs included in municipal waste management. On a per month basis – for the share of mixed waste only

Cost summary	PLN
Cost of waste collection order in PLN	970992.00
Profit margin 15% in PLN	145649.00
Sorting plant in PLN	365712.00
BIO installation in PLN	269089.00

Table 5. cont.

Cost summary	PLN
Landfill site in PLN	313480.00
Landfilling cost (landfill price – including environmental fee) in PLN	1494021.00
Overhead costs in PLN	190216.00
Administrative costs in PLN	53836.00
Costs of Municipal Waste Selective Collection Facilities in PLN	12833.00
Costs of purchasing containers and bags in PLN	179471.00
Total in PLN	3995298.00

The values of the costs of mixed waste management in particular sectors are presented in Table 4.

Table 6. The monthly cost of managing mixed municipal waste

Total cost of waste management	PLN
Sector I	2397179.00
Sector II	1284203.00
Sector III	2654019.00
Sector IV	2225951.00
Total	8561352.00

The final total cost is ca. PLN 8561352. The fee for management of mixed municipal waste in Wroclaw per the number of Wroclaw residents who do not sort waste is presented in Table 5.

Table 7. Garbage fee rate

Summary of cost estimate	
Number of residents who do not sort	347195.00
Cost of mixed waste management [PLN]	8561351.88
Calculated cost per person [PLN]	24.66
Average rate in Wrocław [PLN]	30.75

The calculations for variant II (for mixed waste) can be found in Table 6.

It is obvious that part of the sorted waste will not be used as recyclable. Residues after sorting in the north-central region are transported from Wroclaw to the Disposal, Recycling and Treatment Facility for Municipal and Industrial Waste in Rudna Wielka and to the Ecological Disposal Centre in Rusko. This waste goes to the facility coded as 191212. The average cost of landfilling them is PLN 329.10 per [Mg].

The calculated cost of storing the sorted waste and the costs of maintaining the installation, the Municipal Waste Selective Collection Facilities, as well as the final calculated cost are presented in Table 7.

Table 8. The total cost of transporting a monthly quantity of sorted municipal waste

Transport cost – whole Wrocław	
Number of runs	2199.00
Average distance to Regional Municipal Waste Processing Facility in km	55.00
Number of km to be covered per month	241890.00
Amount of fuel required in litres	108 851.00
Cost of fuel in PLN	544253.00
Depreciation and insurance cost in PLN	1161072.00
Total cost of transport excluding employees in PLN	1705325.00
Cost of managing waste such as rubble, oversize items, etc. in PLN	36333.00
Cost of bio waste management in PLN	363977.00
Cost of glass preparation in PLN	27000.00
Cost of preparing plastics and waste paper in PLN	1063000.00
Number of trucks	50.00
Number of employees	150.00
Total remuneration of employees in PLN	450000.00
Costs of intervention collections in PLN	100000.00
Total in PLN	3745635.00

Table 9. Other costs included in municipal waste management. Per month – only for the share of selectively collected waste

Cost summary	PLN
Cost of waste collection orders	3745635.00
Profit margin 15%	561845.00
Sorting plant	1068638.00
BIO plant	786300.00
Landfill	916013.00
Cost of storing the remaining sorted waste	127661.00
Overhead costs	555825.00
Administrative costs	157313.00
Collection of expired medicines	19583.00
Municipal Waste Selective Collection Facility	37500.00
Costs of purchasing containers and bags	146840.00
Total	8123152.00
40% of costs are covered by companies	3249261.00
Final cost	4873891.00

A comparison of the actual rate and the rate calculated from the model is included in Table 8.

Taking into account the possibility of selling the previously sorted and prepared fractions, a balance of costs and profits has been drawn up and compared with the potential profitability of waste sorting and its subsequent recycling.

Once the fractions such as plastics, glass and paper are prepared – they are sold to processors for recycling at a price individually determined by the recycling company. The calculated sales revenue amounts are shown in Table 9 and the adjusted fee rates are shown in Table 8, column 3.

Table 10. Garbage fee rate

Cost	No sale	Includes sales
Number of residents who sort, Assumes 100% payers	284068.00	284068.00
Cost of managing sorted waste [PLN]	4873891.00	4180698.00
Calculated cost per person [PLN]	17.16	14.72
Average rate in Wrocław [PLN]	20.50	20.50

Table 11. Estimated profit from sales of sorted fractions

Profit from sales of raw materials – monthly quantity				
Fraction	Purchase price in PLN/kg	Quantity put up for sale in kg	Profit in PLN	Total
Plastics	0.60	465794.00	279477.00	693194.00
Waste paper	0.26	856240.00	222622.00	
Scrap	0.70	124189.00	86932.00	
Glass	0.06	1736043.00	104163.00	

5. Summary

Analysing the results of the estimated garbage fee rates in Wrocław and the municipal waste management existing in that city, one may conclude that the sorting of municipal waste is hardly profitable at present. The main reason for low profitability is the high cost, which results from high prices of fuel or maintenance of waste treatment facilities. Low profit is also connected with the fact that the preparation of sorted fractions for recycling is expensive, while the amounts of collected recyclables are also not high enough to cover most of the costs. Based on the estimated costs and profits of the management of sorted municipal waste, it may be seen that the profit from the sale of recyclables is able to cover only about 14.2% of the total costs of the management of sorted municipal waste. On the basis of analyses, studies and observations, it may also be concluded that as time passes, the sorting of municipal waste by residents may be at an increasingly higher level, which may significantly reduce the costs of preparing such waste for recycling. One of the factors that can lead to this is the continuous running of programmes promoting an ecological attitude, making the public aware of how significant the problem of garbage is.

References

Bendkowski, J., Wengierek, M. (2002). *Logistyka odpadów, Procesy logistyczne w gospodarce odpadami*. Publishing house of the Silesian University of Technology. (in Polish)

Bendkowski, J., Wengierek, M. (2004). *Logistyka odpadów, Obiekty gospodarki odpadami*. Publishing house of the Silesian University of Technology (in Polish).

Bujak, A., Zając, P. (2013). Monitoring of cargo in logistic systems of transport and storage. *In International Conference on Transport Systems Telematics*, 361-369. Springer, Berlin, Heidelberg.

Chamier-Gliszczynski, N., Krzyzynski, T. (2005). On modelling three-stage system of receipt and automotive recycling. *REWAS'04, Global Symposium on Recycling, Waste Treatment and Clean Technology 2005*, 2813-2814, Madrid, Spain, 26-29 September 2004, Conference Paper, ISBN: 8495520060.

Chamier-Gliszczyński, N. (2010). Optimal Design for the Environment of the Means Transportation: a Case Study of Reuse and Recycling Materials. *Sold State Phenomena, 165*, 244-249. DOI: 10.4028/www.scientific.net/SSP.165.244

Chamier-Gliszczyński, N. (2011). Environmental aspects of maintenance of transport means, end-of life stage of transport means. *Eksploatacja i Niezawodnosc - Maintenance and Reliability, 50(2*), 59-71. http://ein.org.pl/podstrony/wydania/50/pdf/07.pdf

Chamier-Gliszczyński, N. (2011a). Reuse, Recovery and Recycling System of End-of Life Vehicles. *Key Engineering Materials, 450*, 425-428. DOI: 10.4028/www. scientific.net/KEM.450.425

Chamier-Gliszczyński, N. (2011b). Recycling Aspect of End-of Life Vehicles. Recovery of Components and Materials from ELVs. *Key Engineering Materials, 450*, 421-424. DOI: 10.4028/www.scientific.net/KEM.450.421

Czwajda, L., Kosacka-Olejnik, M., Kudelska, I., Kostrzewski, M., Sethanan, K., Pitakaso, R. (2019). Application of prediction markets phenomenon as decision support instrument in vehicle recycling sector. *Logforum, 15*(2), 265-278. DOI: 10.17270/J.LOG.2019.329

Directive 2008/98 / EC of the European Parliament and of the Council of 19 November 2008 on waste and sensitizing certain directives, OJ. UE L 312/3 of 22 November 2008.

Gabryelewicz, I., Stryjski, R., Wędrycowicz, M., Dąbrowski, T. (2020). The State of the Air Quality in Poland 2020. *Rocznik Ochrona Środowiska, 22*(2), 998-1013.

Izdebski, M. (2014). The use of heuristic algorithms to optimize the transport issues on the example of municipal services companies. *Archives of Transport, 29*(1), 27-36. DOI: 10.5604/08669546.1146961

Izdebski, M., Jacyna, M. (2018). The organization of municipal waste collection: The decision mode. *Rocznik Ochrona Środowiska, 20*, 919-933.

Izdebski, M., Jacyna, M. (2021). An efficient hybrid algorithm for energy expenditure estimation for electric vehicles in urban service enterprises. *Energies, 14*(7), 2004. DOI: 10.3390/en14072004

Jacyna, M., Wasiak, M., Lewczuk, K., Chamier-Gliszczyński, N., Dąbrowski, T. (2018). Decision Problems in Developing Proecological Transport System. *Rocznik Ochrona Środowiska, 20*(2), 1007-1025.

Jacyna-Gołda, I., Izdebski, M., Podviezko, A. (2017). Assessment of efficiency of assignment of vehicles to tasks in supply chains: a case study of municipal company. *Transport, 32*(3), 243-251. DOI: 10.3846/16484142.2016.1275040

Jajczyk, J. (2016). Use of Personal Computers with Multi-core Processors for Optimization Using the Genetic Algorithm Method, IEEEXplore Electronic. DOI: https://doi. org/10. 1109/CPEE.2016.7738731

Jajczyk, J., Filipiak, M. Dąbrowski, T. (2020), Reducing the use of electrochemical sources of electricity through the use of wireless power supply. *Rocznik Ochrona Środowiska*, *22*(1).

Jędrczak, A. (2007). *Biologiczne przetwarzanie odpadów*. Wydawnictwo Naukowe PWN, Warszawa.

Korzeń, Z. (2001). Ekologistyka, Instytut Logistyki i Magazynowania, Poznan.

Kosobudzki, M., Jamroziak, K., Bocian, M., Kotowski, P., Zając, P. (2018). The analysis of structure of the repaired freight wagon. *In AIP Conference Proceedings, Vol. 2029, 1,* 020030. AIP Publishing LLC. DOI: 10.1063/1.5066492

Ligus, G. (2006). *Separacja niemetalicznych frakcji zmieszanych odpadów komunalnych*. Warszawa-Opole (in Polish).

Maćków, I., Małysa, H., Sebastian, M., Szpadt, R. (2004). Zmienność składu i właściwości odpadów komunalnych miasta Wrocławia w latach 1992-2004, Instytut Inżynierii Ochrony Środowiska, Politechnika Wrocławska (in Polish).

Merkisz-Guranowska, A (2012). Bicriteria models of vehicles recycling network facility location. *Archives of Transport, 24(2)*, 187-202. DOI: 10.2478/v10174-012-0012-6

Merkisz-Guranowska, A. (2010). Issues related to the optimization of location of vehicle recycling network entities. *Archives of Transport, 22*(3), 303-318. DOI: 10. 2478/v10174-010-0018-x

Merkisz-Guranowska, A. (2018). Waste recovery of and-of-life vehicles. *IOP Conference Series: Materials Science and Engineering, 421*(3), 032019. DOI: 10.1088/ 1757-899X/421/3/032019

Ohno, H., Matsubae, K., Nakajima, K., Kondo, Y., Nakamura, S., Nagasaka, T. (2015). Toward the recycling of alloying elements from end of life vehicle steel scrap. *Resources, Conservation and Recycling, 100*, 11-20. 2375-2383, ISBN: 978-0-9860419-6-9

Robak, A. (2015) *Analiza aspektów ekonomicznych selektywnej zbiórki odpadów komunalnych.* Wrocław (in Polish).

Sieja, L. (2006). Charakterystyka odpadów komunalnych na podstawie badań wybranych miast Polski. *Ochrona powietrza i problemy odpadów, 1* (in Polish).

Siemiątkowski, G. (2011). *Kompostowanie i mechaniczno-biologiczne przetwarzanie odpadów*. Wydawnictwo Instytut Śląski, Opole (in Polish).

Stryjski, R., Woźniak, W., Niedziela, M. (2020). Selected methods for supporting the growth of economic efficiency in transportation orders originating in electronic transport exchanges, *Proceedings of the 36th International Business Information Management Association Conference (IBIMA)*, Granada, Spain, ISBN: 978-0-9998551-5-7, 9569-9577.

Styś, T. (2014). *Wpływ nowelizacji ustawy o odpadach na system gospodarowania odpadami*. Warszawa, Analiza Instytutu Sobieskiego (in Polish).

Styś, T., Foks, R., Moskwik, K. (2016). *Krajowy plan gospodarki odpadami 2030*. Warszawa: Instytut Sobieskiego (in Polish).

Styś, T., Witwicki, B. (2013). *Nowy system gospodarowania odpadami komunalnymi w Polsce. Wybrane aspekty*, Analiza Instytutu Sobieskiego (in Polish).

Ustawa z dnia 23 kwietnia 2008 r., Obwieszczenie Marszałka Sejmu RP, tekst jednolity – Prawo ochrony środowiska (Dz. U. 2008 nr 25, poz. 150).

Ustawa z dnia 27 czerwca 1997 r. o odpadach (Dz. U. 1997 nr 96, poz. 592).

Ustawa z dnia 27 kwietnia 2001 r. o odpadach (Dz. U. 2001 nr 62, poz. 628).

Ustawa z dnia 27 kwietnia 2001 r. o odpadach (Dz. U. 2007 nr 39, poz. 251).

Ustawa z dnia 30 maja 2008 r. o zmianie ustawy – Prawo ochrony środowiska (Dz. U. 2008 nr 111, poz. 708).

Van Schaik, A., Reute,r M.A. (2004). The time-varying factors influencing the recycling rate of products. *Resources, Conservation and Recycling, 40*(4), 301-328.

Wędrychowicz, M., Bydałek, A., Skrzekut, T., Noga, P., Gabryelewicz, I., Madej, P., (2019): Analysis of the mechanical strength, structure and possibilities of using waste phosphogypsum in aluminum powder composites. *SN Applied Sciences, 992*(1). DOI: https://doi.org/10.1007/s42452-019-0995-1

Wolny, P. (2010). *Sprawdzone metody gospodarowania odpadami komunalnymi.* Stowarzyszenie Technologii Ekologicznych SILESIA, Opole.

Woźniak, W., Wojnarowski, T. Stryjski, R., Mielniczuk, J. (2016). The Concept of the Profitability for the Transport Orders Acquired From the Transport Exchange Market, 27th IBIMA Conference, Milan 2016.

www.archiwum.komunalny.home.pl (11.06.2020).

http://www.pojemniki.magazynowe.com.pl/ (11.07.2021).

http://www.bys.com.pl (11.01.2021).

http://greenworld.serwus.pl (04.02.2020)

Zajac, P. (2015). *Evaluation method of energy consumption in logistic warehouse systems*. Switzerland: Springer International Publishing.

Zajac, P., Kwasniowski, S. (2017). Zero energy buildings in the logistics warehouse systems. *In E3S Web of Conferences, 22, 00198*. EDP Sciences. DOI: 10.1051/e3sconf/20172200198

Zajac, P., Haladyn, S., Kwasniowski, S. (2019). Concept of reducing harmful emissions by road transport vehicles in the tourist route Karpacz-Jelenia Góra. *In E3S Web of Conferences, 100,* 00091. EDP Sciences. DOI: 10.1051/e3sconf/201910000091

Zajac, P., Skoczynski, W., Romanowicz, W. (2019a). *Studies of properties of rfid tags used in mechatronic and logistic systems*. 25th International Conference Engineering Mechanics 2019, Svratka, Czech Republic, 13-16 May 2019, 415-418. DOI: 10.21495/71-0-415

Zajac, P., Stas, D., Lenort, R. (2020). Noise Charge in Rail Transport-EU Regulations Versus Operation of Logistics Systems. *Rocznik Ochrona Środowiska, 22*, 226-241.

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Impact Estimation of a Transient Temperature Field on the Service Life of the High Pressure Rotor of K-1000-60/3000 Turbine

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Abstract: The one of purposes of this paper is to estimation some impact on the service life of the high-pressure cylinder rotor of a typical high-speed turbine K-1000-60/3000. The residual life assessment of power equipment would require determining viability and damage of its base metal. Typical degradation mechanisms of steam turbine equipment include long-term strength reduction and low cycle fatigue accumulation. Intensity of their impact is determined by a numerical examination of equipment thermal (TS) and stress strain states (SSS) for standard operation modes. To perform a numerical examination of the stress strain state would require solving a thermal conductivity boundary problem in quasi-stationary (for nomal operation modes) and nonstationary models (for transients). It is convenient to solve such problems of mathematical physics through discretization of the calculation object using the finite element method (Chernousenko et al. 2018). The service life of steam turbine is determined as an individual one and is assigned based on the results of individual an inspection of a separate element or the largest group of single-type equipment elements of the considered plant. The fleet service life being reached is followed by diagnostics of specific units of power installations and analysis of their operation, measurement of actual dimensions of components, examination of structure, properties and damage accumulation in the metal, non-destructive testing and estimate of stress strain state and residual service life of the component. The results of performed studies are used to determine an individual service life of each element of energy equipment (Nikulenkov et al. 2018).

Keywords: service life, steam turbine, temperature, ANSYS, 2-D and 3-D geometrical models, K-1000-60/3000, nuclear power plants, CFD-codes

1. Introduction

The problem of defining service life of nuclear power plants considering life cycles of their major equipment is becoming increasingly important each year. This raises questions relating to reasonable decision-making scheme on the due time for decommissioning of NPPs and feasibility of replacing of any major equipment considering safety and economic factors.

With extended operation of power plant equipment, the definition of its service life has changed. After the fleet life is reached, an in-depth diagnostic is carried out for specific nodes of electric power installation, including analysis of its operating conditions, measurement of the actual component geometry, examination of steel structure, its properties and accumulated damage, non-destructive testing and calculated estimate of stress state and residual service life of components.

Based on the results of performed studies an individual residual service life is established for a specific component of the power equipment.

The decision-making algorithm regarding capability and conditions for equipment operation throughout the individual service life can be described as follows (Nikulenkova et al. 2020):

1) assessment of actual operating conditions for the entire period of component use;
2) conducting repeated strength analysis based on the refined operation data;
3) defectoscopy (visual inspection, ultrasonic testing, X-ray examination, magnetic particle testing, lab examinations of steel samples);
4) assessment of the expired service life and forecasting further operation after defining equipment conditions.

This approach allows combining calculation methods, results of steel examination and samples tests, which complement each other. The set purpose is to be achieved by reaching the objectives as follows:

1) analysis of the known ways for service life extension of energy equipment that has reached the end of its fleet service life;
2) the results of metal inspection throughout the entire operating lifetime and analysis of technical audit data relating to damages and geometry changes during refurbishment of steam turbine elements;
3) analysis of the results of experimental researches and estimate of residual service life of steam turbines considering actual operating conditions and local damages of separate turbine components;
4) elaborating proposals regarding approaches to extension of service life of steam turbines.

2. Materials and methods

Approaching the end of the established life of NPP equipment poses a number of challenges to nuclear industry:

1) to increase the installed capacity while maintaining the required safety level of operating power units using the built-in engineered margins of operating units along with the ever increasing pace of science and technology development, and taking due account of international practice;
2) to carry out a range of works and upgrades to ensure operation of power units beyond their design life while maintaining the required safety level.

The range of works to be carried out when assessing the service life of the critical elements of the turbine is comprised of several phases.

In the fist phase, the 3-D analogues of the rubine machine elements were built based on the results of the technical audit and conclusions of the visual inspection, when different types of damages are localized in the geometrical model of a turbine element in the form of steel samples of differenet shape. Such approach allows to bring the calculation model of the steam turbine element close to real conditions after continiuous operation.

The next phase is to calculate initial and boundary conditions (using CFD-codes or criterial equations as specified in (Nikulenkov et al. 2018, Nikulenkov et al. 2019)) and determine a nonstationary temperature field in the solid critical element for further calculation of thermal load.

It starts with solving the non-stationary thermal conductivity equation and assigning boundary conditions for heat transfer on the surfaces of the rotor based on 2-D and 3-D geometrical models. The non-stationary thermal conductivity equations are given below:

$$\mathrm{div}[\lambda(\mathrm{T})\cdot\mathrm{grad}(\mathrm{T})] = \mathrm{c}(\mathrm{T})\cdot\gamma(\mathrm{T})\cdot\mathrm{dT/d}\tau \qquad (1)$$

where: λ – coefficient of thermal conductivity, c – specific heat capacity, γ – specific weight, which are functions of temperature and coordinates under initial conditions $T_0 = T(x, y, z, 0) = f_0(x, y, z)$.

The third phase involves using the ANSYS package to determine the stress strain state of the high pressure cylinder rotor considering its complex spatial geometry, damages over ther period of operation, and repair and renewal changes of the design geometry (Peshko et al. 2016, Chernousenko et al. 2020).

The outcome is calculations of equivalent elastic strain, von Mises equivalent strain, principal stresses, taking into account the effect of the centrifigual forces, temperature and steam pressure loads during start-up of the K-1000/60-3000 turbine from cold (CS), warm (WS) and hot states (HS).

1) Equivalent elastic strain shall be calculated by the formula:

$$\varepsilon_e = (1/1 + \nu')(1/2[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2])^{1/2} \quad (2)$$

where ν' – the effective Poisson's ratio defined as: 1) the Poisson's ratio at the relevant temperature of the considered body for elastic and thermal deformations; 2) 0.5 for plastic differmations.

2) Von Mises equivalent strain shall be calculated by the formula:

$$\sigma_e = [((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)/2]^{1/2} \quad (3)$$

3. Principal stresses

It is well-known from the theory of elasticity that an infinitely small volume of material in the arbitrary point of the solid body and inside it can be rotated so that there remain only normal stresses, and all shear stresses are equal to zero. The three remaining normal stresses are called principal stresses.

Principal stresses are always arranged as follows: $\sigma_1 > \sigma_2 > \sigma_3$, where: σ_1 – maximum principal stress, σ_2 – middle principal stress, σ_3 – minimum principal stress.

To calculate transient temperature fields for CS, WS and HS the boundary conditions were determined for temperature distribution in the rotor (t = f(x,y) at the time τ = 0, τ = 2760, τ = 6600, τ = 22740). The boundary conditions and the rotor temperature field are presented in Fig. 1-9.

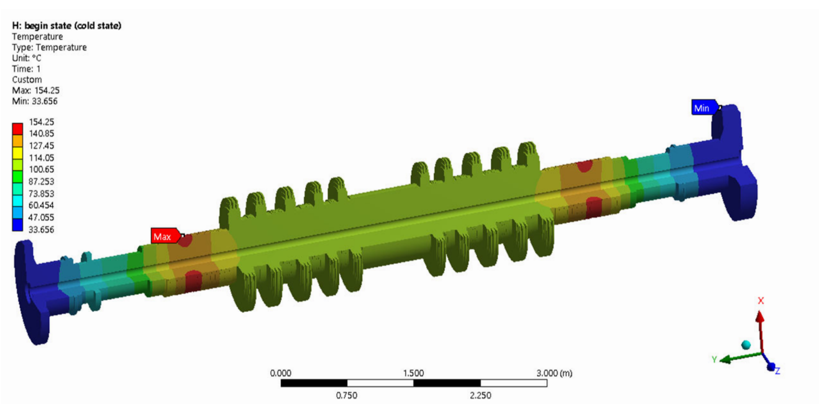

Fig. 1. Initial temperature distribution in the rotor during cold start-up

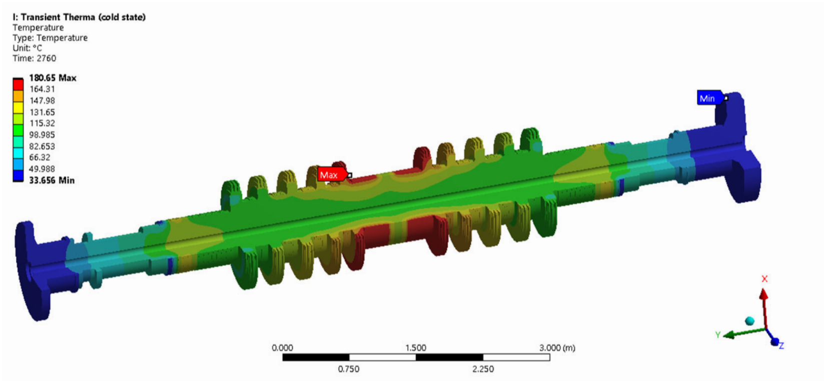

Fig. 2. Temperature field of the 1000/60-3000 steam turbine rotor 2760 seconds after cold start-up of the turbine

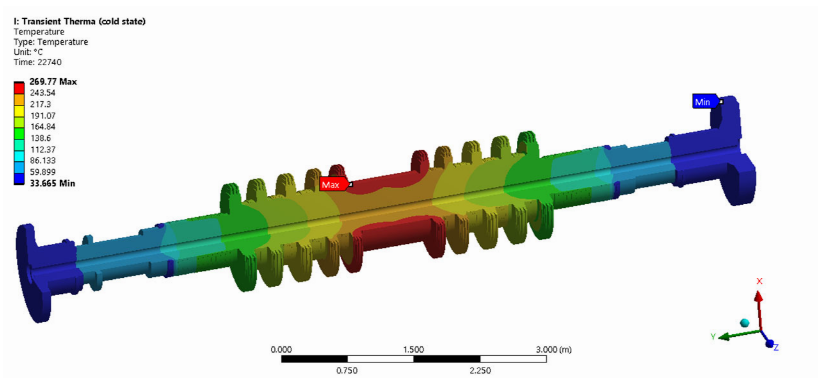

Fig. 3. Temperature field of the 1000/60-3000 steam turbine rotor 22740 seconds after cold start-up of the turbine

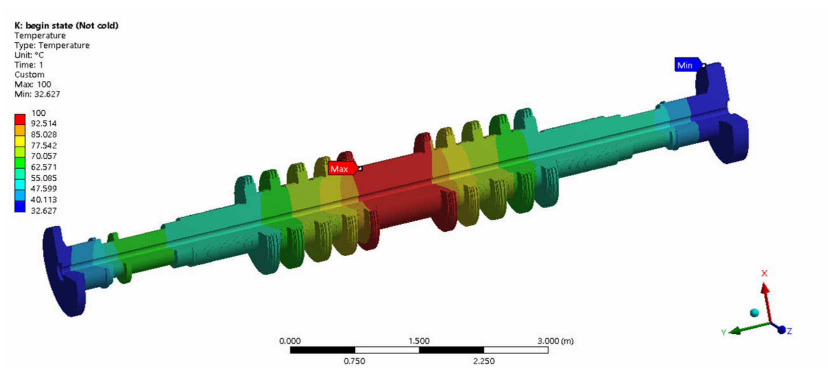

Fig. 4. Initial temperature distribution in the rotor during warm start-up

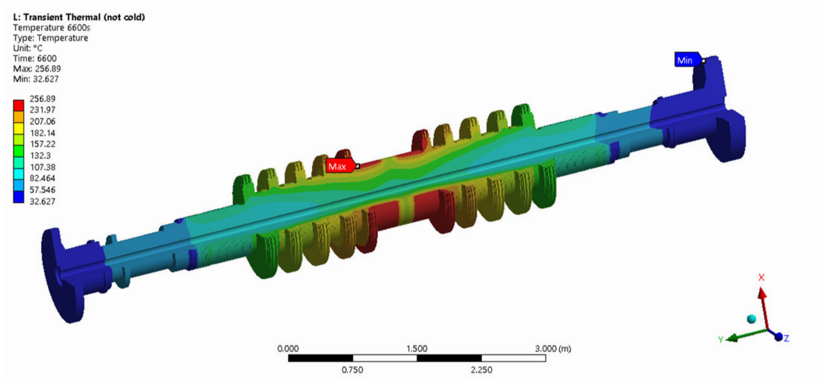

Fig. 5. Temperature field of the 1000/60-3000 steam turbine rotor 6600 seconds after warm start-up of the turbine

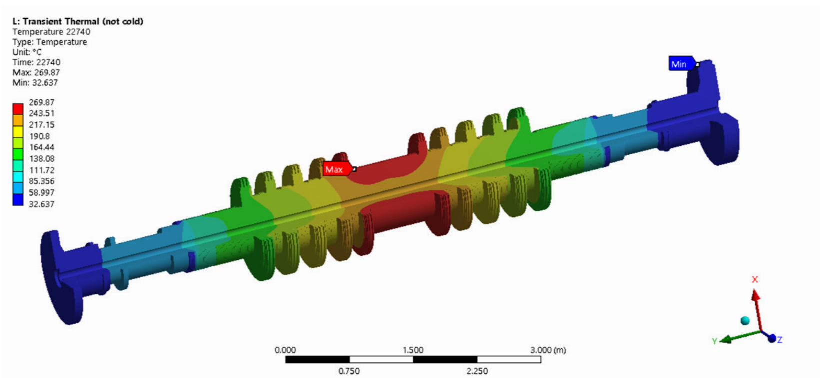

Fig. 6. Temperature field of the 1000/60-3000 steam turbine rotor 22740 seconds after warm start-up of the turbine

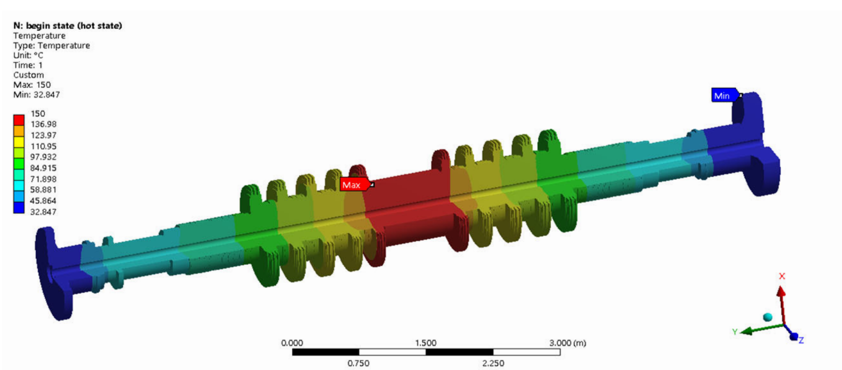

Fig. 7. Initial temperature distribution in the rotor during hot start-up

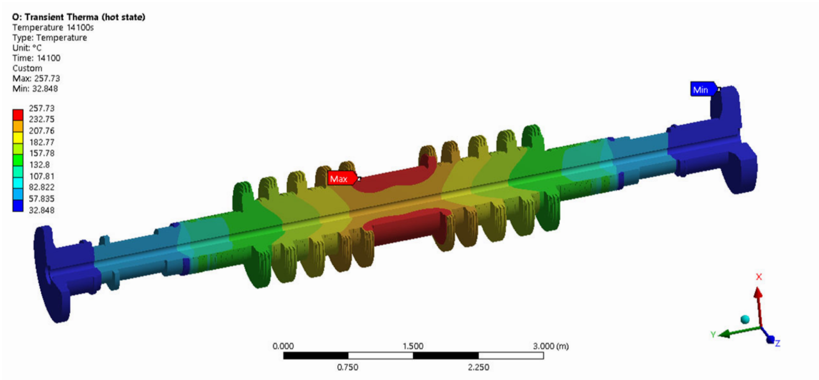

Fig. 8. Temperature field of the 1000/60-3000 steam turbine rotor 14100 seconds after hot start-up of the turbine

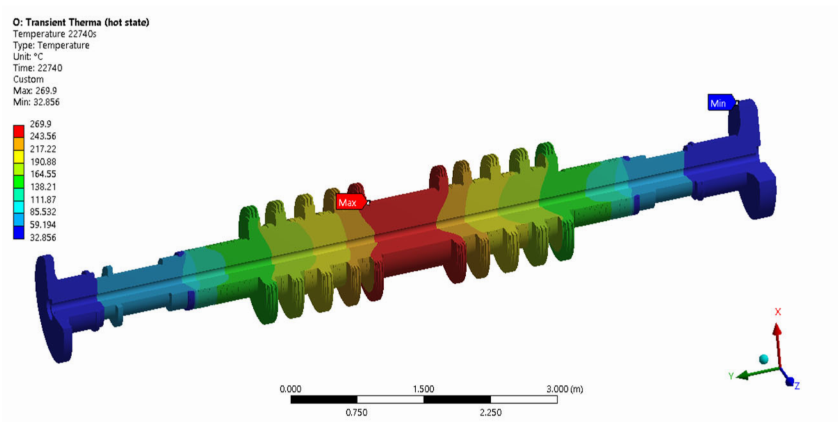

Fig. 9. Temperature field of the 1000/60-3000 steam turbine rotor 22740 seconds after hot start-up of the turbine

4. Results and discussion

Initial data

The condensate steam turbines of thermal and nuclear power plants with high temperature elements in 3-D setting are considered. The boundary conditions are established for heat exchange on the rotor surfaces using ANSYS digital model based on built geometrical 3-D models corresponding to operating modes by start-up types from cold, hot and warm conditions and stationary mode (Nikulenkova et al. 2019).

Model testing and setup

The calculations determine principal stresses and intensity of stresses over entire life corresponding to start-up and stationary operating conditions in all division points of hight temperature elements of the stream turbine.

The results of stress and deformation calculations under cold start-up of the K-1000/60-3000 turbine are provided below.

Fig. 10-15 show the change of maximum stress (equivalent (von-Mises) stress, principal sress) during the cold, warm and hot start-up.

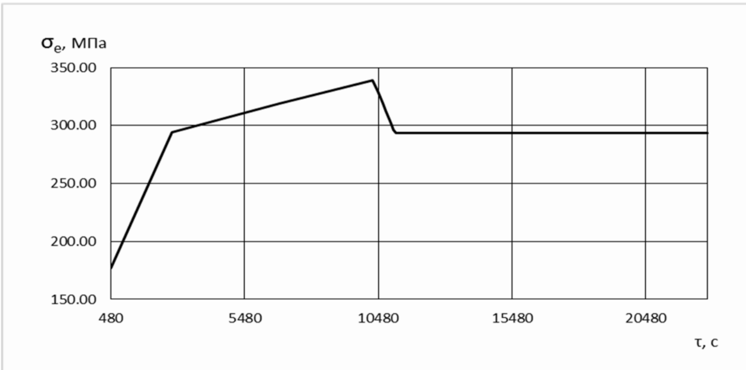

Fig. 10. Time change of maximum equivalent stress (von Mises) during cold start-up

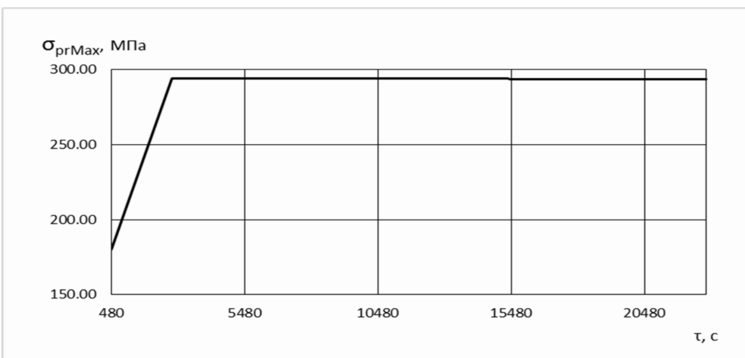

Fig. 11. Time change of the maximum value of maximum principal stress during cold start-up

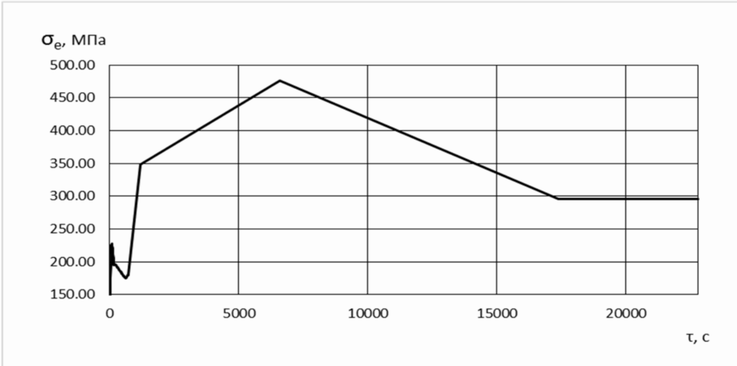

Fig. 12. Time change of maximum equivalent stress (von Mises) during warm start-up

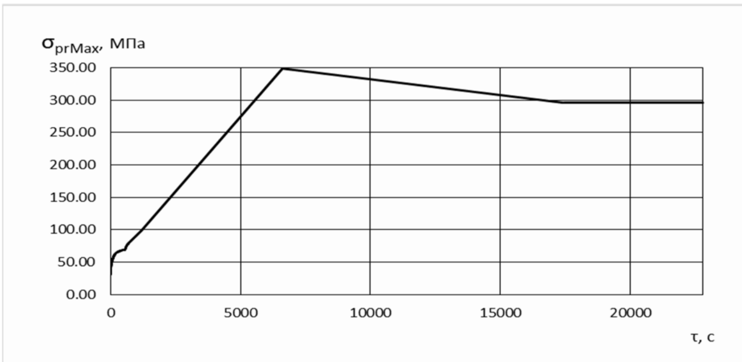

Fig. 13. Time change of the maximum value of maximum principal stress during warm start-up

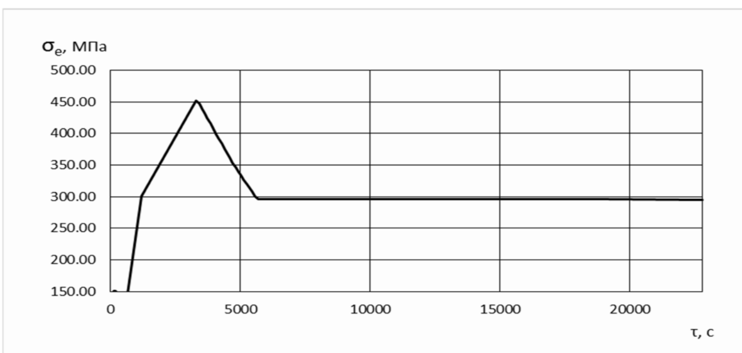

Fig. 14. Time change of maximum equivalent stress (von Mises) during hot start-up

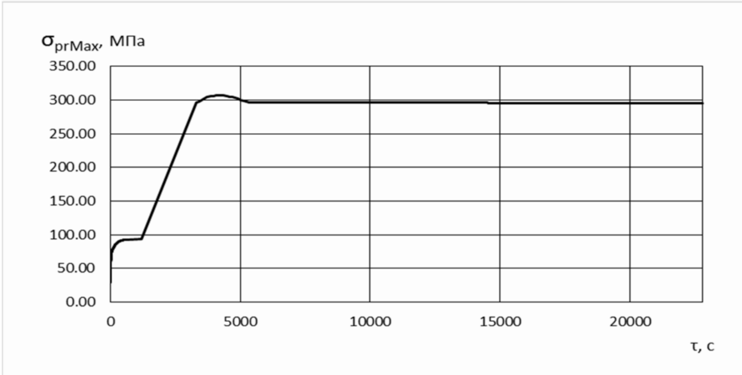

Fig. 15. Time change of the maximum value of maximum principal stress during hot start-up

The maximum equivalent stress is 338.9 MPa reached at 10260 s during cold start-up. The stress peak shifts from end seals (during warming-up of the turbine due to steam directed onto seals) to the first stage disk and further to the coupling when reaching nominal conditions. The maximum value of maximum principal stress is 294.16 MPa reached at 2760 s.

The maximum equivalent stress is 452.14 MPa reached at 3300 s during hot start-up. The stress peak shifts from end seals (during warming-up of the turbine due to steam directed onto seals) to the first stage disk and further to the coupling when reaching nominal conditions (Nikulenkova et al. 2020).

The calculation results of the stress strain state of the high-temperature elements of the steam turbine obtained using ANSYS in different spatial settings (2-D and 3-D) were compare between each other and with the results obtained by other authors (Bakhmutskaya et al. 2017, Shulzhenko et al. 2011).

According to the calculations the maximum stress is 338.9 MPa reached at 10260 s. The stress peak shifts from end seals to the first stage disk and further to the coupling when reaching nominal conditions.

The final phase implies development of a methodological approach to calculaton of the low cycle fatigue with account of changes in the stress strain state of the К-1000/60-3000 turbine elements for optimization of strength margins by number of cycles and deformations (Nikulenkov et al. 2018).

The described methodology was used to develop a software for numerical analysis of the residual service life of steam turbines used at thermal and nuclear power plants.

5. Conclusions

1. The set of works to estimate the service life of the critical elements of the K-1000/60-3000 turbine has been described in phases.
2. The calculations have been made for equivalent elastic strain, von Mises equivalent strain, principal stresses, taking into account the effect of the centrifugal forces, temperature and steam pressure loads during start-up of the K-1000/60-3000 turbine from cold, warm and hot states.
3. The maximum stress has been calculated as 338.9 MPa reached at 10260 s during cold start-up, 476.55 MPa reached at 6600 s during warm start-up, 452.14 MPa reached at 3300 s during hot start-up of the K-1000/60-3000 steam turbine.
4. The maximum equivalent elastic strain has been calculated as 1.76E-03 m/m reached at 10260 s during cold start-up, 2.47E-03 m/m reached at 6600 s during warm start-up, 2.35E-03 m/m reached at 3300 s during hot start-up of the K-1000/60-3000 steam turbine.

References

Bakhmutskaya, Y., Goloshchapov, V. (2017). K-325-23,5 Steam Turbine High-Pressure Rotor Thermal and Thermo-structural State During Cold Start-up. *Journal of Mechanical Engineering*, *2*(20), 3-11.

Chernousenko, O., Nikulenkov, A., Nikulenkova, T., Butovskiy, L. & Bednarska, I. (2018). Calculating boundary conditions to determine the heat state of high pressure rotor of the turbine NPP K-1000-60/3000. *Bulletin of the National Technical University "KhPI"*, *12*(1288), 51-56. DOI: 10.20998/2078-774X.2019.03.01

Chernousenko, O., Rindyuk, D., & Peshko, V. (2019). The strain-stress state of K-1000-60/3000 turbine rotor for typical operating modes. *Bulletin of the National Technical University "KhPI"*, *3*(1328), 4-10. DOI: 10.20998/2078-774X.2019.03.01

Chernousenko, O., Nikulenkova, T., Peshko, V., & Nikulenkov, A. (2020). Approach to impact assessment of the rated power up-rate of NPP unit on the service life of the turbine critical elements. *Rocznik Ochrona Srodowiska*, *22*(1), 105-116.

Nikulenkov, A., Chernousenko, O., & Nikulenkova, T. (2018). Analysis of influence of heat power rate increase on beyond design basis accident for NPP unit. *Bulletin of the National Technical University "KhPI"*, *13*(1289), 37-45. DOI: 10.20998/2078-774X.2018.13.07

Nikulenkov, A., Samoilenko, D., & Nikulenkova, T. (2018). Study of the impact of NPP rated thermal power uprate on process behaviour at different transient conditions. *Nuclear & Radiation safety*, *4*(80), 9-13.

Nikulenkova, T., Nikulenkov, A. (2019). Calculation of boundary conditions using CFD modeling as part of a comprehensive approach to impact assessment of modifications on the service life of critical elements of a nuclear power plant turbine. *The 16th International Conference of Young Scientists on Energy Issues*, VII, 267-278.

Nikulenkova, T., Nikulenkov, A. (2020) Impact analysis of a transient temperature field on the service life of the high pressure rotor of K-1000-60/3000 turbine. *Bulgarian Chemical Communications*, *52*, 36-41

Peshko, V., Chernousenko, O., Nikulenkova, T., & Nikulenkov, A. (2016). Comprehensive rotor service life study for high & intermediate pressure cylinders of high power steam turbines. *Propulsion and Power Research*, *5*(4), 302-309. DOI: 10.1016/j.jppr.2016.11.008

Shulzhenko, M., Hontarovskyi, P., Matiukhin, Yu., Melezhyk, I., & Pozhydaiev, O. (2011). Determination of estimated resource and evaluation of rotor life and body parts of turbines: Methodological guidelines, *Regulatory document SOU-N MEV* 0.1–21677681–52: approved by the Ministry of Energy and Coal Mining of Ukraine: effective as of 07.07.11. Kyiv: MECM of Ukraine, 24.

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The Influence of Atmospheric and Subsoil Impact on the Evaporation Process During Firefighter's Events

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Abstract: The influence of sun rays, wind speed, and different type of subsoil on the evaporation process was analyzed. A dedicated experimental set-up for investigation of evaporation process of three liquids (ethanol, petrol and tap water) deposited on glass and sand was created. Results indicated that for porous surfaces wind decreased the amount of evaporated liquids. After substitution of wind with sun rays for porous surface evaporation process increased for ethanol and petrol, respectively. Finally, the influence of both wind and sun rays indicated a 1% and 5% decrease of evaporation intensity for tap water and petrol, respectively. While, a 2% increase of evaporated liquid was observed for ethanol. It was noticed that application of porous surface caused the highest improvement of evaporation process for petrol and tap water, while the lowest for ethanol. Moreover, application of wind together with porous surface increased the intensity of evaporation for all analyzed liquids.

Keywords: basis, evaporating liquids, atmospheric factors

1. Introduction

Rapid elimination of the effects of uncontrolled spill is important for firefighters to quickly handle a hazard (Polanczyk 2018, Kahn et al. 2019). Leakage of hazardous liquids may aggravate or inhibit natural environmental factors (Li et al. 2019, Polanczyk et al. 2019, Polanczyk et al. 2020). The most important think for firefighters taking part in the event is to secure the area of action and immediately provide help to people, life stock and surrounding area (Polanczyk & Salamonowicz 2018, Colburn et al. 2019, Majder-Lopatka et al. 2020). Safety operations critically reliant on the practices and expertise of firefighters (Maslen 2014, Polanczyk 2018, Salamonowicz et al. 2021). A variety of factors such as natural disaster, corrosion, third party damage, mechanical failure, may cause pipeline leakage and rupture, thereby leading to personal injury, facility damage, and environmental pollution (Batzias et al. 2011, Czapczuk et al. 2017, Zhang et al. 2018). Depending on the size of the pool and the type of liquid, it is possible to estimate the level of hazard and to establish a dangerous zone (Piecuch et al. 2015, Stefana et al. 2016). These actions require the knowledge of soil permeability and liquid evaporation rate (Moon et al. 2018, Polanczyk et al. 2018, Yu et al. 2019, Singh et al. 2020). The intensity of evaporation process depends on the type of liquid. Fingas observed that light crude oils can be reduced by up to 75% of their initial volume and medium crudes by up to 40% of their volume (Fingas 1997). Moreover, drying with evaporation in the soil is associated with coupled heat and mass transfer and depends on the the requirement of evaporation in the atmosphere and the exchange of steam and heat between the surface of the earth and the atmosphere (Polanczyk & Salamonowicz 2018, Qubaja et al. 2020). The rate of evaporation of liquid deposited in soil is also influenced by atmospheric factors such as humidity, temperature and velocity of the surrounding air, as well as by the pore space and transport properties of the soil including thermal and hydraulic conductivity and the diffusivity of steam (Teng et al. 2019). This complexity leads to very dynamic interactions between media properties and transport processes and initiate a broad spectrum of evaporation behaviors (Wawrzyniak et al. 2012, Wawrzyniak et al. 2012, Polanczyk et al. 2013, Zieminska-Stolarska et al. 2015, Chen et al. 2020, Polanczyk et al. 2020). At the critical surface water content or the depth of the pre-drying the first stage ends suddenly, followed by a lower degree, controlled mainly by diffusion mass transfer (Abdel-Aziz 2013). Therefore, in this work, the impact of different types of subsoils, spilled liquids as well as sun rays and wind speed on the evaporation process was investigated.

2. Materials and methods

A dedicated experimental set-up composed of an aerodynamic tunnel made of polycarbonate with a square cross-section (equal to 0.09 m^2) with a hole in the lower part (cross-section equal to 0.00785 m^2) where a 10 cm diameter Petrie dish with investigated liquid was localized. Additionally, the Petrie dish was situated on a scale (Radwag WPS 720/C) to analyze weight changes. Moreover, the liquid temperature was measured with the use of thermocouple pt100 placed in the liquid on the Petrie dish. The temperature in the laboratory was equal to 25 ±1°C and humidity was equal to 55%. For the reconstruction of air flow, a fan, allowing set of constant air velocity value equal to 1.5 m/s (measured with anemometer CFM AZ 8901), was localized at the inlet to the tunnel. A halogen bulb (100W) was placed over the Petrie dish to simulate sun influence.

Evaporation process was analyzed for 100 ml of three different liquids (98% alcohol (ethanol), petrol (95 octanes), and tap water as a reference). Moreover, to reconstruct the real environmental conditions that meets firefighters during events, we analyzed different surfaces (impermeable surface (an empty Petrie dish) and 25 g evenly distributed of sand) as well as different atmospheric conditions. The following cases were analyzed: (1) liquid poured on the surface without additional factors, (2) poured liquid with wind, (3) poured liquid with sun ray, (4) poured liquid with simultaneous wind and sun ray. Each time the evaporation process was monitored for 600 seconds with time intervals equal to 10 seconds.

The measurements were repeated three times to receive an average value. Data are presented as mean ±standard error (SD). Comparison between groups was performed using one-way ANOVA after verification of normality and Person's correlation coefficient (rho) and was calculated with Statistica 12.0 software. Data were considered statistically different when $p < 0.05$ (Polanczyk et al. 2018).

3. Results and discussion

Evaporation is a very important process for most hazardous substances (Abdel-Aziz 2013). Most of the events where firefighters are directed have in general impact on surrounding environment. The methodological framework presented herein considers both evaluation of received results and description with polynomials functions. Evaporation models can be divided into the one which use the basis of air-boundary-regulation or the other that use diffusion-regulated evaporation physics (Moon et al. 2018).

3.1. Impermeable surface

Distribution of mass and temperature for three liquids on an impermeable surface without additional interrupting factors was treated as a reference point. A decrease of density value caused an increase in evaporated liquid which amount 0.17 ±0.02 g, 0.93 ±0.14 g and 4.82 ±0.49 g for tap water, ethanol, and petrol, respectively (Fig. 1a). Approximately 5.37-fold increase of ethanol evaporation intensity compare to tap water was observed ($p < 0.01$).

The comparison of tap water and petrol indicated about 27.84-fold increase of petrol evaporation intensity ($p < 0.001$). Furthermore, comparability of ethanol and petrol indicated about 5.18-fold rise of petrol evaporation intensity ($p < 0.001$). This observation can be associated with the fact that ethanol is a polar molecule with a strong dipole, which undergoes hydrogen bonding to the extent that its boiling point is higher than would be expected based on its molecular weight (Aulich et al. 1994). Moreover, for each of analyzed liquid the following decrease of temperature was observed: 0.55 ±0.18°C, 1.38 ±0.45°C and 3.09 ±0.21°C for tap water, ethanol, and petrol, respectively. Further comparison of a degree of temperature decreases for all liquids indicated that about 2.49-fold higher reduction of ethanol temperature compare to tap water ($p < 0.001$). While comparison of tap water and petrol indicated 5.58-fold higher decrease of petrol temperature ($p < 0.001$). When comparing ethanol and petrol we noticed a 2.24-fold decrease of petrol evaporation ($p < 0.001$). Additionally, there was a strong positive correlation between changes in temperature and mass of tap water (rho = 0.998), ethanol (rho = 0.966) and petrol (rho = 0.983) for the case without additional factors.

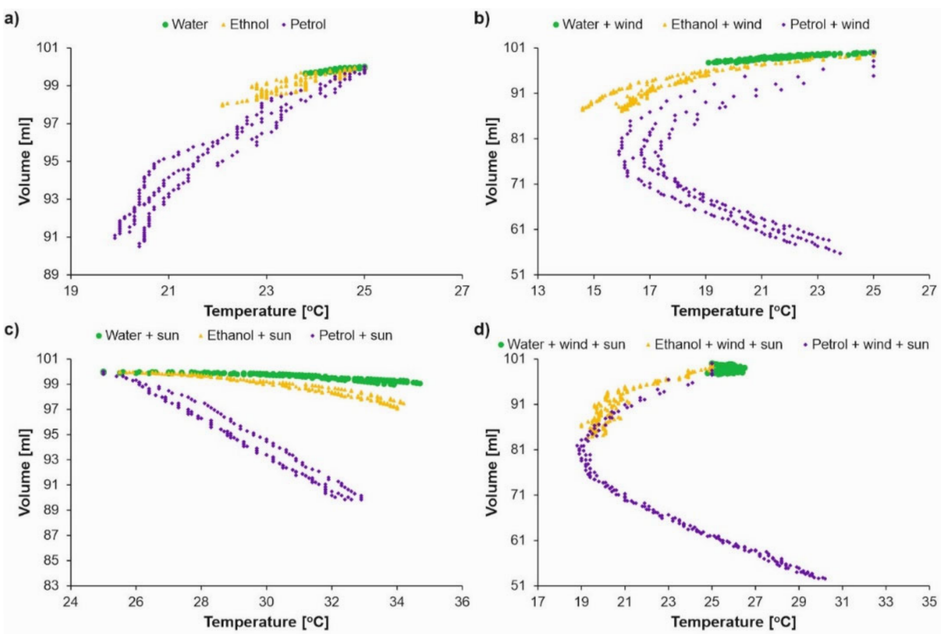

Fig. 1. Scatterplot graphic presentation of liquid evaporation for: a) case without external factors, b) with wind impact, c) with sun impact, d) with wind and sun impact, in contact with impermeable surface

Addition of wind factor increased evaporation intensity for all liquids which amount 1.19 ±0.09 g, 7.13 ±0.12 g and 27.47 ±1.42 g for tap water, ethanol and petrol, respectively (Fig. 1b). The highest increase was observed for the ethanol (7.67 times, $p < 0.001$), while the lowest for the tap water (5.70 times, $p < 0.001$). A 5.98-fold increase of ethanol evaporation intensity compare to tap water was recorded ($p < 0.001$). While comparison of tap water and petrol showed 23.04-fold increase of petrol evaporation intensity ($p < 0.001$). Contrarily, comparison of ethanol and petrol indicated 3.85-fold increase ($p < 0.001$).

Moreover, for each liquid different decrease of temperature was observed and amount 3.40 ±0.03°C, 7.01 ±0.60°C and 5.67 ±0.81°C for tap water, ethanol and petrol, respectively. A 2.06-fold higher decrease of ethanol temperature compare to tap water was observed ($p < 0.001$). While, in the case of tap water vs petrol we noticed a 1.66-fold higher decrease of petrol temperature ($p < 0.001$). Comparison of ethanol and petrol indicated approximately 0.81-times higher decrease of petrol evaporation ($p < 0.01$). Additionally, there was a strong positive correlation between changes in temperature and mass of tap water (rho = 0.981), ethanol (rho = 0.934) and a weak negative correlation for petrol (rho = -0.238).

After substitution of wind with sun rays it was observed that the evaporation process was not so intensive like for wind factor, however it was higher comparing to the reference one without additional interrupting factors such as wind or sun rays (Mehrizi & Wang 2017). The highest increase was observed for the tap water (2.57 times, $p < 0.001$), while the lowest increase for the petrol (1.06 times, $p < 0.001$). A comparison with wind factor indicated that the highest increase was observed for the tap water (approximately 0.37 times, $p < 0.001$), while the lowest for the ethanol (approximately 0.17 times, $p < 0.001$). Adding of sun rays factor showed that evaporated volume of liquid was equal to 0.44 ±0.05 g, 1.18 ±0.12 g and 5.10 ±0.04 g for tap water, ethanol and petrol, respectively (Fig. 1c). A 2.67-fold increase of ethanol evaporation intensity comparing to tap water was noticed ($p < 0.001$). While comparison of tap water and petrol indicated approximately 5.10-times increase of petrol evaporation ($p < 0.001$). Comparison of ethanol and petrol indicated approximately 1.18-fold increase of petrol evaporation intensity ($p < 0.001$).

Moreover, for each of analyzed liquid the following decrease of temperature was noticed: 6.15 ±0.32°C, 5.45 ±0.16°C and 4.11 ±0.39°C for tap water, ethanol and petrol, respectively. A 0.89-fold higher decrease of ethanol temperature compare to tap water was observed ($p < 0.01$). While comparison of tap water and petrol indicated a 0.67-fold higher decrease of petrol temperature ($p < 0.001$). Comparison of ethanol and petrol showed 0.75-times higher reduction of petrol evaporation ($p < 0.001$). Additionally, there was a strong negative correlation between changes in temperature and mass of tap water (rho = -0.940), ethanol (rho = -0.971) and petrol (rho = -0.998).

Finally, the influence of both factors (wind and sun rays) was investigated. The highest increase compare to the reference case was observed for the ethanol (9.14 times, $p < 0.001$), while the lowest increase was observed for the petrol (6.22 times, $p < 0.001$). Moreover, comparison with wind factor indicated that the highest increase in evaporation intensity was observed for the ethanol (1.19 times, $p < 0.001$), while the lowest increase was observed for the tap water (1.06 times, $p < 0.001$). Further comparison with sun rays indicated that the highest increase was observed for the ethanol (7.17 times, $p < 0.001$), while the lowest increase was observed for the tap water (2.83 times, $p < 0.001$). Adding of wind and sun rays indicated that evaporated volume of liquid was equal to 1.26 ±0.11 g, 8.50 ±0.16 g and 29.95 ±0.41 g for tap water, ethanol and petrol, respectively (Fig. 1d). A 6.75 increase of ethanol evaporation intensity compare to tap water was recorded ($p < 0.001$). While comparison of tap water and petrol showed 23.80-fold rise of petrol evaporation intensity ($p < 0.001$). Furthermore, comparison of ethanol and petrol indicated 3.52-fold increase of petrol evaporation intensity ($p < 0.001$).

Moreover, for each of analyzed liquid the following decrease of temperature was observed and amount 0.60 ±0.32°C, 3.94 ±0.32°C and 1.45 ±0.21°C for tap water, ethanol and petrol, respectively. A 6.51-fold higher decrease of ethanol temperature compare to tap water was observed ($p < 0.001$). While comparison of tap water and petrol indicated 2.40-fold higher decrease of petrol temperature ($p < 0.001$). Comparison of ethanol and petrol indicated 0.37-fold higher reduction of petrol temperature ($p < 0.001$). Additionally, there was a weak negative correlation between changes in temperature and mass of tap water (rho = -0.127) and strong negative petrol (rho = -0.713) and strong positive correlation for ethanol (rho = 0.889).

3.2. Porous surface

Distribution of mass and temperature for three liquids without additional interrupting factors and on a porous surface (sand) was analyzed. It was accordance with the data of (Volchkov 2006, Nasr et al. 2010). Similarly, to impermeable surface with a decrease of density value an increase in the amount of evaporated liquid was noticed and amount 0.21 ±0.02 g, 0.80 ±0.02 g and 5.53 ±0.37 g for tap water, ethanol and petrol, respectively (Fig. 2a). Additionally, a 3.79-fold increase of ethanol evaporation intensity compare to tap water was observed ($p < 0.001$). The comparison of tap water and petrol indicated a 26.16-times rise of petrol evaporation intensity ($p < 0.001$). While comparison of ethanol and petrol indicated 6.90-times increase of petrol evaporation intensity ($p < 0.001$). Moreover, for each of analyzed liquid the following decrease of temperature was observed (0.67 ±0.11°C, 1.27 ±0.32°C and 3.14 ±0.23°C for tap water, ethanol and petrol, respectively). A 1.91-fold higher decrease of ethanol temperature compare to tap water was observed ($p < 0.001$). While comparison of tap water and petrol indicated 4.71-fold higher decrease of petrol temperature ($p < 0.001$). A comparison of ethanol and petrol indicated approximately 2.46-fold higher reduction of petrol evaporation ($p < 0.001$). Additionally, there was a strong positive correlation between changes in temperature and mass of tap water (rho = 0.998), ethanol (rho = 0.996) and petrol (rho = 0.991) for the case of without additional interrupting factors.

Adding of wind factor increased of evaporation intensity for all liquids (0.97 ±0.10 g, 6.80 ±0.26 g and 26.91 ±0.87 g for tap water, ethanol and petrol, respectively) (Fig. 2b). The highest increase was observed for the ethanol (8.48 times, $p < 0.001$), while the lowest increase was observed for the tap water (4.57 times, $p < 0.001$). Moreover, 7.03 increase of ethanol evaporation intensity compares to tap water was recorded ($p < 0.001$). While comparison of tap water and petrol indicated 27.83-times increase of petrol evaporation intensity ($p < 0.001$). Furthermore, comparison of ethanol and petrol showed a 3.96 increase of petrol evaporation intensity ($p < 0.001$).

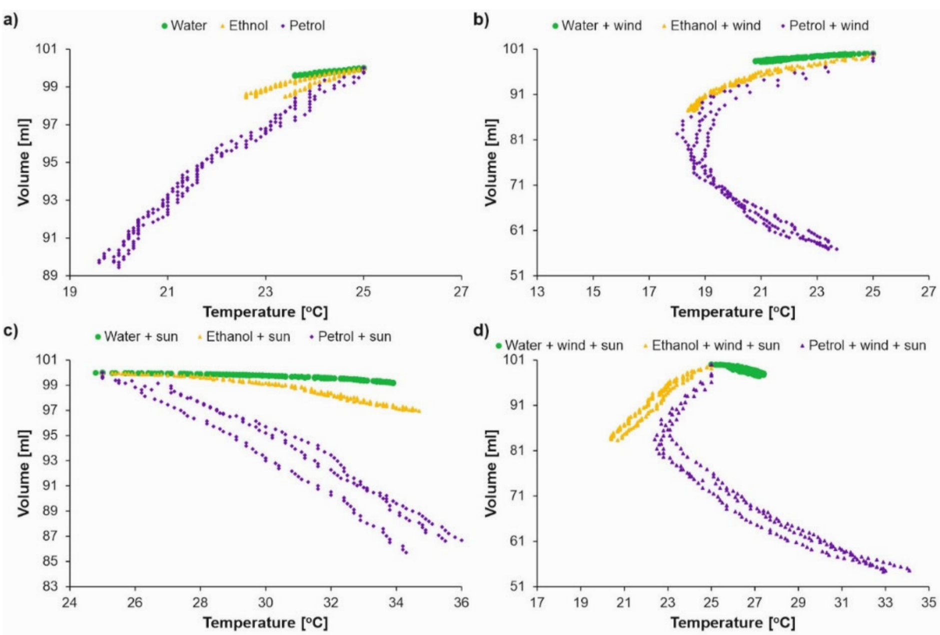

Fig. 2. Scatterplot graphic presentation of liquid evaporation for: a) case without external factors, b) with wind impact, c) with sun impact, d) with wind and sun impact, in contact with porous surface

Moreover, for each of analyzed liquid the following decrease of temperature was observed and amount 2.59 ±0.015°C, 4.55 ±0.10°C and 4.41 ±0.21°C for tap water, ethanol and petrol, respectively. A 1.76-times higher decrease of ethanol temperature compare to tap water was observed ($p < 0.001$). While comparison of tap water and petrol indicated approximately 1.70-fold higher decrease of petrol temperature ($p < 0.001$). A comparison of ethanol and petrol indicated 0.97-fold higher reduction of petrol evaporation ($p < 0.001$). Additionally, there was a strong positive correlation between changes in temperature and mass of tap water (rho = 0.988), ethanol (rho = 0.952) and weak negative correlation for petrol (rho = -0.245) for the case of wind factor.

After substitution of wind with sun rays it was observed that the evaporation process intensity was not so intensive like for wind factor, however it was higher comparing to the reference one (without any external factors). The highest increase compare to the reference case was observed for the tap water (1.72 times, $p < 0.001$), while the lowest increase was observed for the petrol (1.26 times, $p < 0.001$). Moreover, comparison with wind factor indicated that the highest increase was observed for the tap water (0.38 times, $p < 0.001$), while the lowest for the ethanol (approximately 0.20 times, $p < 0.001$). Adding of sun rays factor showed that evaporated volume of liquid was equal to 0.36 ±0.01 g, 1.35 ±0.02 g and 6.98 ±0.18 g for tap water, ethanol and petrol, respectively (Fig. 2c). A 3.71-fold increase of ethanol evaporation compared to tap water was recorded ($p < 0.001$). While comparison of tap water and petrol indicated a 19.23- fold increase of petrol evaporation ($p < 0.001$). On the contrary, only 5.19 increase of petrol evaporation ($p < 0.001$) was noticed when compared ethanol and petrol.

Moreover, for each of analyzed liquid the following decrease of temperature was observed (5.52 ±0.07°C, 5.59 ±0.23°C and 5.93 ±0.83°C for tap water, ethanol and petrol, respectively). A 1.01 higher decrease of ethanol temperature compare to tap water was recorded ($p < 0.001$). While comparison of tap water and petrol indicated approximately 1.07 higher decrease of petrol temperature ($p < 0.001$). Furthermore, comparison of ethanol and petrol indicated a1.06 higher reduction of petrol evaporation ($p < 0.001$). Additionally, there was a strong negative correlation between changes in temperature and mass of tap water (rho = -0.955), ethanol (rho = -0.965) and petrol (rho = -0.992).

Finally, the influence of both factors (wind and sun rays) was investigated. It was observed that the evaporation process was the highest compare to the previous cases. The highest increase compare to the reference case was observed for the ethanol (10.78 times, $p < 0.001$), while the lowest increase for the petrol (5.16 times, $p < 0.001$). Moreover, comparison with wind factor indicated that the highest rise was noticed for the tap water (1.28 times, $p < 0.001$), while the lowest increase was observed for the petrol (1.06 times, $p < 0.001$). Furthermore, comparison with sun rays showed that the highest intensification was observed for the ethanol (6.43 times, $p < 0.001$), while the lowest increase was noticed for the tap water (3.42 times, $p < 0.001$). Adding of wind and sun rays indicated that evaporated volume of liquid was equal to 1.24 ±0.08 g, 8.64 ±0.22 g and 28.55 ±0.11 g for tap water, ethanol and petrol, respectively (Fig. 2d). Also, a 6.96 increase of ethanol evaporation compare to tap water was noticed ($p < 0.001$). While comparison of tap water and petrol showed a 22.98 increase of petrol evaporation ($p < 0.001$). Furthermore, comparison of ethanol and petrol indicated approximately 3.30 increase of petrol evaporation intensity ($p < 0.001$). Moreover, for each of analyzed liquid the following decrease of temperature was observed (1.43 ±0.26°C, 2.69 ±0.22°C and 2.03 ±0.55°C for tap water, ethanol and petrol, respectively). We noticed a 1.89 higher decrease of ethanol temperature compare to tap water ($p < 0.001$). While comparison of tap water and petrol indicated approximately 1.42 higher reduction of petrol temperature ($p < 0.001$). Furthermore, comparison of ethanol and petrol indicated a 0.75 higher decrease of petrol evaporation ($p < 0.001$). Additionally, there was a strong negative correlation between changes in temperature and mass of tap water (rho = -0.977) and petrol (rho = -0.875) and strong positive correlation for ethanol (rho = 0.990) for the case of wind and sun rays factor.

3.3. Comparision of flat and porous surfaces

Application of porous surface involved increase of evaporated liquid for tap water (1.22 times) and petrol (1.15 times). It was accordance with (Zhou et al. 2020). While, for ethanol application of porous surface decrease of evaporated amount of liquid (14%).

Moreover, for porous surfaces adding of wind factor decreased the amount of evaporated liquid by 19%, 5% and 2% for tap water, ethanol and petrol, respectively. After substitution of wind with sun rays it was observed that the evaporation process increased by 1.14 and 1.37 times for ethanol and petrol, respectively. While a 18% decrease of evaporated liquid for tap water was recorded. Finally, the influence of both factors (wind and sun rays) indicated a 1% and 5% decrease of evaporated liquid for tap water and petrol, respectively. While, for ethanol 2% increase of evaporated liquid was observed. Moreover, graphical results of evaporation process for each of analyzed liquids was described with an umbrella shape (Fig. 3).

For tap water and impermeable surface an umbrella had vertical shape. However, substitution of flat surface with porous one indicated aberration from vertical configuration into right side (Fig. 3a and Fig. 3b). While analysis of ethanol instead of tap water indicated aberration of umbrella from vertical configuration into left side for flat surface and porous surface (Fig. 3c and Fig. 3d). Finally, for petrol the shape of umbrella was deformed by collapse into right side for impermeable surface and porous surface (Fig. 3e and Fig. 3f).

In Table 1 mathematical functions for each of analyzed liquids were presented. Each liquid was described with several functions to reflect the shape of umbrella. Each time the range of function was selected that regression coefficient was not lower than 0.769. While the highest regression coefficient was equal to 0.989.

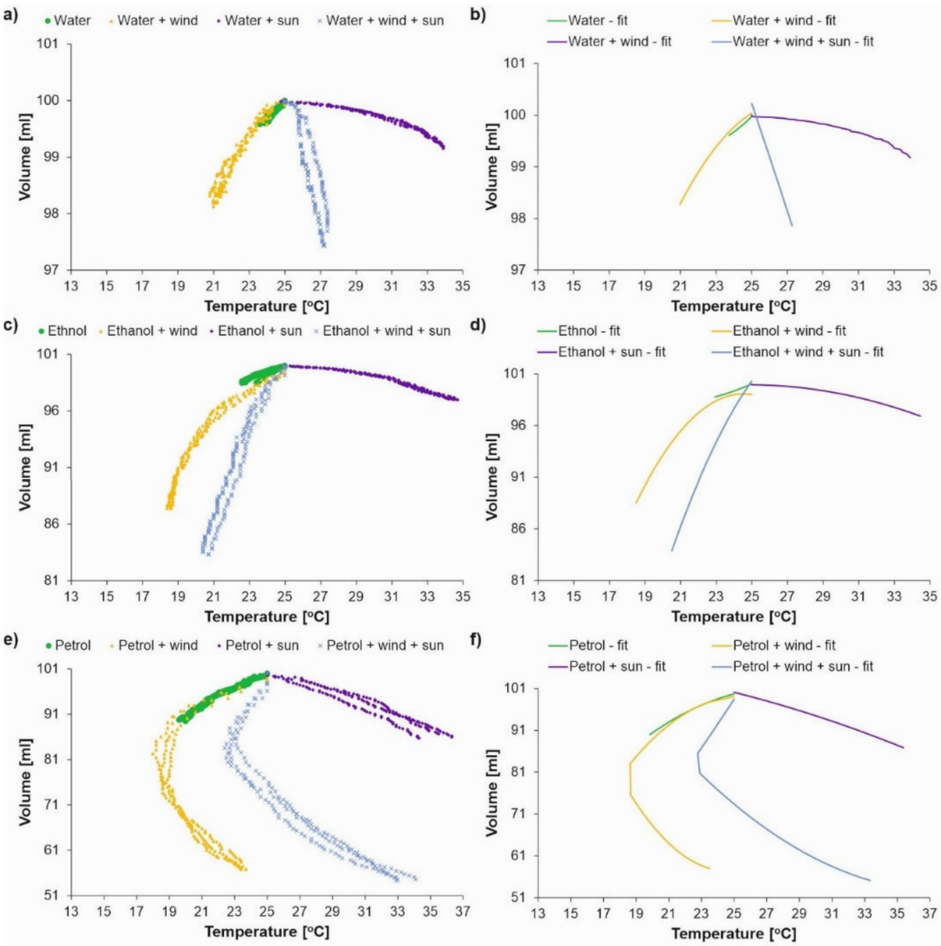

Fig. 3. Scatterplot graphic representation of porous surface for: a) tap water, b) tap water fit function, c) ethanol, d) ethanol fit function, e) petrol, f) petrol fit function

Table 1. Graphical description of analyzed cases. IS – impermeable surface, PS – porous surface, WO – without external conditions, W – wind, S – sun, TW – tap water, E – ethanol, P – petrol

Case	Liquid	Factors	Form of mathematical function	Range	R^2
IS	TW	WO	$y = -0.0439x^2 + 2.4238x + 66.831$	$x \in \langle 23.80 - 25.00\rangle$	0.868
		W	$y = -0.0313x^2 + 1.767x + 75.312$	$x \in \langle 19.10 - 25.00\rangle$	0.926
		S	$y = -0.0116x^2 + 0.599x + 92.255$	$x \in \langle 25.00 - 34.70\rangle$	0.911
		W+S	$x = 25.6$	$y \in \langle 97.68 - 100.00\rangle$	–
PS	TW	WO	$y = 0.0428x^2 - 1.8003x + 118.23$	$x \in \langle 23.60 - 25.00\rangle$	0.914
		W	$y = -0.0558x^2 + 3.0036x + 59.823$	$x \in \langle 20.80 - 25.00\rangle$	0.956
		S	$y = -0.0108x^2 + 0.5546x + 92.84$	$x \in \langle 24.79 - 33.90\rangle$	0.988
		W+S	$y = -0.0116x^2 - 0.4362x + 118.38$	$x \in \langle 25.00 - 27.40\rangle$	0.769
IS	E	WO	$y = -0.0177x^2 + 1.472x + 74.066$	$x \in \langle 22.10 - 25.00\rangle$	0.810
		W	$y = -0.0979x^2 + 5.0704x + 33.986$	$x \in \langle 14.60 - 25.00\rangle$	0.882
		S	$y = -0.029x^2 + 1.4281x + 82.394$	$x \in \langle 25.00 - 34.20\rangle$	0.966
		W+S	$y = -0.4304x^2 + 21.325x - 165.45$	$x \in \langle 19.00 - 25.00\rangle$	0.823
PS	E	WO	$y = 0.0664x^2 - 2.5753x + 122.9$	$x \in \langle 22.60 - 25.00\rangle$	0.806
		W	$y = -0.2904x^2 + 14.246x + 75.648$	$x \in \langle 18.40 - 25.00\rangle$	0.977
		S	$y = -0.0325x^2 + 1.6125x + 79.942$	$x \in \langle 25.00 - 34.70\rangle$	0.989
		W+S	$y = -0.2715x^2 + 16.002x - 130.06$	$x \in \langle 20.40 - 25.00\rangle$	0.954
IS	P	WO	$y = -0.1575x^2 + 8.7402x - 20.323$	$x \in \langle 19.90 - 25.00\rangle$	0.929
		W	$y = 0.094x^2 + 5.9751x + 7.7743$	$x \in \langle 15.90 - 25.00\rangle$	0.796
		W	$y = 0.1303x^2 + 7.6915x + 166$	$x \in \langle 16.10 - 23.80\rangle$	0.918
		S	$y = -0.0229x^2 - 0.038x + 115.56$	$x \in \langle 25.00 - 32.90\rangle$	0.973
		W+S	$y = -0.2826 + 15.127x - 103.04$	$x \in \langle 18.80 - 25.00\rangle$	0.973
		W+S	$y = -0.0911x^2 - 6.6428x + 170.78$	$x \in \langle 18.90 - 30.20\rangle$	0.988
PS	P	WO	$y = -0.1744x^2 + 9.704x - 33.915$	$x \in \langle 19.60 - 25.00\rangle$	0.985
		W	$y = -0.3533x^2 + 17.942x - 128.66$	$x \in \langle 18.00 - 25.00\rangle$	0.811
		W	$y = -0.5239x^2 - 25.721x + 373.11$	$x \in \langle 18.50 - 23.70\rangle$	0.966
		S	$y = -0.0286x^2 + 0.4499x + 106.72$	$x \in \langle 25.00 - 36.30\rangle$	0.931
		W+S	$y = 0.0938x^2 + 1.3273x + 6.64$	$x \in \langle 22.40 - 36.30\rangle$	0.909
		W+S	$y = 0.127x^2 - 9.5973x + 233.93$	$x \in \langle 22.50 - 36.10\rangle$	0.967

4. Conclusions

The impact of external factors on the evaporation process in the laboratory scale, which simulated a hazard that firefighters may meet in their work, was analyzed. Application of porous surface caused the highest improvement of evaporation process for petrol and tap water, while the lowest was observed for ethanol. Moreover, application of wind together with porous surface increased the intensity of evaporation for all analyzed liquids compare to the case without additional interrupting factors such as wind or sun rays. However, application of sun rays instead of wind caused the highest improvement of evaporation process for ethanol and petrol and the lowest for tap water. Finally, application of both external factors provided similar intensity of evaporation.

References

Abdel-Aziz, M. H. (2013). Solid-liquid mass transfer in relation to diffusion controlled corrosion at the outer surface of helical coils immersed in agitated vessels. *Chemical Engineering Research and Design, 8*.

Aulich, T.R., He, X., Grisanti, A.A. & Knudson, C. L. (1994). Gasoline Evaporation-Ethanol and Nonethanol Blends. *Journal of Air & Waste Management Association, 6*.

Batzias, F.A., G. Siontorou, C. & Spanidis, P. M. P. (2011). Designing a reliable leak bio-detection system for natural gas pipelines. *Journal of Hazardous Materials, 24*.

Chen, X., Li, Y., Gao, W. & Chen, C. (2020). Experimental investigation on transport property and emulsification mechanism of polymeric surfactants in porous media. *Journal of Petroleum Science and Engineering*.

Colburn, D., Russo, L., Burkard, R. & Hostler, D. (2019). Firefighter protective clothing and self contained breathing apparatus does not alter balance testing using a standard sensory organization test or motor control test in healthy, rested individuals. *Appl Ergon*, 187-192.

Czapczuk, A., Dawidowicz, J. & Piekarski, J. (2017). Application of Multilayer Perceptron for the Calculation of Pressure Losses in Water Supply Lines. *Rocznik Ochrona Srodowiska, 11*.

Fingas, M. F. (1997). Studies on the evaporation of crude oil and petroleum products: I. the relationship between evaporation rate and time. *Journal of Hazardous Materials, 10*.

Kahn, S. A., Leonard, C.Y., Lee, G., Boatwright, R., Flamm, T. & Woods, J. (2019). A pilot survey of Southeastern firefighters: Safety practices, use of protective gear, and injury. *Burns*.

Li, Z., Feng, H., Liang, Y., Xu, N., Nie S. & Zhang, H. (2019). A leakage risk assessment method for hazardous liquid pipeline based on Markov chain Monte Carlo. *International Journal of Critical Infrastructure Protection*.

Majder-Lopatka, M., Wesierski, T., Dmochowska, A., Salamonowicz, Z. & Polanczyk, A. (2020). The Influence of Hydrogen on the Indications of the Electrochemical Carbon Monoxide Sensors. *Sustainability*.

Maslen, S. (2014). Learning to prevent disaster: An investigation into methods for building safety knowledge among new engineers to the Australian gas pipeline industry. *Safety Science, 8*.
Mehrizi, A. A. & Wang, H. (2017). Evaporating thin film profile near the contact line of a partially wetting water droplet under environmental heating. *International Journal of Heat and Mass Transfer, 5*.
Moon, J. H., Lee, S. M., Choi, C. K. & Lee, S. H. (2018). Modeling of the evaporation rate of liquid droplets on anodized heated surfaces. *International Communications in Heat and Mass Transfer, 7*.
Nasr, A., Debbissi, C. & Nasrallah, S. B. (2010). Evaporation of a thin binary liquid film by forced convection into air and superheated steam. *Journal of Thermal Science, 11*.
Piecuch, T., Andriyevska, L., Dabrowski, J., Dabrowski, T., Juraszka, B. & Kowalczyk, A. (2015). Treatment of Wastewater from Car Service Station. *Rocznik Ochrona Srodowiska, 19*.
Polanczyk, A. & Salamonowicz, Z. (2018). Computational modeling of gas mixture dispersion in a dynamic setup – 2d and 3d numerical approach. *E3S Web of Conferences, 8*.
Polanczyk, A. (2018). The usefulness of Gram staining method for analysis of the effectiveness of decontamination of firefighter's protective outfit. *MATEC Web of Conferences*.
Polanczyk, A., Ciuka-Witrylak, M., Synelnikov, O. & Loik, V. (2018). Analysis of sorption of vehicle liquids with sand that appear after car accidents reproduced in laboratory scale. *MATEC Web Conf., 8*.
Polanczyk, A., Majder-Lopatka, M., Dmochowska, A. & Salamonowicz, Z. (2020). Analysis of combustion process of protective coating paints. *Sustainability, 8*.
Polanczyk, A., Piechota-Polanczyk, A. & Dmochowska, A. (2019). The influence of the soil type on the permeability of petroleum derivatives. *Rocznik Ochrona Srodowiska, 13*.
Polanczyk, A., Piechota-Polanczyk, A., Dmochowska, A., Majder-Lopatka, M. & Salamonowicz, Z. (2020). Analysis of the Effectiveness of Decontamination Fluids on the Level of Biological Contamination of Firefighter Suits. *Int J Environ Res Public Health*.
Polanczyk, A., Wawrzyniak, P. & Zbicinski, I. (2013). CFD Analysis of Dust Explosion Relief System in the Counter-Current Industrial Spray Drying Tower. *Drying Technology, 10*.
Qubaja, R., Amer, M., Tatarinov, F., Rotenberg, E., Preisler, Y., Sprintsin, M. & Yakir, D. (2020). Partitioning evapotranspiration and its long-term evolution in a dry pine forest using measurement-based estimates of soil evaporation. *Agricultural and Forest Meteorology.*
Salamonowicz, Z., Majder-Lopatka, M., Dmochowska, A., Piechota-Polanczyk, A. & Polanczyk, A. (2021). Numerical Analysis of Smoke Spreading in a Medium-High Building under Different Ventilation Conditions. *Atmosphere, 13*.
Singh, V.K., Kumar, D., Kashyap, P.S., Singh, P.K., Kumar, A. & Singh, S. K. (2020). Modelling of soil permeability using different data driven algorithms based on physical properties of soil. *Journal of Hydrology*.

Stefana, E., Marciano, F. & Albert, M. (2016). A predictive model for estimating the indoor oxygen level and assessing Oxygen Deficiency Hazard (ODH). *Journal of Loss Prevention in the Process Industries, 21*.

Teng, J., Zhang, X., Zhang, S., Zhao, C. & Sheng, D. (2019). An analytical model for evaporation from unsaturated soil. *Computers and Geotechnics, 10*.

Volchkov, E.P. (2006). Evaporation of a thin binary liquid film by forced convection into air and superheated steam. *International Journal of Heat and Mass Transfer, 8*.

Wawrzyniak, P., Podyma, M., Zbicinski, I., Bartczak, Z., Polanczyk, A. & Rabaeva, J. (2012). Model of heat and mass transfer in an industrial counter-current spray-drying tower. *Drying technology, 9*.

Wawrzyniak, P., Polanczyk, A., Zbicinski, I., Jaskulski, M., Podyma, M. & Rabaeva, J. (2012). Modeling of dust explosion in the industrial spray dryer. *Drying technology, 10*.

Yu, Y., Liu, L., Yang, C., Kang, W., Yan, Z., Zhu, Y., Wang, J. & Zhang, H. (2019). Removal kinetics of petroleum hydrocarbons from low-permeable soil by sand mixing and thermal enhancement of soil vapor extraction. *Chemosphere*.

Zhang, H., Liang, Y., Zhang, W., Xu, N., Guo, Z. & Wu, G. (2018). Improved PSO-Based Method for Leak Detection and Localization in Liquid Pipelines. *IEEE Transactions on Industrial Informatics, 12*.

Zhou, T., Xin, P., Li, L., Barry, D. A. & Simunek, J. (2020). Effects of large macropores on soil evaporation in salt marshes. *Journal of Hydrology*.

Zieminska-Stolarska, A., Polanczyk, A. & Zbicinski, I. (2015). 3-D CFD simulations of hydrodynamics in the Sulejow dam reservoir. *Journal of Hydrology and Hydromechanics, 8*.

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Assessment of the Water Needs of Fruit Plants in the Perspective of Climate Change

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Abstract: The paper includes a detailed water need forecasting analysis of fruit plants: apple trees, pear trees, cherry trees and plum trees, for the area of Poland with particular water deficits. The assessment was carried out for the multiannual period of 1989-2018, using three methods developed by Press, Grabarczyk and Rzekanowski, and Treder. The greatest water needs in the multiannual period (1989-2018) were demonstrated by apple and plum trees. The average water needs of apple trees in the multiannual period were 485 mm (Press method), 599 mm (Rzekanowski and Grabarczyk) and 558 mm (Treder), respectively. The average amount of water needs of plum trees was 506 mm (according to Press), 590 mm (Rzekanowski and Grabarczyk) and 548 mm (Treder). In practice, each of the methods presented should be used to forecast the water needs of fruit plants. This will minimise the risk of water shortages and will also enable determination of irrigation doses.

Keywords: fruit plants, water deficit areas, irrigation needs, water needs

1. Introduction

In Central Poland, where water shortages are frequent, intensive vegetable and fruit growing is exclusively dependent on the course and distribution of precipitation and air temperature. Spatial and temporal variability of precipitation is a characteristic feature of the Polish climate, which makes it difficult to estimate water needs of plants and forecast water balance (Kuchar & Iwański 2011). The studies carried out so far have shown that fruit plants in Poland require annual precipitation of 700 to 800 mm (Słowik 1973) and even 800 to 900 mm (Hołubowicz et al.1993) for optimal growth and yielding.The average amount of precipitation over multiannual period is 602 mm, with deviations from the average of +/-30% in some years (Rzekanowski 2009). The vegetation period is prolonged, which has a positive effect on fruit farming, but is associated with a higher risk of water deficit for fruit trees. Water needs of fruit plants are very high, especially at the time of growth and ripening of fruits. In Poland, irrigation is not developed on a wider scale. The development of irrigation systems should primarily concern fruit plants and vegetables. This is linked to the need to increase the modernity and competitiveness of farms and the projected climate changes (Bac & Rojek 1979). Water needs of fruit plants are assessed as high (Słowik 1973, Drupka 1976, Hołubowicz et al.1993). The demand for water increases as the period of growth and ripening of fruits is extended. On the other hand, water needs of fruit plants grow with the shallowing of the root system, which depends on the species and type of rootstock. Therefore, it is assumed that out of all fruit plants, berry plants have the greatest water needs, and among them blueberry, strawberry and wild strawberry, followed by raspberry, currant and gooseberry (Rzekanowski, 2009). Moreover, the analysis of water needs of fruit plants indicates that fruit trees also have relatively high water needs (Drupka 1976). Among the trees, especially on dwarf and semi-dwarf rootstock, apple and plum have high water needs; peach, cherry, pear and walnut have medium water needs;, and apricot and cherry trees have relatively low needs (Rzekanowski 2009). There is, therefore, a great need to adapt models to practice based on simple meteorological measurements such as air temperature and humidity. This condition is met by the following models: Grabarczyk, Rzekanowski and Treder and others (Treder et al. 2013). The use of models allowing the calculation of reference evapotranspiration to estimate water needs of not only fruit plants requires the determination of plant coefficients, depending on the plant species and development phase (Treder et al. 2013). There is no information in Polish scientific literature on the calculation of water needs of fruit plants. In this part of Poland, as opposed to countries located in warmer climate zones, plant irrigation is of an interventional nature. Its purpose is to supplement periodic precipitation deficits in relation to the water demand of cultivated plants (Żarski et al. 2013). This applies especially to the lowland part of the country, defined as an area particularly scarce in water for agriculture (Ballif 1995, Treder & Pacholak 2006). These areas include light and very light soils located in the lowland, central part of Poland, in the zone of in the summer half-year precipitation(IV-IX) limited by the 350 mm isohyet. Rzekanowski (2009) believes that these areas show the greatest need for irrigation in Poland as they meet the climatic criterion of irrigation application. They cover the central lowland part of Poland, defined by Romer as the Land of the Great Valleys. These areas are characterised by the lowest precipitation during the growing season, extremely unfavourable climatic water balances and an increased frequency of long-term rain-free periods. In Polish literature on estimating water needs of fruit trees, the amounts of precipitation necessary to obtain high yields are given, described as optimal precipitation according to Kemmer and Schulz (Słowik 1973, Hołubowicz et al.1993, Święcicki 1981) and Press (Rzekanowski 2009, Łabędzki 2009, Rzekanowski et al 2011). Water needs of fruit trees according to Drupka (Rzekanowski et al 2011, Drupka 1986) were defined as water consumption from a controlled moisture layer. These formulas enable calculation of water needs of fruit trees in each month of the growing season (IV-IX) for two soil species: cohesive and sandy. In rain-free periods, these values represent a shortage of water needed to cover the potential evapotranspiration of fruit trees. Water needs of fruit trees according to the Treder model are estimated in three stages: estimation of Reference Evapotranspiration (ETo), estimation of evapotranspiration of a specific species (ETr) and estimation of the evapotranspiration of a specific planting taking into account the size of trees (ETr). The formula for reference evapotranspiration given by Treder, using the coefficient α and plant coefficients k adapted to this equation, makes it possible to determine the evapotranspiration of plums, pears, apple trees and cherries during the period IV-X. The formulas for reference evapotranspiration according to Hargreaves modified by Droogers and Allen and Hargreaves modified by Bogawski and Bednorz, as well as the Blaney-Criddle formula modified by Żakowicz (Treder et al 2010, Dzieżyc 1988, Bogawski & Bednorz 2014), using plant coefficients k according to Doorenbos and Pruitt, allow for determination evapotranspiration of: peach, cherry, pear, apple, apricot, plum and cherry in the period IV-X and evapotranspiration of vines in the period V-X. The comparison of thermal and rainfall conditions of a given region of Poland with water needs determined by the developed formulas may be helpful in the estimation of rainfall deficits for fruit trees in relation to such needs. The presented methods may also be helpful in the estimation of orchard irrigation needs and in making decisions on the location of irrigation equipment and possible use of irrigation in orchards and vineyards in Central Poland. The aim of the study was to predict water needs of fruit plants typical for Central Poland: apple trees, pear trees, cherry trees and plum trees.

2. Materials and methods

This fact prompted the author of this paper to undertake a comprehensive estimation of water needs of four species of fruit trees (apple, pear, cherry and plum) in the first five years after planting, based on field water consumption and models for which plant coefficients were determined. On their basis the potential evapotranspiration during the vegetation period was calculated. The obtained results can be used to calculate the water needs of these species of fruit trees in the conditions of central Poland, in an area particularly scarce in water. Based on Press, Rzekanowski and Grabarczyk and Treder methods, rainfall deficits were calculated as water needs of four selected fruit plants (apple, pear, cherry and plum). The calculations used meteorological data (precipitation amount and average air temperatures) from the IMGW stations in Toruń, Bydgoszcz and from the meteorological stations of KWB "Konin" in Lubstów and Kleczew in the years 1989-2018. The objects of the research were typical orchard farms in Kujawy, in Topolinek, 20 km from Bydgoszcz and eastern Wielkopolska (Gutowo near Września, Komorowo near Kleczew). The facilities that are located in the area with the lowest precipitation in Poland were selected (Fig. 1).

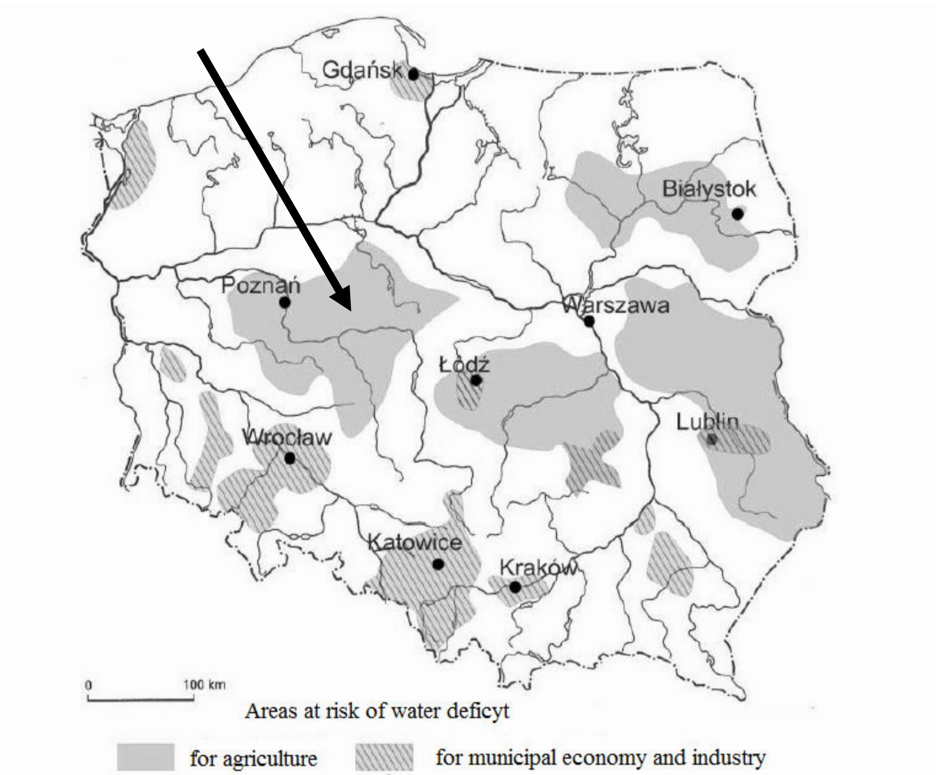

Fig. 1. Areas at risk of water deficit for agriculture, for municipal economy and industry

The orchard farms of various areas ranging from 30 ha to 75 ha were located on luvisols of IVa valuation class, which are characteristic soils of this part of Poland. In this area, the climatic risk of fruit plant cultivation is particularly high, which translates into the need for irrigation systems and, above all, precise determination of irrigation doses. On the basis of the daily and monthly air temperatures obtained, water needs for apples, pears, cherries and plums were read from a table prepared by Press for each month of the vegetation period. Next, the dependencies developed by Grabarczyk on potential evapotranspiration of ETp and Rzekanowski on actual evapotranspiration of ETr were used.

In this method, the Grabarczyk formula was used to calculate the amount of potential evapotranspiration (Grabarczyk & Żarski 1992):

$$ETp = 0.32\ (\Sigma d + 1/3\ \Sigma t) \quad (1)$$

where:
ETp – potential evapotranspiration (mm),
Σd – sum of average daily air humidity deficiency (hPa),
Σt – sum of average daily air temperatures (t°C).

The Press method was used to determine the water needs of fruit trees as optimal precipitation (Żakowicz 2010). For pear, apple and plum trees, the water requirements were calculated for the growing season (April-September) and for cherry trees for the period from April to August. According to Press (Ostromęcki 1973), three variants of water requirements are possible in each month of the growing season, depending on the height of the average air temperature.

Table 1. Monthly values of the plant k coefficient of fruit plants (Treder et al 2010)

	plant factor k	apple	pear	cherry	plum
IV	0.28	0.50	0.45	0.45	0.45
V	0.21	0.75	0.75	0.75	0.75
VI	0.19	1.10	1.05	1.00	1.10
VII	0.18	1.20	1.15	1.10	1.20
VIII	0.17	1.20	1.15	1.10	1.15
IX	0.16	1.15	1.10	0.90	1.15

When the temperature rises by 2°C, the amount of precipitation or artificial rainfall in the form of irrigation should be higher by 5 to 10 mm to provide the plants with the sufficient amount of water The potential ETp evapotranspiration for all months of the growing season was calculated according to the formula. Then, for each fruit plant studied, the actual evapotranspiration was calculated by multiplying it by the plant coefficient k (Table 1) according to Rzekanowski's formula (Rzekanowski 2009): $ETr = k \times ETp$, (2), where: ETr – actual evapotranspiration (mm), k – plant coefficient depending on the development phase and the condition and type of vegetation (Table 1), ETp – potential evapotranspiration (mm). Using the Rzekanowski formula (Rzekanowski 2009), the values of actual evapotranspiration and the amount of precipitation, precipitation deficits were calculated: $N = ETp - P$, (3), where: N – precipitation deficit in the absence of water reserves in the soil (mm), ETp – potential evapotranspiration (mm), P – precipitation during the growing season (mm).

3. Results and discussion

Potential evapotranspiration ETp was calculated using the following meteorological data: sum of daily average air temperatures and sum of daily average air humidity deficits. In order to determine the average monthly air humidity deficiency, the difference between saturated steam pressure value (from the table) and average monthly water vapour pressure value was calculated. Next, the actual evapotranspiration ETr for apple, pear, cherry and plum trees was determined by multiplying the value of potential evapotranspiration ETp obtained from Grabarczyk's formula by the plant factor. The third method of determining the water needs of fruit plants was the Treder's method (Drupka 1986). The value of index evapotranspiration ($ET_{0)}$ of each plant for each month obtained using the method of Grabarczyk was multiplied by the plant factor *k*, obtaining the actual evapotranspiration value (ETr). Water needs of the analysed fruit plants according to the Treder's model were calculated using the Web-based Decision Support System (Treder et al. 2010, www.nawa-dnianie.inhort.pl/eto/26-eto-temp). The results were developed through the statistical determination of the following values: mean, median, maximum and minimum, standard deviation and coefficient of variation. An attempt was also made to determine possible tendencies (trends) towards changes in the examined index of water needs of fruit plants in the Kujawy and eastern Wielkopolska regions. The methodology proposed by Rolbiecki was used here (Rolbiecki 2018). In the analysed period, no tendencies towards changes in precipitation levels were observed. For the analysed period of thirty years (1989-2018), the average amount of precipitation for the period between April and September was 343 mm. The lowest amount of precipitation occurred in 1989 (145 mm) and was by 198 mm lower than the long-term average, and the highest amount of precipitation was observed in 2010 (565 mm) and was by 222 mm higher than the average. In the analysed period of years, the amount of precipitation satisfied the water needs of apple trees only in 3 vegetation periods. In 2001, the precipitation was higher than the water needs of apple trees (by 79 mm), in 2010 (by 55 mm) and in 2017 by 29 mm. The water needs of apple trees calculated using the Press method ranged from 435 mm in the 1991 vegetation period to 560 mm in the 2002 vegetation period. The water needs of pear trees were lower than those of apple trees. In the evaluated period of thirty years, the amounts of precipitation were greater than the water needs of pear trees thirteen times. On the other hand, only in seven vegetation periods the amounts of precipitation met the water needs of pear trees: in 1993 (49 mm), in 2000 (11 mm), in 2001 (154 mm), in 2007 (12 mm), in 2010 (150 mm), in 2013 (32 mm), and in 2017 (124 mm). For cherries, the growing season is by one month shorter (IV-VIII), compared to apple, pear and plum trees, which results in a lower water requirement. In the analysed period, the lowest demand for water occurred in 1991 (315 mm) and the highest in 2002 (400 mm). The highest water deficit for cherry orchards was found in 1989 (185 mm). Higher amounts of precipitation in relation to the demand for water of cherry trees occurred in 2010. (by 200 mm). In fourteen growing seasons from 1989 to 2018, the amount of precipitation was higher than the water demand of the cherry trees. The highest water demand of plum tree occurred in 2002 (580 mm) and the lowest in 1991 (455 mm). The amount of precipitation in the analysed growing seasons was higher than the water needs of plums in: 2001 (by 59 mm), in 2010 (by 30 mm), and in 2017 (14 mm). The differences between the amount of precipitation during the growing seasons and the water demand of fruit trees over the long-term period (1989-2018) show that plum tree is the most demanding in terms of water demand among all fruit plants (from 455 mm in 1991 to 580 mm in 2002). Whereas the smallest water needs according to the Press method were observed in cherry tree (from 315 mm in 1991 to 400 mm in 2002). The greatest water shortages occurred in the periods from April to September 1989 and amounted to: 315 mm for apple trees, 240 mm for pear trees, 185 mm for cherry trees and 345 mm for plum trees. Water needs calculated with the use of the method of Rzekanowski and Grabarczyk in the growing periods from 1989 to 2018 were from 471 mm to 729 mm for apple trees, from 451 mm to 700 mm for pear trees, from 427 mm to 660 mm for cherry trees, and from 462 mm to 718 mm for plum trees. In 2001 and 2010, the water needs of fruit plants were met by precipitation (Fig. 2). For apple, pear, cherry and plum trees, the lowest water demand was in April 1997 and it amounted to 23 mm for apple trees, and 21 mm for pear, cherry and plum trees. The highest water needs were observed in July 2006: for apple and plum trees they amounted to about 174 mm, for pear trees 167 mm and cherry trees 160 mm (Table 2). The lowest water needs in the growing seasons 1989-2018 in relation to precipitation were observed in 1990 and the highest in 2002. The water demand of apple trees ranged from 498 mm to 643 mm, of pear trees from 476 mm to 618 mm, cherry trees from 450 mm to 585 mm, and of plum trees from 489 mm to 632 mm. The calculations carried out using the Treder's method showed a clear shortage of precipitation in the analysed period. The water needs of apple trees calculated using the method of Press ranged from 435 mm (in 1991) to 560 mm (in 2002), method of Rzekanowski and Grabarczyk – from 471 mm (in 1996) to 729 mm (in 2018), and the method of Treder from 498 mm (in 1990) to 643 mm (in 2002).

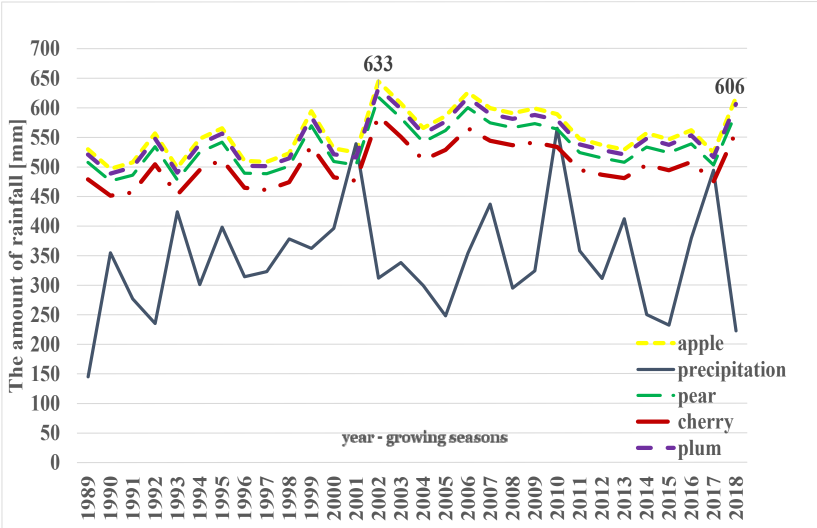

Fig. 2. Water needs of apple, pear, cherry and plum trees determined by the Rzekanowski and Grabarczyk method plotted against the background of atmospheric precipitation during the growing season (1989-2018) (own elaboration)

Table 2. Minimum and maximum values of the water needs of fruit plants in 1989-2018 determined by means of the Treder's method (own elaboration)

	apple		pear		cherry		Plum	
	min	max	min	max	min	maxi	min	max
IV	**23**	55	21	50	21	50	21	50
V	49	92	49	92	49	92	49	92
VI	94	131	90	125	86	119	94	131
VII	107	**174**	103	**167**	98	**160**	107	**174**
VIII	105	160	101	153	96	147	101	153
IX	59	102	56	97	46	79	59	102

Average water requirements of apple trees for the studied long-term period were 485 mm, 599 mm and 558 mm respectively. The obtained results are consistent with the calculated water needs of fruit trees according to Drupka (1986). The water needs of pear trees according to the method of Press ranged from 356 mm (1990) to 455 mm (2002). According to the method of Rzekanowski and Grabarczyk they ranged from 451 mm (1996) to 700 mm (2018) and to the method of Treder from 476 mm (1990) to 618 mm (2002). Average water requirements of pear trees for the methods were respectively: 399 mm, (Press), 575 mm (Rzekanowski & Grabarczyk) and for the method of Treder

534 mm (Fig. 3). The results obtained are consistent with the water needs of fruit trees determined by means of the Kemmer and Schulz method (500-710 mm) (Rolbiecki 2018).

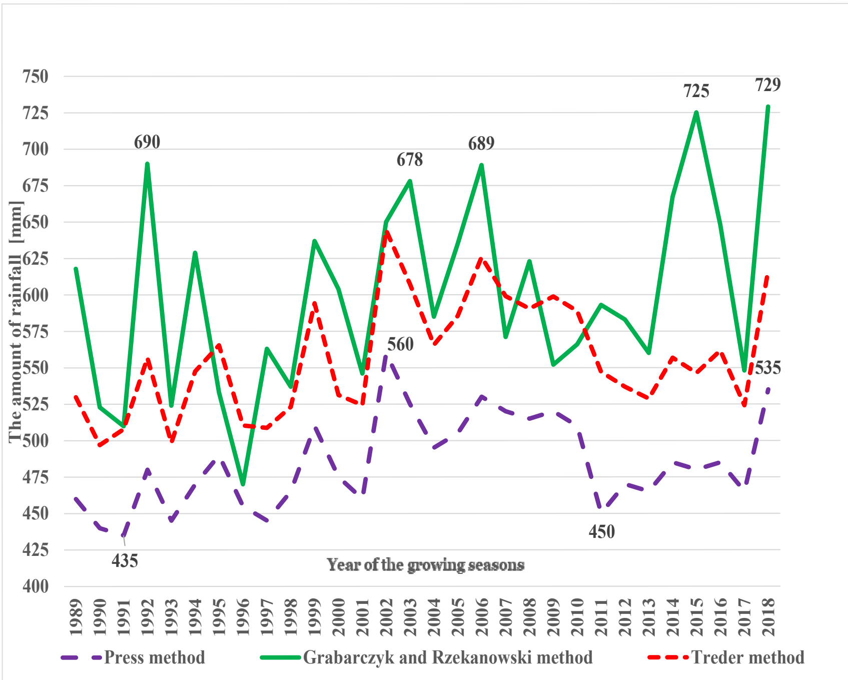

Fig. 3. Apple water needs calculated by three methods in the growing seasons (1989-2018) (own elaboration)

For comparison, the average annual (I-XII) water needs of cherry trees in the medium soil in the Bydgoszcz region determined by means of the method of Kemmer and Schulz for the period 1981-2015 constituted 532 mm (Kielak 1986). In turn, the annual water requirements for cherry trees determined by Rzekanowski (1989) for the north-western Kujawy region in the period 1981-1985 ranged from 473 mm to 539 mm (495 mm on average). During the forty-year period (1976-2015) analysed by Rolbiecki (2018), the water needs of cherry trees during the growing season in medium soils (IV-VIII) were 316 mm in the Bydgoszcz region and 326 mm in the Wrocław region. The average water needs of cherry trees were 379 mm in the Bydgoszcz area and 391 mm in the Wrocław area, while their maximum values reached 424 mm and 432 mm respectively. Thus, the average precipitation deficits in light soils were 115 mm (maximum 160 mm) in the Bydgoszcz area and 72 mm (maximum 113 mm) in the Wrocław area. According to Rzekanowski (2009), the highest water deficits occur in the case of fruit plants in the central strip of Poland (the Land of Great Valleys) and for sour and sweet cherry trees (in medium soils) they are from 20 to 42 mm. In order to obtain positive production effects in cherry growing in this area, sprinkling (Treder et al 2018), drip irrigation (Rojek 2006, Rolbiecki & Piszczek 2016a, 2016b) and sub-irrigation (Rolbiecki & Piszczek 2016c) should be performed. The water needs of plum trees varied: for the Press method from 455 mm (in 1991) to 580 mm (in 2002), for the Rzekanowski and Grabarczyk method from 462 mm (in 1996) to 718 mm (in 2018), and for the Treder method from 489 mm (in 1990) to 632 mm (in 2002). The average annual water needs of plum trees calculated by the Press method were as follows: 506 mm, 590 mm using Rzekanowski and Grabarczyk's method and 548 mm using Treder's method. The analyses conducted show that between 1989 and 2018, the water needs of fruit plants increased by 4.1 mm in each decade. (apple), 3.3mm (pear) and from 3.5 mm to 3.9 mm (cherry and plum) in each decade. As a result of similar analyses carried out by Rolbiecki (2018) over the years 1976-2015, the water needs of cherry trees in each decade increased by 3,9 mm on heavy soils, 4.9 mm on medium soils and 5.9 mm on light soils in the Bydgoszcz region and 8.6 mm on heavy soils, 10.7 mm on medium soils and 12.8 mm on light soils in the Wrocław region.

4. Conclusions

A detailed analysis of the results obtained allows us to conclude that in the meteorological conditions prevailing in this part of Poland, the amount of precipitation during the vegetation period in the last thirty years did not meet the water needs of the fruit plants analysed. Therefore, an urgent need arose to forecast and estimate the amount of water to be supplied to them by irrigation in order to cover their water needs. Apple trees and plum trees had the greatest water needs throughout these years (1989-2018). The detailed analysis of water needs showed that the average water needs of apple trees over the years amounted to 485 mm (Press method), 599 mm (Rzekanowski & Grabarczyk) and 558 mm (Treder), respectively. The average amount of water needs of plum trees was 506 mm (according to Press), 590 mm (Rzekanowski & Grabarczyk) and 548 mm (Treder). The obtained results confirmed the observations of other authors (Rolbiecki 2018, Treder et al 2018, Bąk Łabędzki 2014a) that cherry trees had the lowest water needs. The average water needs varied from 347 mm (Press method), 542 mm (Rzekanowski & Grabarczyk) and 505 mm (Treder). In practice, each of the methods presented should be used to forecast the water needs of fruit plants. Their use should minimise the risk of water shortages and, above all, enable a more precise determination of the irrigation doses. They can be particularly helpful in assessing the irrigation needs of orchards, plantations, and vineyards in Central Poland, equipment in this area of the country. Especially since, according to Rzekanowski et al. (2011), by 2025, irrigation should cover an area of approx. 1 million ha in Poland and should be located mainly on light soils of the Land of the Great Valleys.

References

Bac, S., Rojek, M. (1979). *Meteorology and climatology*. 1979, PWN, Warszawa.

Ballif, J.L. (1995). Rnoff water and infiltraton of a viticultural soil in Champagne.Resilts of mulching with municipal compost and crushed bark 1985-1994. *Progresc Agricole et Viticole, 112*(24), 534-544, 34 ref.

Bąk, B., Łabędzki, L. (2014a). Prediction of precipitation deficit and excess in Bydgoszcz Region in view of predicted climate change. *Journal of Water and Land Development*. *23*, 11-19.

Bogawski, P., Bednorz, W. (2014). Comparison and validation of selected evapotranspiration models for conditions in Poland (Central Europe). *Water Resour Manage*, *28*, 5021-5038.

Drupka, S. (1976). *Technical and agricultural operation of the sprinkler*. PWRiL, Warszawa, 103-122.

Drupka, S.(1986). *Irrigation and drip irrigation*. In: Basics of agricultural melioration (collective work edited by red. P. Prochala), Warszawa: PWRiL, 1, 449-620.

Dzieżyc, J. (1988). *Agriculture under irrigation conditions*. Warszawa: PWN, 1415.

Grabarczyk, S. (1987). Effects, needs and possibilities of sprinkler irrigation in agricultural regions of the country. *Zesz. Probl. Postęp. Nauk Roln., 314*, 49-64.

Grabarczyk, S., Żarski, J. (1992). An attempt to statistically verify some of the formulas determining potential evapotranspiration. *Zesz. Nauk. ATR, 180*. 44-49.

Hołubowicz, R., Tylkowska, K., Gruchała, L (1993). Ethylene production as a biochemical marker for radish seed vigour. *Folia Horticulturae 5*, 19-28.

Internet Platform of Irrigation Decisions, accessed 01/09/2019: Downloaded from: website address: http://www.nawadnianie.inhort.pl/eto/26-eto-temp -

Kielak, Z. (1986). Influence of irrigation on the growth and yielding of cherries *Zesz. Problem. Postęp. Nauk Roln, 268*, 611-616.

Kuchar, L., Iwański, S. (2011). Atmospheric precipitation simulation for the assessment of the irrigation needs of plants in the perspective of the expected climate changes. *Infrastructure and Ecology of Rural Areas., 5*, 35-46.

Łabędzki, L. (2009). Predicted climate changes and the development of irrigation in Poland *Infrastructure and ecology of rural areas,* 3, 7-18.

Ostromęcki, J. (1973). *Basics of irrigation drainage*. Warszawa: PWN, 1-450.

Rojek, M.. (2006). *Irrigation needs in Poland*. W: Nawadnianie roślin (praca zbiorowa pod red. S. Karczmarczyka i L. Nowaka), 91-108.

Rolbiecki, St. (2018). Comparison of the water needs of cherries in the region of Bydgoszcz and Wrocław. *Infrastructure and ecology of rural areas*. *II*(1), Polish Academy of Sciences, Cracow Branch, Commission of Technical Rural Infrastructure. 349-360.

Rolbiecki, S., Piszczek, P. (2016a). Effect of the forecast climate change on the peach tree water requirements in the Bydgoszcz region. *Infrastructure and Ecology of Rural Areas*, *4*(3), 1499-1508.

Rolbiecki, S., Piszczek, P. (2016b). Effect of the forecast climate change on the sweet cherry tree water requirements in the Bydgoszcz region. *Infrastructure and Ecology of Rural Areas, 4*(3), 1559-1568.

Rolbiecki, S., Piszczek, P. (2016c). Effect of the forecast climate change on the plum tree water requirements in the Bydgoszcz region. *Infrastructure and Ecology of Rural Areas, 4*(3), 1615-1624.

Rzekanowski, C. (1989). The impact of drip irrigation on the yielding of the most important species of fruit trees under the conditions of a production orchard. *Zeszyty Naukowe ATR* w Bydgoszczy, Rozprawy, *35*, 1-79.

Rzekanowski, C. (2009). Shaping the irrigation needs of fruit plants in Poland. *Infrastructure and Ecology of Rural Areas, 3*, 19-27.

Rzekanowski, C., Żarski, J., Rolbiecki, St. (2011). Needs, effects and prospects of irrigating plants in areas with particular water deficit. *Postępy Nauk Rolniczych, 1*, 51-63.

Rzekanowski, C., Rolbiecki, S. (2000). The influence of drip irrigation on yields of some cultivars of stone fruit-bearing trees in central Poland under different rainfall conditions during the vegetation season. *Acta Horticulturae 537*(2), 937-942.

Słowik, K. (1973). Influence of irrigation and fertilization on the growth and fruiting of fruit plants. *Zesz. Probl. Post. Nauk. Roln*., *2*, 59-67.

Święcicki, Cz. (1981). *Soil science of drainage*. PWN, Warszawa, 218-228.

Treder, W., Pacholak, E.. (2006). *Irrigation of fruit plants*. W: Nawadnianie roślin (praca zbiorowa pod red. S. Karczmarczyka i L. Nowaka), 333-365.

Treder, W., Wójcik, K., Żarski, J. (2010). Initial assessment of the possibility of estimating the water needs of plants based on simple meteorological measurements. *Zesz. Nauk. Instyt. Sadownictwa i Kwiaciarstwa, 18*, 143-153.

Treder, W., Jakubiak, B., Klamkowski, K., Rudnicki, W., Kursa, M., Tryngiel-Gac, A., (2013). Forecast of water needs – an online platform for forecasting water needs of fruit plants implemented under the Prose project.. *Infrastructure and Ecology of Rural Areas* 2/I, 115-125.

Treder, W., Klamkowski, K., Wójcik, K. (2018). A new approach to the method of drawing the Gaussen-Walter climate diagram. *Meteorology Hydrology and Water Management, 6*(2), 1-7.

Żakowicz, S.(2010). *Fundamentals of irrigation technology of reclaimed municipal waste landfills*. Wyd. SGGW, Rozprawy Naukowe i Monografie, 1-95.

Żarski, J. Dudek, St., Kuśmierek-Tomaszewska, R. (2011). Needs and effects of potato irrigation in areas with particular water deficits. *Infrastructure and ecology of rural areas., 5*, 175-182.

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Some Issues Quantifying Low-carbon of an Achievement Energy and Industry

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Abstract: In this work, for use as a unified tool within the framework of ISO 50001, a methodology for rating assessment of the processing of emissions with global pollutants is proposed, which was developed by the authors and recommended for use by state documents of the Republic of Tatarstan, Russia. It is distinguished by the absence of not transparences elements. As the initial data, the actual background concentrations (according to WMO data), the annual ceiling of greenhouse gas emissions and the maximum permissible emissions of toxic compounds, information on the characteristics of emission sources are taken for the enterprise, and as operational constants, the global warming potentials of greenhouse gases (GWP100) and officially approved values of maximum permissible concentrations of toxic compounds (MPC). The method is based on the equation (presented here at annotation in a simplified form), which gives a numerical indicator (rating) R of the efficiency of a production facility in terms of hazardous emissions into the atmosphere, taking into account greenhouse gases and energy costs arising from their removal. Currently, the technique is adapted to the energy sector; for wider adaptation to various industries, a low-carbon rating program has been drawn up for boiler houses, thermal power plants and industrial enterprises. It also meets the needs of understanding and predicting possible deviations of emission parameters from the standardized indicators. Therefore, it can serve as a tool within the framework of ISO 50001, providing objective control over the choice of means to ensure compliance with the requirements for harmful components emissions including greenhouse gases in the design and modernization of production facilities. The developed program is embedded for Russian enterprises in the shell of the '1C: Enterprise' platform – a software product for automating accounting and management at enterprises. The program can also be used in the software shell of the automated accounting of the activities of a particular organization in a one or the other country.

Keywords: global pollutants, emission sources, greenhouse gas, low-carbon achieve quantifying, energy efficiency, energy and industry

1. Introduction

In the present world, the overwhelming majority of countries are members of international organizations of the planet, solving the problem achieving of the low-carbon and energy efficiency production and consumption. Among them, a number of international organizations consider low-carbon as the most significant characteristic of a country, region, enterprise, and its achievement as the most significant goal. These are, for example, the obligations of the countries belonging to the "Group of 20" (G20), which are consumers of 80% of the world's energy resources. And the WTO member countries (162 countries plus the EU) are obliged to create conditions for fair competition, including energy saving. Finally, the States Parties to the Framework Convention on Climate Change (FCCC) at the UN (195 countries of the world plus the EU), at the 2015 Paris Conference, made a direct commitment to achieve real low-carbon production by 2030.

It can be seen that practically the entire global community is covered by the commitment to achieving low-carbon. At the same time, there are no generally accepted methods of assessing the achievement of low-carbon content in the world. Consequently, there are no ways to control and self-control the fulfillment of obligations. They did not appear during the time that has passed since the adoption of the Paris Agreement, which was characterized by the absence of specific methods and tools for implementing decisions.

The problem of the lack of criteria for a transparent quantitative assessment of the achievement of low-carbon leads to biased decisions on a global, national and local scale, from which it is necessary to have, at least, methods and tools of protection. This applies to all areas of generation and consumption of energy resources based on both fossil fuels and renewable sources. The above commitments of the G20 member countries cover the sectors of activity formed and substantiated at the 2014 Brisbane summit (Communiqué 2014), which prescribe: progress towards real low-carbon industrial production with the intensification of the implementation of an energy efficiency management system in industry; development of low-carbon power generation; improving the energy efficiency of buildings; reduction of emissions from transport and agricultural production.

Let us now turn to the document of our day – "U.S.-China Joint Statement Addressing the Climate Crisis" (U.S.-China 2021), the following areas of joint activity are highlighted:

a. Policies, measures, and technologies to decarbonize industry and power, including through circular economy, energy storage and grid reliability, CCUS, and green hydrogen;
b. Increased deployment of renewable energy;
c. Green and climate resilient agriculture;

d. Energy efficient buildings;
e. Green, low-carbon transportation;
g. Cooperation on addressing emissions from international civil aviation and maritime activities...

It can be seen that the two countries with the largest greenhouse gas emissions have exactly the same problems as 7 years ago before the Paris Agreement. The same applies to all other countries belonging to various world institutions aimed at achieving low-carbon and energy efficiency (Rubino M, Etheridge DM, et al. 2019, WMO Greenhouse Gas Bulletin 2019). In recent decades, only an increase in CO_2 emissions can be observed for all countries (see data on emissions by countries of the world from 1990 to 2018 by IEA – International Energy Agency CO_2 data, https://www.iea.org/).

Increasing energy efficiency in the buildings sector continues to be a one of main viable way to achieve reductions in carbon dioxide emissions. This is due to the fact that at present about a third of the energy generated in the world is spent on the energy supply of buildings and structures, which it is generated by more than three quarters by burning fossil fuel. However, on this path, the possibilities of traditional methods are close to exhaustion, and breakthrough technologies are required, and they can be found even in thermal insulation structures. At the same time, it should be borne in mind that new solutions must be checked, whether their production and / or application will lead to a greater release of greenhouse gases into the atmosphere than, for example, the generation of energy to replenish heat losses using just good thermal insulation. To do this, we must have reliable control tools - numerical criteria that would make it possible to transparently and correctly compare new technologies, for example, in this case – conventional and thermal insulation with "zero" heat loss. Today, advanced technologies that can provide a significant increase in the energy efficiency of buildings and structures, in addition to thermal insulation materials with nanoelements that provide "zero" thermal conductivity, include, for example: equipping buildings with energy storage devices based on high-temperature superconductivity (HTSC) for efficient power supply from solar and wind generators to the electrical network of a building with lighting and household electrical appliances, air conditioners, electric heaters and kitchen equipment; a radical reduction in the resistance of ventilation and air conditioning networks in buildings by means of computer profiling of shaped elements; energy efficient use of geothermal heat pumps in high latitudes.

In view of the difficult (even “crisis”, according to the joint statement of the United States and China) state of the planet, at this stage only those that reduce the release of greenhouse gases into the atmosphere should be selected from breakthrough technologies. This can be done if there is, first of all, a transparent and reliable selection tool – a numerical efficiency criterion for greenhouse gases, which would exclude any subjectivity in the technology selection process. In the transport sector, there are general prerequisites for creating such an instrument. The transport sector is both the largest consumer of energy and a source of emissions. According to 2014 IEA estimates, It accounted for about 20% of global energy consumption and about 15% of carbon emissions. Transport energy consumption could rise to 35% by 2050 if the global energy efficiency policy is not accelerated. The IEA proposes to focus primarily on heavy transport, as its impact on the environment is disproportionately high. It was assumed that the countries of the world would jointly develop techniques for effective control of fuel consumption and the impact of heavy vehicles on the environment and climate with the introduction of common approaches and coordination of national standards. Approaches were considered to reduce the impact of heavy vehicles by improving engine efficiency and performance, improving aerodynamics and tires, and increasing the use of biofuels and low-carbon fuels. However, now the transition to electric transport is becoming more and more urgent, since the generation of electricity by stationary generators has a higher fuel utilization factor than ICE. And technologies based on HTSC become breakthrough here, both for the accumulation of electricity and for replacing wheeled vehicles with the MAGLEV technology. To select from seeming successful projects, criteria for a transparent quantification of low-carbon achievement are also required.

To reduce greenhouse gas emissions in the sector of industrial and agricultural production, the world community needs to ensure a significant increase in the energy efficiency of production processes. The strategy is considered not only environmentally necessary, but also economically justified: the starting point is that production processes are accompanied by significant energy consumption.

The basis for effective cooperation is considered the agreement of the participating countries G20 in the direction of intensification of the activities of the IPEEC Working Group on Industrial Energy Management of the Global Sustainable Electricity Partnership (GSEP). Also, great hopes are pinned on the wider implementation of an energy management system based on the ISO 50001: 2011 protocol, which takes into account the diversity of industrial and technological systems in the G20 countries and is easily adaptable to the needs of any the above-identified sectors.

The protocol is acceptable for the development and implementation of the energy policy of any industrial enterprise in industry and agriculture, regardless of legal relations, size, climate, etc. It is an algorithm for organizing a systematic approach, first to achieving energy efficiency, and then to a constant decrease in energy consumption, with a corresponding reducing greenhouse gas emissions. The algorithm operates according to the principle: planning – executing – checking – adjusting – achieving – subsequent planning, and the ISO 50001 standard does not indicate any quantitative estimates. Each company chooses the ways to achieve the goal itself. At the same time, it requires the enterprise to demonstrate improvement in its energy efficiency indicators within the limits of the energy efficiency requirements in accordance with the energy policy of the enterprise itself. The standard specifically stipulates that it does not predetermine the description of special criteria for the level of energy efficiency, which makes it universally. However, this advantage of the protocol does not make it possible to use the achievements of the indicators as numerical criteria that would allow transparently and correctly adjusting such local actions as reducing greenhouse gas emissions and other hazardous emissions, within the framework of a regional, national and global scale. Indeed, the ISO 50001 standard can be met by businesses that produce the same products, but with different energy efficiency levels.

Meanwhile, the structure of the standard makes it possible to include in the agenda the adjustment of any variables and measured values, leading to an increase in the level of energy efficiency of the enterprise, from design and procurement of equipment to methods of documentation and reporting or for attracting specialized personnel, etc. Consequently, the achievement of indicators by enterprises according to the ISO 50001 protocol can and should be used on a national and global scale. For this their values must be further presented in form able to compare enterprises of the one industry, then – to compare industries on a regional scale, regions – nationally and countries – in globally.

2. Materials and methods

The tools for comparing enterprises, industries, regions, countries in terms of achieving low-carbon emissions should be ratings for reducing greenhouse gas emissions, which should be based on transparent adequate numerical criteria, which were mentioned earlier. This will ensure screening and timely adjustment of the movement towards reducing energy consumption and greenhouse gas emissions at the local, regional, national and global levels.

There are now many online carbon footprint calculators for businesses around the world. Further briefly consider some of them as typical low-carbon numerical identification tools. Let us the possibilities of using them as an additional tool for comparing the low-carbon ratings after establishing the level of achievement enterprises of energy efficiency indicators within the framework of the ISO 50001 protocol.

The calculator of carbon dioxide (CO_2) emissions, offered by one of the largest operating associations of energy auditors in Russia[1] is based on the conversion ratios provided in the guidelines environmental reporting by the government department UK for Environment, Food and Rural Affairs (Defra), designed for various organizations and households. The calculator gives the total CO_2 emissions from the organization's fuel and electricity consumption and from transportation by road, train, bus and airplane. Arbitrariness in the selection of conversion factors for the conversion of consumed electricity into carbon dioxide equivalent is not excluded, which can, due to the large, as a rule, consumption of electricity by enterprises, give a large error in the final value of emissions, and make it difficult to compare the results of reducing energy consumption and CO_2 emissions from different enterprises.

The possibility of using the online tool of the COMBI project ("Calculation and Implementation of the Multiple Benefits of Energy Efficiency in Europe") presented by the EU in 2018 also deserves close scrutiny. Achieving energy efficiency, in line with the Paris Agreement, has been identified as the key among the possible ways to reduce greenhouse gas emissions and address climate change. Also energy saving, in addition to directly reducing energy costs, improves air quality and the ecosystem as a whole, public health. The last with in terms of financial costs brings save another 30%, according to the Wuppertal Institute (Multiple Impacts 2020). The online tool COMBI allows to recalculate energy savings into reimbursement of investment costs and the amount of profit, according to the development models of all EU countries until 2030. To quantify the multiple impacts of the potential for additional energy savings on the economy of a country or region, the COMBI online tool uses detailed data on energy savings and investment costs of a large number of energy-related manufacturing items. Some of them could be used to create a methodology for determining the ratings of low-carbon regions and countries of the EU.

In the Republic of Tatarstan, Russia, more than 10 years ago, on the basis of recommendations contained in state documents on the state of natural resources[2] and the sanitary and epidemiological situation[3] a method was developed for direct quantitative assessments of low-carbon enterprises (Ziganshin 2019). It was used in the design of heat supply for a number of non-energy facilities. Currently, the technique has been adapted to power generation facilities. The method is fully prepared for use as an additional tool to the ISO 50001 pro-

[1] Non-profit Partnership "Interregional Alliance of Energy Auditors" https://sro150.ru/

[2] State report of the Ministry of Economic Development of the Republic of Tatarstan "On the state of natural resources and on environmental protection of the Republic of Tatarstan in 2007".

[3] State report of Rospotrebnadzor in the Republic of Tatarstan "On the sanitary and epidemiological situation in the Republic of Tatarstan in 2007".

tocol to quantitative assesment of the low-carbon achievment and to compare of enterprises industrial, generating and the construction sector.

So, the analysis of the methods shows next. The simple and transparent methods can give a significant error due to taking into account a small number of factors, and the inaccuracy of the results of complicated methods that take into account many factors is due to the impossibility of their correct inclusion due to the need to supplement with forecast data, but forecasts are often not justified. At the same time, our proposed methodology use just real data can give transparent and reliable results on low-carbon and toxic emissions of enterprises, but so far it has not been tested at the global, national and/or regional levels.

3. Results and discussion

Thus, today it is impossible to find ready-made and tested methods of quantitative assessment of the approach of energy and industrial production in the world to low-carbon content. It seems reasonable enough to use the proposed at this work methodology with its testing in the pilot region, necessary adjustments and further dissemination of experience. Let us dwell in more detail on the discussion of the design equations and properties of the proposed method for quantitative assessments of low-carbon energy and industry.

The methodology is based on equations (1, 2), which give weighted average numerical indicators R, η_{COMP} of the efficiency of generating enterprises for the emission of toxic ingredients and greenhouse gases, and taking into account the energy costs that may arise during CCS.

$$\mathrm{R} = \mathrm{C_u} \cdot \eta_{COMP} = \mathrm{C_u} \cdot EER \cdot \mathrm{T_1} = \mathrm{C_u} \cdot EER \cdot (\mathrm{T_1}/\mathrm{T_2}) \cdot \mathrm{T_2}; \quad (1)$$

$$\eta_{COMP} = \frac{EER \cdot V}{\tau_0 \cdot W} \left(\frac{\sum_{i=1}^{m} (BC_i \cdot GWP_{i100}) \cdot \prod_{i=1}^{m} \left(2 - \frac{C_{iAAU}}{C_{ib}} \right)}{\sum_{i=1}^{m} (C_{iAAU} \cdot GWP_{i100})} + \frac{\sum_{j=1}^{n} \text{ПДК}_j \cdot \prod_{j=1}^{n} \left(2 - \frac{C_{je}}{C_{jb}} \right)}{\sum_{j=1}^{n} C_{je}} \right) =$$

$$= EER \left(\frac{\sum_{i=1}^{m} (BC_i \cdot GWP_{i100})}{\sum_{i=1}^{m} (C_{iAAU} \cdot GWP_{i100})} \prod_{i=1}^{m} \left(2 - \frac{C_{iAAU}}{C_{ib}} \right) + \frac{\sum_{j=1}^{n} \text{ПДК}_j}{\sum_{j=1}^{n} C_{je}} \prod_{j=1}^{n} \left(2 - \frac{C_{je}}{C_{jb}} \right) \right) \times$$

$$\times \frac{100\pi H^2}{\tau_0 \cdot W} \left\{ H + D \left[\mathrm{w_0^r} \left(1{,}239 - 0{,}147\ \mathrm{u_m^r} \right) - 0{,}514 \right] \frac{(\rho_{ar} - \rho)}{(\rho_{ar} - \rho_e)} \right\}. \quad (2)$$

In equations (1, 2):
W, m^3/s – emission intensity,
τ_0, s – time scale, s,
τ_1, $T_1 = \tau_1/\tau_0$ – time, s, and dimensionless time parameter, of filling the control volume of the expert assessment V, m^3 with greenhouse gases,
$\tau_2 = V/W_a$, $T_2 = V/(\tau_0 W_a)$ – time, s, and dimensionless time parameter, of filling the control volume of the expert assessment V, m^3 by the emission,
C_{ib}, C_{iAAU}, BC_i, GWP_{i100} – the initial and maximum permissible in terms of carbon credits, and the background concentration, mg/m^3, and the global warming potential of the i-th type of emitted greenhouse gases,
M_{AAU}, t CO_2-eq/year – permissible mass emission of greenhouse gases equal in value to the AAU (Assigned Amount Unit) carbon credits,
C_{jb} mg/m^3, C_{je} mg/m^3, MPC_j, mg/m^3 – initial, final and maximum permissible concentration of the j-th type of toxic substances in emissions,
ρ, ρ_e – density of combustion products at the outlet from the pipe, kg/m^3, calculated (at a calculated temperature t_a) and benchmarking (at the temperature $t_e = 150°C$),
ρ_{ar} – density of atmospheric air, kg/m^3,
w^r_e, u^r_m – dimensionless velocities of the jet and wind at the cross section of the pipe mouth with height H, m, and diameter D, m,
C_u – capacity utilization.

The values of w^r_e, u^r_m are obtained by scaling the real velocity of the jet exit from the pipe w_e, calculated at the reference temperature $t_e = 150°C$, and the velocity of the wind um, according to the minimum admissible (for reasons of stability of the result of a numerical experiment) jet exit velocity $w = 1$ m/s and calm speed $u_{calm} = 1$ m/s. Formula (2) is valid under the following restrictions on the speed of the jet and the wind speed: $w_0 \geq 1$ m/s; 1 m/s $< u_m <$ 7 m/s; $u_m/w_0 < 3$.

The estimated parameter *EER* was obtained from a comparison of energy costs for removing from emissions and from a reference gas mixture of CO_2 and H_2O with a decrease in their concentrations to the actual background content in an unpolluted atmosphere. An analysis of the energy consumption of possible methods for removing CO_2 and H_2O showed that it is convenient to take condensation at atmospheric pressure as a calculation method. The energy consumption $E^{dn}_{a\,H_2O} + E^{dn}_{a\,CO_2}$ for removing the heat of condensation of CO_2 and H_2O from emissions is divided to the total energy consumption E_a for cooling the emissions, taking into account the condensation of the CO_2 and H_2O contained in them:

$$EER = 1 - \frac{E^{dn}_{aH_2O} + E^{dn}_{aCO_2}}{1{,}1 E_a} \tag{3}$$

Ultimately, the *EER* parameter characterizes the efficiency of systems in terms of the type of fuel used and the method of its combustion, regardless of the performance of the systems. For facilities that use hydrocarbon gases and do not use any technologies that lead to a change in CO_2 and / or H_2O emissions (for example, steam injection into the furnace to suppress NO_x, etc.), the value of the parameter changes insignificantly and is usually within the range 0.55...0.60. The *EER* value will change significantly during the combustion of artifical gases and/or hydrogen fuel.

Dimensionless numerical indicators R and η_{COMP} allow you to numerically compare production facilities for the emission of toxic pollutants and greenhouse gases. The complex indicator of the efficiency of energy generation and cleaning of emissions η_{COMP} in the presence of greenhouse gases in them is the product of:

$$\eta_{COMP} = EER \times T_1 = EER \times (T_1/T_2) \times T_2 \tag{4}$$

The *EER* factor determined by (3) takes into account the energy costs for a hypothetical return of the atmosphere quality in order to avoid possible climate changes on a global scale. This condition is realized through the energy-ecological rating coefficient of perfection of the *EER* systems, which represents the efficiency of the systems under consideration in the form of a dimensionless energy consumption for the restoration of the quality of the environment.

The next factor (T_1/T_2), nominally represents the ratio of dimensionless times of filling the control volume of the expert assessment V, m^3 with polluting components T_1 and emission T_2. In essence, this is a weighted average ceiling norm (the maximum acceptable in terms of the requirements for limiting greenhouse gas emissions and the maximum permissible according to the hygienic standards of harmful effects):

$$\frac{T_1}{T_2} = \frac{\sum_{i=1}^{m}\left(BC_i \cdot GWP_{i100}\right)}{\sum_{i=1}^{m}\left(C_{iAAU} \cdot GWP_{i100}\right)} \prod_{i=1}^{m}\left(2 - \frac{C_{ie}}{C_{ib}}\right) + \frac{\sum_{j=1}^{n} \text{ПДК}_j}{\sum_{j=1}^{n} C_{je}} \prod_{j=1}^{n}\left(2 - \frac{C_{je}}{C_{jb}}\right) \tag{5}$$

In the first term of expression (5), as the final concentration of the greenhouse pollutant, the maximum acceptable carbon allowances concentrations C_{iAAU}, mg/m^3, of greenhouse gases emitted are used, normalized using the global warming potentials GWP_{i100} to the equivalent CO_2 emission, mg CO_2-eq/m^3, in form $\sum_{i=1}^{m}\left(C_{iAAU}\cdot GWP_{i100}\right)$.

The C_{iAAU} value is determined by M_{AAU}, t CO_2-eq/year. This is the emission ceiling (permissible mass emission) of greenhouse gases equal in value to the *AAU* (Assigned Amount Unit) carbon quota. The corresponding maximum permissible carbon emissions concentration of C_{iAAU} GWP_{i100}, mg CO_2-eq/m^3, can be approximated through the second emission consumption W of the source as 101.5 M_{AAU}/W. In the future, instead of M_{AAU}, it is necessary use the current limits on the greenhouse gases, which, apparently, will be adopted soon.

In any case, greenhouse gas control measures are intended to ensure that the existing background concentration *BC* is not exceeded by a certain amount. Therefore, to characterize the change in the quality of the atmosphere due to the emission of a greenhouse pollutant, as the concentration scale is take the sum of the background concentrations of the emitted gases B_{Ci}, which, in terms of mg CO_2-eq, has the form $\sum_{i=1}^{m}\left(BC_i\cdot GWP_{i100}\right)$. An analogue of the maximum permissible emission of MPE, here is the intensity of greenhouse gas emissions, which corresponds to the value of a carbon quota of the type AAU $W\sum_{i=1}^{n}\left(C_{iAAU}\cdot GWP_{i100}\right)$. Taking this into account, the time τ_1 for filling the control volume of the expert assessment V with greenhouse gases from zero to their background concentrations (in terms of mg CO_2-eq) will be:

$$\tau_1=\left(V\sum_{i=1}^{n}BC_i\cdot GWP_{i100}\right)\Bigg/\left(W\sum_{i=1}^{n}C_{iAAU}\cdot GWP_{i100}\right),\qquad(6)$$

and at dimensionless form:

$$\mathrm{T}_1=\left(V\sum_{i=1}^{n}BC_i\cdot GWP_{i100}\right)\Bigg/\left(\tau_0 W\sum_{i=1}^{n}C_{iAAU}\cdot GWP_{i100}\right).\qquad(6a)$$

In expressions (6, 6a), the value of the control volume of the air space around the emission source V, m^3, for expert assessment of the intensity of atmospheric pollution, is determined by the formula:

$$V = 100\pi H^2 \left\{ H + D\left[w_0^r \left(1{,}239 - 0{,}147\ u_m^r\right) - 0{,}514 \right] \frac{(\rho_{ar} - \rho)}{(\rho_{ar} - \rho_e)} \right\}. \quad (7)$$

Formula (7) was obtained on the basis of numerical experiments by the author of this article (Ziganshin & Sivkov 2016). It is a refinement to a formula similar in structure (Berlyand & Genikhovich 1971, Berlyand & Kiselev 1972), which was the basis for the first Russian normative method for dispersing pollutants OND-86, on the basis of which programs of the type UPRZA "Ecolog" and its modern improved version of the UPRZA "Eco Center" were further developed. The main refinement according to formula (7) consists in determining the effective emission height, taking into account the height of the emission plume rise above the source, which makes it possible to more accurately reflect the differences in emission sources along the height, the diameter of the mouth the pipe and by the rate of release into the atmosphere.

The proposed technique is relatively simple and fairly transparent. Calculations performed for generating enterprises (without of nuclear and hydropower) show the possibility of easy adaptation of the methodology to local conditions, for example, when working with underutilized capacities, when using hydrogen fuel and / or alternative energy sources. At present, a calculation program has been drawn up according to the proposed methodology, which is embedded in the software product for automating the activities of Russian enterprises "1C: Enterprise". Similar software are available at EU enterprises.

4. Conclusion

The versatility of the methodology proposed in this paper allows joint to ISO 50001, complementing the local results of the enterprise with a universal rating on greenhouse gases, showing true achievements in the direction of low-carbon. According to the ratings of enterprises, the rating of the region is easily assembled, and according to it – the national rating. The practice of collecting data according to this scheme has been tested around the world with ozone-depleting and greenhouse gases, and it works well. But today there are no methods with the ability to generalize results at all levels of activity – local (enterprise or region), national (state or region) and global. For example, for one of the most powerful COMBI systems, it is possible to obtain data only for regions and EU countries based on long-term forecasts for EU countries. Therefore, in the COMBI system, it is fundamentally impossible to work with enterprises, and, therefore, it is impossible to work with ISO 50001. The method proposed in this work provides transparent numerical criteria that allow you to correctly determine the low-carbon of the breakthrough technology and compare them with traditional ones, providing reliable tools for monitoring the achievement of low-carbon by enterprises, regions and states.

References

Berlyand, M.E., Genikhovich, E.L. (1971). Atmospheric diffusion and air flow structure over a heterogeneous underlying surface. // Meteorological aspects of atmospheric pollution – L.: *Gidrometizdat*, 49-69.

Berlyand, M.E., Kiselev, V.B. (1972). On the influence of relief on the distribution of impurities taking into account their initial rise. *Meteorology and Hydrology, 3*, 3-10.

Communiqué (2014) by the G20 Leaders following the 2014 Brisbane Summit (Australia) http://news.kremlin.ru/media/events/files/41d51ac333c6c9b83233.pdf

Multiple Impacts (2020) of Energy Efficiency. Horizon-2020 project COMBI presents results. Press Releases 05/18/2018 https://wupperinst.org/en/a/wi/a/s/ad/4331

Rubino, M., Etheridge, D.M., et al. (2019). Revised records of atmospheric trace gases CO_2, CH_4, N_2O, and $\delta^{13}C\text{-}CO_2$ over the last 2000 years from Law Dome, Antarctica. *Earth System Science Data, 11*(2), 473-492, DOI: https://doi.org/10.5194/essd-11-473-2019

U.S.-China (2021) Joint Statement Addressing the Climate Crisis https://www.state.gov/u-s-china-joint-statement-addressing-the-climate-crisis/

WMO Greenhouse Gas Bulletin (2019) (GHG Bulletin) – No. 15: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2018 https://library.wmo.int/index.php?lvl=notice_display&id=21620#.YMNdwuAza70

Ziganshin, M.G. (2019). Method of assessment generation efficiency at thermal power plants taking into account emissions of pollutants. *Power engineering: research, equipment, technology*, *21*(6), 29-38. DOI: https://doi.org/10.30724/1998-9903-2019-21-6-29-38

Ziganshin, M.G. & Sivkov, A.L. (2016). The system of rating assessment of the activities of organizations on the basis of "low-carbon". *Reliability and safety of energy, 4*(35), 7-11. In: https://www.sigma08.ru/jour/article/view/135/136

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Changing Energy and Exergy Comfort Level after School Thermomodernization

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Abstract: Increasing the level of thermal resistance of the building envelope in combination with the choice of heat source is an urgent task. It is important to take into account changes in the cost of energy over time. Thermal modernization, in its turn, allows to increase the level of thermal comfort, which is not taken into account and evaluated in practice, although the relevant standards for comfort conditions and categories of buildings to ensure comfort have been introduced in Ukraine. This paper analyzes the change in the level of comfort after thermal modernization, determines the category of the building to provide comfortable conditions, as well as identifies the change in the average radiation temperature of the fences, as one of the main factors of PMV change in these conditions.

Keywords: energy need, PMV, mean radiant temperature, comfort temperature, thermomodernization

1. Introduction

Improvement of the energy efficiency in buildings is an important and complex public task. Particular attention should be paid to increasing the energy efficiency of public buildings, the level of thermal comfort, which is regulated by the relevant requirements (Zare et al. 2018) and is widely covered in recent studies

(Deshko et al. 2020, Deshko et al. 2016, Hurnik et al. 2017, Dylewski et al. 2012). In addition, the human factor is taken into account by determining the level of use and the degree of occupancy of the building (Rodrigues et al. 2017), which creates the need to consider economic, environmental (Javid et al. 2019), energy and social factors in assessing and making decisions during thermal modernization of the building. Starting from the end of 2020, all new buildings should be highly energy efficient after thermal modernization (Moran et al. 2020). Similarly, this requirement is relevant for all public buildings from the end of 2018. In order to determine the energy performance requirements of buildings for nZEB, the EU countries had to use a cost-optimal methodological framework to assess cost-effective minimum energy consumption levels of building / building elements / building materials performance requirements (Moran et al. 2020).

This methodological system estimates the total costs (or life cycle costs) of buildings / building elements / building materials and their corresponding impact on primary operating energy needs for heating, cooling, ventilation, hot water, and lighting systems.

It is clear that thermal modernization can increase the energy performance and energy efficiency of existing buildings and reduce their energy demand. However, its effect on the level of thermal comfort has only recently been studied (Park et al. 2020). The application of modern economic approaches will reveal the economic potential of thermal modernization in the construction stock, and the use of modern models of thermal comfort will assess the impact and opportunities to increase the level of thermal comfort. Modern economic approaches have been developed to show the example of Sweden's economic potential for thermal modernization in the housing stock using 3 main methods, namely: 1) full investment costs and energy savings (complete approach), 2) approach that takes into account the cost of improvements related to energy efficiency and energy saving (respectively) and 3) an approach that corresponds to the approach of improvement, but additionally assigns a residual value to each building element (reduction approach) (Streicher et al. 2020).

A building is a complex energy system. And the issues of energy consumption are investigated starting from the heat source and ending with enclosing structures, however, the requirements for thermal comfort are set by a human, which is reflected in the following works (Dovjak et al. 2015, Deshko et al. 2020, Deshko et al. 2016). Thermal comfort models that are developed by Fanger (Fanger 1973) formed the basis of the ISO 7730 standard. They are based on energy balance for the human body. An exergetic approach is being developed not only to assess the destruction of exergy in enclosures (Choi et al. 2020), but also to determine the exergy spent on the mechanism of human thermoregulation (Dovjak et al. 2015, Prek & Butala 2017, Shukuya 2018, Deshko et al. 2019). The possibilities of adaptation of the human body to environmental conditions is generalized by adaptive models and relevant studies that also reflect the importance of environmental conditions (Dinesh et al. 2021, de Dear et al. 2020, Vellei et al. 2017, Rijal et al. 2020, Hellwig et al. 2019). The most recent studies (Sayadi 2020) that evaluated the thermal modernization of buildings show that it is necessary to take a comprehensive approach to the system as a whole to improve the energy efficiency of the building. Given the growing demands for thermal comfort, it is necessary to take into account both the social aspects (PMV and exergy consumption of human body) and the application of life cycle analysis of the building. The purpose of the study is to analyze the impact of thermal modernization on the level of human energy and exergy thermal comfort and economic assessment of changes in the heat source in combination with fences.

2. Materials and methods

The choice of heat source in combination with fences is carried out using the method of cash flow, which allows to take into account the change in the cost of energy and money over time:

$$B = \sum_{\tau=0}^{n} \frac{B_\tau^{\mathrm{ot}}}{(1+E)^\tau} + \sum_{\tau=0}^{n} \frac{B_\tau^{en}(1+l \cdot \tau)}{(1+E)^\tau}) + I_0 + I_{\mathrm{iz}} + I_{\mathrm{ha}} \tag{1}$$

where:
B_τ^{en} – annual energy costs, UAH,
B_τ^{ot} – other costs, UAH,
I_0 – capital costs for the purchase of heat generating equipment, UAH,
I_{iz} – costs aimed at improving the thermal protection of the building, UAH,
I_{ha} – the cost of purchasing heating appliances, UAH,
l – coefficient that takes into account the increase in energy prices,
n – time for which the integrated discounted costs are determined, years,
E – discount rate, selected according to the level of inflation, type of financing,
B – net present value of costs.

Function B is also called the integral value function of the system – it is the net present value of costs. This function allows you to take into account the change in the cost over time of energy l, take into account the discounting with E and take into account the efficiency of the heating system ε. The discount rate is chosen according to the interest rate on bank deposits.

The level of thermal comfort is based on the Fanger method, which is presented in the ISO 7730 standard and which is based on the equations of human heat balance:

$$PMV = (0.303 \cdot e^{-2.1 \cdot M} + 0.028) \times [(M - W) - H - E_c - C_{res} - E_{res}] \tag{2}$$

where:
M – metabolism level, W/m^2,
W – effective mechanical work, W/m^2,
H – sensitive heat losses, W/m^2,
E_c – heat transfer by evaporation from the skin, W/m^2,
C_{res} – heat transfer by convection, during respiration, W/m^2,
E_{res} – heat exchange by evaporation during respiration, W/m^2.

The Fanger model, namely the PMV index, is based on a large number of experiments, but it does not take into account the mechanism of thermoregulation, which has a rather large influence in the calculations of human heat transfer. It also helps to assess the acceptability of environmental conditions to ensure the thermal comfort for a human. The exergy approach to creating comfortable conditions is to determine the value of human body exergy consumption (HBExC). HBExC is calculated according to the approach proposed by M. Shukuya (Shukuya 2018). Finding the minimum consumption of exergy and the corresponding value of indoor air temperature will ensure that the indoor air temperature at which the thermoregulatory mechanisms will be activated the least, and therefore the body will work in the best conditions. Therefore, this algorithm is presented in the paper.

3. Description of the research model

The object of this study is a specialized school №64, Kyiv, built in 1973. The average heat transfer coefficient of the walls significantly exceeds the normative heat transfer coefficient U = 0.3 $W/m^2 \cdot K$ and equals U = 1.3 $W/m^2 \cdot K$. The total wall area is 2814 m^2. We suggest to insulate the external walls. Additional thermal insulation will reduce excessive heat loss through the walls and improve the appearance of the building. For the insulation material we choose mineral wool boards, 0.2 m thick and 30 kg/m^3 thick. The average heat transfer coefficient of the windows of the building exceeds the estimated standard heat transfer coefficient U = 1.33 $W/m^2 \cdot K$ and equals U = 2.05 $W/m^2 \cdot K$. The total window area is 1251.53 m^2. It is suggested to replace existing metal-plastic windows with double-glazed windows with energy-efficient spraying. The average heat transfer coefficient of the roof significantly exceeds the standard heat transfer coefficient U = 0.2 $W/m^2 \cdot K$ and equals U = 0.58 $W/m^2 \cdot K$. The total roof area is 2251 m^2. Modeling of changes in the level of thermal comfort before and after thermal modernization is possible under the room model and due to the determination of the average radiation temperature. The object of the study was a typical study room located on the second floor of the building in block B, size 10×10 m with three window openings, size 2.05×2.1 m. The model of the study room is shown in Fig. 1. The glazing ratio is 0.3. This model was created in the software product sketchUp and all engineering systems were added, namely, the simulation was performed by EnergyPlus software. Table 1 shows the basic characteristics of the research model and Table 2 presents the characteristics of the internal and external environment.

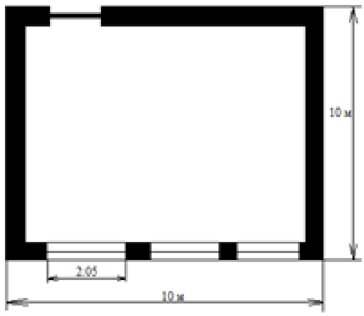


Fig. 1. Room model

Table 1. Basic Characteristics of the Research Model

External Wall Area F_z, m^2	17.4
Window Area F_v, m^2	12.6
Thermal resistance of the outer wall R_z, $m^2 \cdot °C/W$	0.77
Thermal resistance of the window R_v, $m^2 \cdot °C/W$	0.40
Air exchange n, hr^{-1}	1.0

Table 2. Characteristics of internal and external environment

Outside Temperature T_0, K	273
Relative Environment Humidity φ_0, %	78
Relative Room Humidity, φ_v, %	50
Air Pressure, Pa	101325
The average power of solar radiation on a vertical surface W/m^2	30

Also, the metabolic rate was 70 W/m^2, because in this room the main activity is sedentary work, which is typical for educational institutions and the thermal resistance of typical clothing combinations, respectively, is 0.155 $m^2 \cdot K/W$ (Zare et al. 2018).

4. Results and discussion

4.1. Cash flows for the system before and after thermal modernization

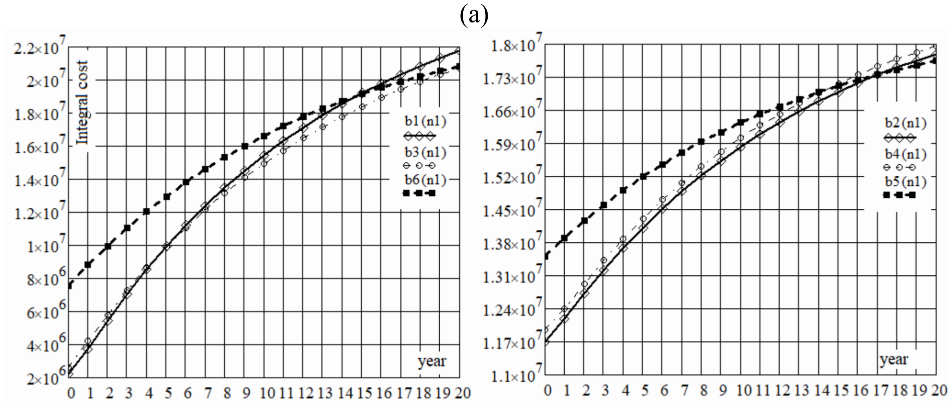
As a result of complex thermal modernization of the building, the percentage difference of the calculated value of specific energy consumption, EP, from the maximum allowable value, EPmax is 20%. The energy efficiency class after thermal modernization, established by the ratio corresponds to the class – "B" and before – class “E”. The increasing of thermal resistance of the walls will be considered in conjunction with a change in the source of heat supply. Currently, the appropriate microclimate in the room is created through the use of a centralized heating system. As an alternative, one can choose autonomous gas heating, a system with a heat pump installation. Table 3 shows the change in the cost of energy over time through the use of appropriate coefficients, considering the cash flows for the selected alternatives before and after thermal modernization. An optimistic and average statistical forecast will be considered.

Table 3. Possible scenarios of energy price changes

l, %	Gas	Electric
Optimistic	0	0
Medium	15	8

The results of cash flow calculations for the system before and after thermal modernization are presented in Fig. 2. Cash flow graphs, as integrated discounted costs, when using district heating, gas boilers and heat pump before and after complex thermal modernization (Figure 2a) will determine the complex payback period of the proposed alternatives compared to the existing option.

(a)



(b)

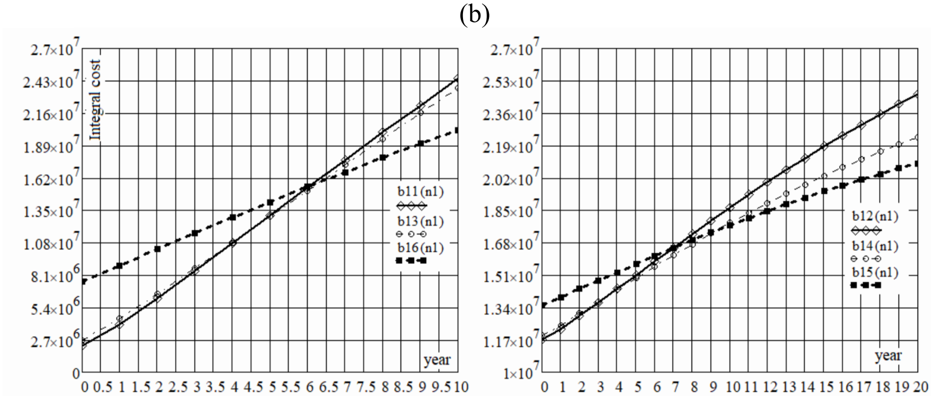


Fig. 2. Cash flows for the system before and after thermal modernization:

b1, b2, b3, b4 ,b5, b6 – integrated discounted costs with the use of central heating before and after thermal modernization, gas boiler before and after thermal modernization and heat pump after and before thermal modernization, UAH;
b11, b12, b13, b14, b15, b16 – integrated discounted costs, using district heating before and after thermal modernization, gas boiler before and after thermal modernization and heat pump after and before thermal modernization, taking into account the changes in energy costs over time, UAH.

Therefore, according to Fig. 2, the complex payback period is defined as the intersection of one heat source with another. Figure 2 presents the impact of the energy cost changes. When we do not take into account changes in the cost of energy, this leads to higher costs and longer payback periods than when we take into account this indicator. Significant changes in the discounted payback periods indicate that the change in the cost of energy over time plays a significant role and must be taken into account. In conclusion, after a comprehensive thermal modernization, it would be appropriate to change the source of the heating system, which will lead to greater savings and faster payback. Hence, comparing Figures 2a and 2b, we can conclude that the change in the cost of energy over time affects the payback period. Taking into account the growth rate of energy prices, the discounted payback period is reduced by almost 2 times.

4.2. Influence of thermal modernization on the level of thermal comfort

Currently, the world is wondering how to achieve efficient energy use and not to reduce the thermal comfort of buildings. Hence, this issue is so important and requires a comprehensive approach to its solution.

The simulation was performed for a typical room located on the south and north sides. The next step was to insulate the walls, roof and replace the old windows with new energy efficient ones. It is proposed to replace window constructions with double-glazed windows with selective coating. After that, re-simulation was performed. The calculation of thermal comfort indicators for the variable hourly average radiation temperature during the before and after thermal modernization for the North and South walls was carried out in Mathcad. The PMV values for the heating period are shown in Figure 3. PMV varies from -0.7 in the cold months to 0.2 in the off-season. Changes in the thermal resistance of the barriers can increase the PMV, and, therefore, improve human heat by about 0.1. The S orientation wall is characterized by larger fluctuations of PMV, which is due to the inflow of solar radiation and as a consequence of the increase in the variation of the room radiant temperature.

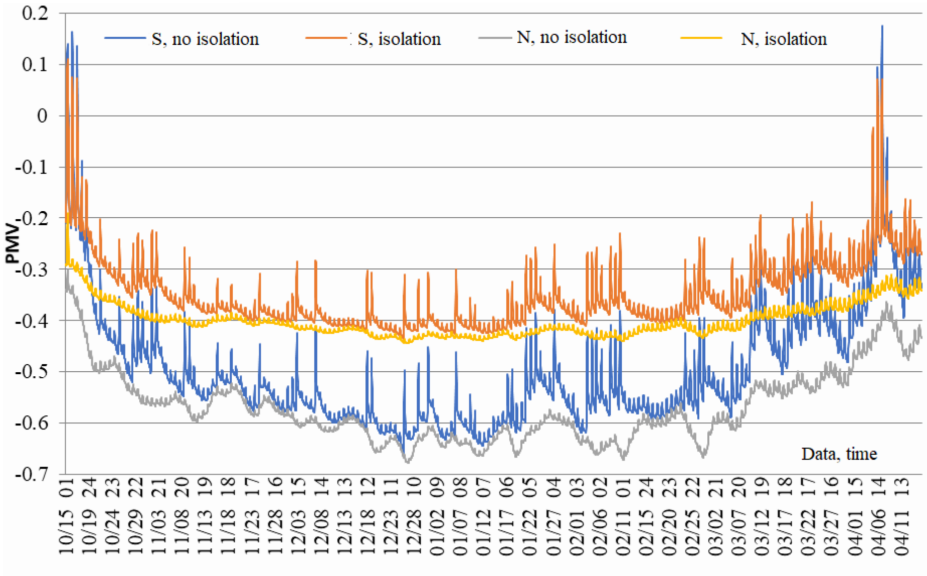
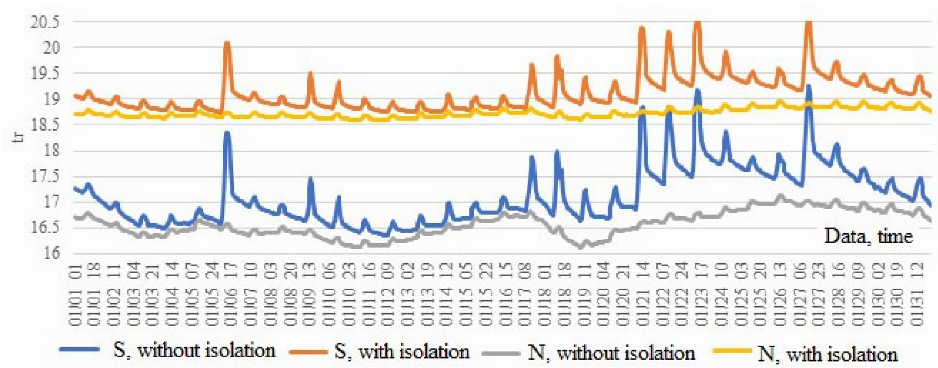


Fig. 3. PMV value for the heating period

Figure 4 shows the change in the average radiation temperature for January (a) and March (b), before and after thermal modernization for the wall of North and South orientation. It is established that the increase of the thermal resistance of enclosing structures allows to increase the average radiation temperature of the room by an average of 2°C. The southern orientation of the wall provides an increase in the average radiation temperature to 1.4°C compared to the Northern. This increase in the average radiation temperature will reduce the temperature in the room without reducing the level of thermal comfort.

Also, the EnergyPlus software calculated energy consumption of this room on the south and north orientation before and after insulation. Energy consumption for Southern orientation after insulation decreased by 32%, and for Northern – by 30%, which indicates the appropriateness of insulation of the building. According to DSTU B EN 15251:2011, different categories of the internal environment are established based on different criteria for PMV and PPD, which are defined respectively (Zare et al. 2018). This research concludes that this building has a third category of comfort, i.e., an acceptable average level of expectations can be used for existing buildings, but for a comfortable living, and, especially, for teaching children, this is not enough. Therefore, this work suggests to conduct a comprehensive thermal modernization of the building, and our research also shows how it was possible to bring this building to the II category of comfort – this is a normal level of expectations to be met for new buildings and renovations.

(a)



(b)

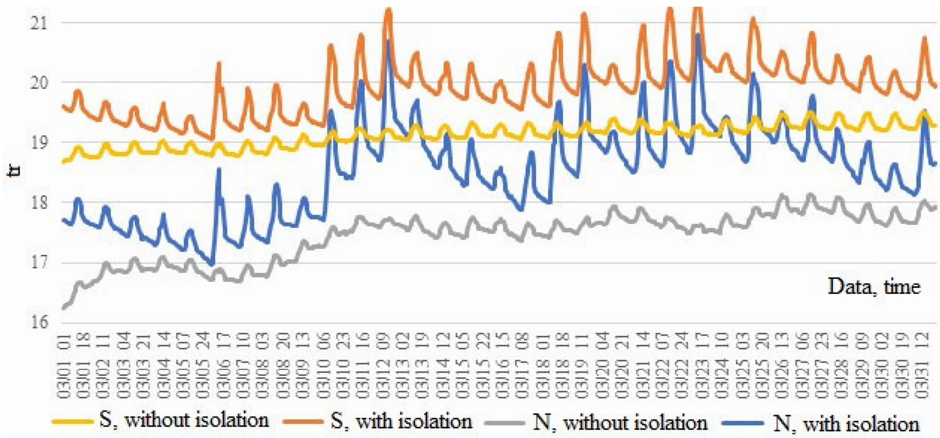


Fig. 4. Changes in the mean radiant temperature in january (a) and march (b)

4.3. Human body exergy consumption

The human body exergy consumption (HBExC) was determined for the average, maximum and ambient temperature. In Fig. 5 the value of exergy consumption by the human body for a room with an external wall of N and S of orientation before and after thermal modernization is presented. The corresponding PMV and HBExC values are also plotted. The trends in PMV change are the same as for HBExC. For the selected model HBExC varies from 3.43 to 3.97 W/m^2. Finding the minimum of this function indicates the conditions when the consumption of exergy on the thermoregulatory mechanism is minimal. However, the lowest HBExC values do not correspond to the PMV values which are the closest to 0.

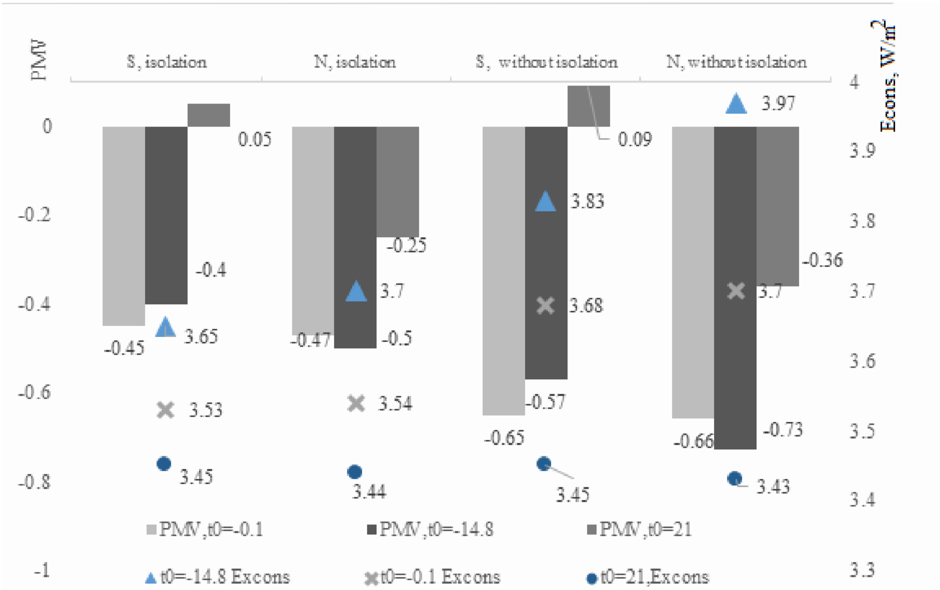


Fig. 5. Change of HBExC, PMV in winter for southern (a) and northern orientation (b) for main temperature point

5. Conclusions and further study

The paper presents a method of choosing a heat source on the example of the school, under different scenarios of changes in energy costs over time. In addition, the dynamic aspect of comfort conditions indicates a change in building category and the possibility of using energy-saving modes. PMV has been found to vary from -0.7 in the cold months to 0.2 in the off-season. Changing the thermal resistance of the barriers can increase the PMV, and, therefore, improve human heat by about 0.1. The wall of the S orientation is characterized by larger fluctuations of PMV, which is due to the inflow of solar radiation and as a consequence of the increase in variation of the room radiant temperature. Based on the calculation of PMV, it is established that this building has a category of comfort III – this is an acceptable average level of expectations to be used for existing buildings, but for a comfortable stay, and, especially for teaching children, this is not enough. Therefore, this paper proposes to carry out a comprehensive thermal modernization of the building, to achieve the second category of comfort-a normal level of expectations to be met for new buildings and renovations. Therefore, in this paper it was proposed to conduct a comprehensive thermal modernization of the building, due to which the category of the building changed to the second category of comfort – this is a normal level of expectations to be met for new buildings and renovations.

References

Choi, Wonjun, Ryozo, Ooka & Masanori Shukuya. (2020). Unsteady-state exergetic performance comparison of externally and internally insulated building envelopes. *International Journal of Heat and Mass Transfer, 163*: 120414.

de Dear, R., et al. (2020). A review of adaptive thermal comfort research since 1998. *Energy and Buildings, 214,* 109893. DOI: 10.1016/j.en-build.2020.109893

Deshko, V., & Buyak, N. (2016). A model of human thermal comfort for analysing the energy performance of buildings. *Eastern European Journal of Advanced Technology, 4*(8), 42-48.

Deshko, V., Buyak, N. &Voloshchuk, V. (2019). *Reference state for the evaluation of energy efficiency of the system "heat source-human-building envelope"*. ECOS 2019-Proceedings of the 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. 2287-2300.

Deshko, Valerii, Bilous, Inna, Buyak, Nadia & Shevchenko, Olena (2020). *The Impact of Energy-Efficient Heating Modes on Human Body Exergy Consumption in Public Buildings*. IEEE 7th International Conference on Energy Smart Systems (ESS), 201-205. DOI: 10.1109/ess50319.2020.9160270

Dinesh, Kumar Shahi, Hom Bahadur, Rijal, Genku, Kayo & Masanori, Shukuya. (2021) Study on wintry comfort temperature and thermal improvement of houses in cold, temperate, and subtropical regions of Nepal. *Building and Environment, 191*(3). 107569.

Dovjak, M., Shukuya, M. & Krainer, A. (2015). Connective thinking of building envelope – Human body exergy analysis. *International Journal of Heat and Mass transfer, 90*, 1015-1025. DOI: 10.1016/j.ijheat-masstransfer.2015.07.021.

Dylewski, R. Adamczyk, J. (2012). Economic and ecological indicators for thermal insulating building investments. *Energy and Buildings, 54*, 88-95. DOI: 10. 1016/j.enbuild.2012.07.021.

Fanger, P. (1973). Assessment of man's thermal comfort in practice. *British Journal of Industrial Medicine, 30*, 313-324.

Hellwig, Runa T., et al. (2019). A framework for adopting adaptive thermal comfort principles in design and operation of buildings. *Energy and Buildings, 205,* 109476. DOI: 10.1016/j.enbuild.2019.109476

Hurnik, M., Specjal, A., Popiolek, Z. & Kierat, W. (2017). Assessment of single-family house thermal renovation based on comprehensive on-site diagnostics. *Energy and Buildings, 8*, 378-400. DOI:10.1016/j.enbuild.2017.09.069

Javid, Atiye Soleimani, Aramoun, Fereshteh, Bararzadeh, Masoomeh & Avami, Akram (2019). Multi objective planning for sustainable retrofit of educational buildings. *Journal of Building Engineering*. DOI: 10.1016/j.jo-be.2019.100759.

Moran, Paul, O'Connell, John & Goggins, Jamie. (2020), Sustainable energy efficiency retrofits as residenial buildings move towards nearly zero energy building (NZEB) standards. *Energy and Buildings*. DOI: 10.1016/j.en-build.2020.109816 .

Park, Ji Hun, Yun, Beom Yeol, Chang, Seong Jin, Wi, Seunghwan, Jeon, Jisoo & Kim, Sumin. (2020). Impact of a passive retrofit shading system on educational building to improve thermal comfort and energy consumption. *Energy and Buildings*. DOI: 10.1016/j.enbuild.2020.109930.

Prek, Matjaž, Butala, Vincenc. (2017). Comparison between Fanger's thermal comfort model and human exergy loss. *Energy, 138*, 228-237. DOI: 10.1016/j.energy.2017.07.045

Rijal, Hom B., Yoshida, K., Humphreys, M.A. & Nicol, J.F. (2020). Development of an adaptive thermal comfort model for energy-saving building design in Japan. *Architectural Science Review*, 1-14. DOI: 10.1080/00038628.2020.1747045.

Rodrigues, Carla, Freire, Fausto. (2017). Building retrofit addressing occupancy: An integrated cost and environmental life-cycle analysis. *Energy and Buildings, 140*, 388-398. DOI: 10.1016/j.en-build.2017.01.084.

Sayadi, S. (2020). Dynamic Exergy-Based Methods for Improving the Operation of Building Energy Systems.

Shukuya, M. (2018). *Exergetic aspect of human thermal comfort and adaptation*. Sustainable Houses and Living in the Hot-Humid Climates of Asia. Springer, Singapore, 123-129.

Streicher, Kai Nino, Mennel, Stefan, Chambers, Jonathan, Parra, David, Patel & Martin K. (2020). Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches. *Energy and Buildings*, 109870. DOI: 10.1016/j.en-build.2020.109870.

Vellei, M., Herrera, M., Fosas, D., Natarajan, S. (2017). The influence of relative humidity on adaptive thermal comfort. *Building and Environment, 124*. 171-185. DOI: 10.1016/j.buildenv.2017.08.005

Zare, S., Hasheminezhad, N., Sarebanzadeh, K., Zolala, F., Hemmatjo, R., & Hassanvand, D. (2018). Assessing thermal comfort in tourist attractions through objective and subjective procedures based on ISO 7730 standard: A field study. *Urban climate, 26*, 1-9.

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Neuromodel of the "Crusher mill" Mechatronic Complex

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Abstract: To create a mechatron model of vacuum tube vibration system for rock cutting by flat auger tools based on physical and mechanical properties of processed array and kinematic characteristics of the instrument. The analytical model of the fracture process of rock cutting by tool vibration with considering of plastic properties of the massif were developed. The main technological parameters of massif vibrating cutting with normal variations were modeled: dependences of normal and tangential pressure in the zone of working body interaction with the medium, normal and shear stresses in the zone of destruction, rock characteristics of the medium, vibration parameters dependences on the characteristics of mechatronic system geometry of the contact area of flat incisors treated with medium. The choice of the computational model of the vibration rock cutting with the normal to the direction of movement of the working body fluctuations with considering arising from processes at once or disorders: the occurrence of compressive and tensile stresses were backgrounded. Main stages and interconnection options in the simulation of vibration cutting were established. Scientific novelty lies in the development of a method of analysis of contact interaction of roller working body molding machine with an array taking into account the changes in the stabilization process of physical and mechanical properties of the treated medium, the aim of which is to predict the required voltage and depth of the formed layer. The theoretical basis of rock cutting by flat auger tool taking into account the normal component of the vibration with respect to the movement direction allowing for the deformation of the rock mass and the contact interaction with the working body were established, that allows to improve the technology of drilling wells by reducing the power consumption of the cutting process. The results enable us to determine the parameters of power and kinematic conditions for the occurrence of the vibration cutting.

Keywords: mechatrone vibration system, massif, cutting

1. Introduction

The technology of crushing and grinding rocks is one of the most energy intensive technologies. Effective management of crushing and grinding is possible with the most complete mathematical model of the situation. Studies show that the work of crushing and grinding complex is determined by dozens of factors, many of which are random. Each combination corresponds to a specific techno-power mode of operation. The more fully taken into account in the operational management factors and system properties that affect the characteristics of the mode, the more effective it management and lower the energy consumption of the processes of crushing and grinding. The increase in the number of considered factors complicates the model, so it is necessary to form the control action, finding a compromise solution that takes into account the degree of informativeness of the factor field and its complexity. It is necessary to solve a number of tasks such as: analysis of operation modes of the equipment of grinding to determine the parameters, which correspond to different operation modes; development of a multicriterial model of optimal technological parameters of equipment of the crushing and grinding complex subject of power consumption, productivity and quality of grinding; development of the model of crushing and grinding complex, which could provide optimal power consumption management of crushing and grinding complex.

2. Literature review

The simulation of crushing and grinding complex is used to optimize its energy consumption. This particular task contains a number of subtasks such as: description of kinematics and dynamics of internal processes, the establishment of energy intensive of processes of destruction of rocks, the construction of control systems for crushing and grinding complex. The analysis of works in the field of simulation of the grinding aggregates and management highlights the following researchers (Meyta 2010).

The most famous equation that establishes a relationship between the energy expended and the fineness of the product resulting from grinding are equations of Rittinger, Kick-Kirpichev, Bond. Comparison of the curves constructed according to the laws of Rittinger, Kick-Kirpichev, Bond, showed that the law of Rittinger can be applied in the case of high specific power consumption regardless of the size of the grains, the law of the bond – in a significant range of intermediate values of the specific energy consumption, the law Kick-Kirpichev - at low specific power consumption. Based on the works of Andreev, Davis, Perov, Tovarov, Olevskii, Kantorovich established that the greatest power consumption characterizes, however, and most work of grinding. Knowing the useful power consumed by the mill and taking into account losses occur in all elements of the system can provide a complete energy picture of the mill as a control object, thereby providing the possibility of its rational exploitation, in terms of energy consumption.

Automatic control of operation of the mills, the variables determining them, the construction of control systems for crushing aggregates considered in the works of Nazarenko V. M., Uteus Z. V., Uteus E. V., Gelfand J. E. and Ginzburg, I. B.

The use of modern CAE-systems for optimizing of parameters of mechatronic systems and complexes, investigated the Pivnyak G.G., Samus V.I., Kirichenko O.E., Kirichenko V.E. (Kyrychenko 2014, Samusya 2015, Pivniak 2014).

The principles of operation and options for the use of ANN were considered by the authors Haykin, Titterington, Picton, Dreyfus (Haykin,1999, Titterington 2009, Picton 2000, Dreyfus 2005).

3. Presentment of the basic material

Technological processes are the basis of many industries and virtually all industries. This process involves primary environment and additionally enter components used physico-chemical, mechanical or hydro-mechanical effects, which are inside of the workspaces of the devices to obtain the final products. Technological processes in grinding equipment belong to the group of mechanical processes that determines the regularities of the processes that are common to the group. Crushing and grinding stands out as a separate subgroup, which characterizes the specifics of the processes and their characteristics.

The technology of crushing and grinding is one of the largest and most energy intensive, therefore costly operations. In concentrating factories and production of building materials, crushing and grinding operations account for up to 50-70% of the total capital expenditure and the same share of total operating costs. The ways to solve the problem of optimal energy consumption of crushing grinding complexes can be further improvement of the grinding and crushing, the use of the most efficient and economical methods of grinding, the simplification of the scheme of layout of crushing plants.

One of the ways to ensure rational operating modes of technological mechanisms of crushing and sorting factories is the use of adaptive control systems, which relate to robotic systems, the element base of which is microprocessor technology. To operate the process control system, the technological process requires mathematical support, which adequately describes the technological processes and the operation of certain types of equipment participating in them. In choosing the mathematical description of technological processes, it is necessary to take into account the regular connections that are repeated in time, and random ones, caused by the variability of process parameters.

The task of constructing an automated control system for simplification can be divided into a number of sub-tasks such as:

1. The definition of the factor of the field system and the allocation of the main factors.
2. Establishment of regularities of changing factors.
3. Identify the relationships between dependent variables.
4. Identification of the current state of the object (nominal, pre-emergency, emergency, ineffective mode).
5. Prediction of the state of the managed object based on its current state.
6. Formation of the control action depending on the available data on the system and their projected values.

As an example, the technological process of production of silicate bricks in the construction industry enterprises is considered, which is a sequence of the following operations:

- delivery of raw materials for making bricks (lime and sand);
- lime burning;
- transportation of burned lime with a conveyor belt to the feed hopper of the crusher;
- crushing of lime in hammer crushers up to size 1 mm;
- transportation of the crushed product by pneumatic transport to the mill feed hopper;
- grinding in the ball mill of cooked lime and sand (binder preparation);
- transportation of ready-made binder by pneumatic transport to a molding shop for manufacturing bricks from prepared raw materials;
- warehousing of finished products.

At each stage of the technology, the physical state of the substance changes at a certain energy expenditure. Changes in the physical state can be both positive (necessary for technology changes, such as reducing the size of the material, giving the necessary properties of lime by burning it, forming the finished product) and negative (re-grinding of the substance, undesirable change in humidity, loss during transport). Regardless of whether a technologically useful or harmful effect occurs, the amount of energy consumed during the transition from one stage to another is constantly increasing, therefore, in order to ensure rational energy-efficient management of the complex, it is necessary to take into account how energy-intensive each stage of production is and how much this energy expenditure is justified. At the same time, for each stage it is necessary to identify the factors determining its energy consumption and those indicators by which its energy state can be estimated.

From the given technological chain of greatest interest are the factor fields of the crusher and mill, as the key objects of the complex.

Research carried out at concentrating plants and enterprises for the production of building materials have made it possible to identify a number of factors that have the most significant effect on the nature of the power consumed. These factors include the magnitude of the ball load, the mill speed and the productivity of the grinding unit. The mode of operation of the mill and the amount of power consumption depend not only on the factors listed, but also on the magnitude of the frictional force between the inner surface of the drum (lining and ball loading) and the type of lining. For the electric drive of such a mill, it is characteristic that the power consumption depends little on the productivity, that is, the specific costs of producing the binder are significantly reduced with increasing productivity.

In the practice of grinding a substance has the following properties density, strength, abrasiveness, moisture content, flowability, lumpiness, specific surface area of mineral raw materials crushability and grindability. The researches have shown, that the specific expenses of the electric power on binder production essentially change depending on the above mentioned factors (up to 30%). The change in the fineness of the grinding occurs intensively at the beginning of the mill, at a time when there are practically no changes at the last meters, which indicates an inefficient grinding of the material.

In addition to the physical properties of matter, there are a number of technological variables that determine the operation of grinding aggregates. These include fineness of grinding; number of grinding media; the size of grinding bodies; the presence of inter-chamber partitions; state of armor; intensity of aspiration; resistance of the material to grinding; introduction of an intensifier of the grinding process. The factorial field of the ball mill can be represented by the Ishikawa diagram (Fig. 1) (Meyta 2016). The main positions in the diagram are assigned to four groups of factors that determine the technological process. The breakdown and sorting of factors within each group makes it easier to assess the impact of a factor.

Based on the above data, it is possible to construct a neural network to control the crushing and grinding complex. The controlled parameters act as the output vector, and the corresponding values of the regulated quantities, the parameters of the equipment and the crushed material are the input vector (Table 1).

In the generalized model, the selected factors will be used as inputs, and as output values, the process parameters or those control actions that will regulate them. A similar network is shown in Fig. 2 The mathematical model describes a real object with some approximation. The degree of correspondence of the description to the real process is determined, first of all, by the completeness of the calculation of disturbing influences. In the absence or insignificance of disturbances, it is possible to unambiguously determine the influence of the input and control parameters on the output.

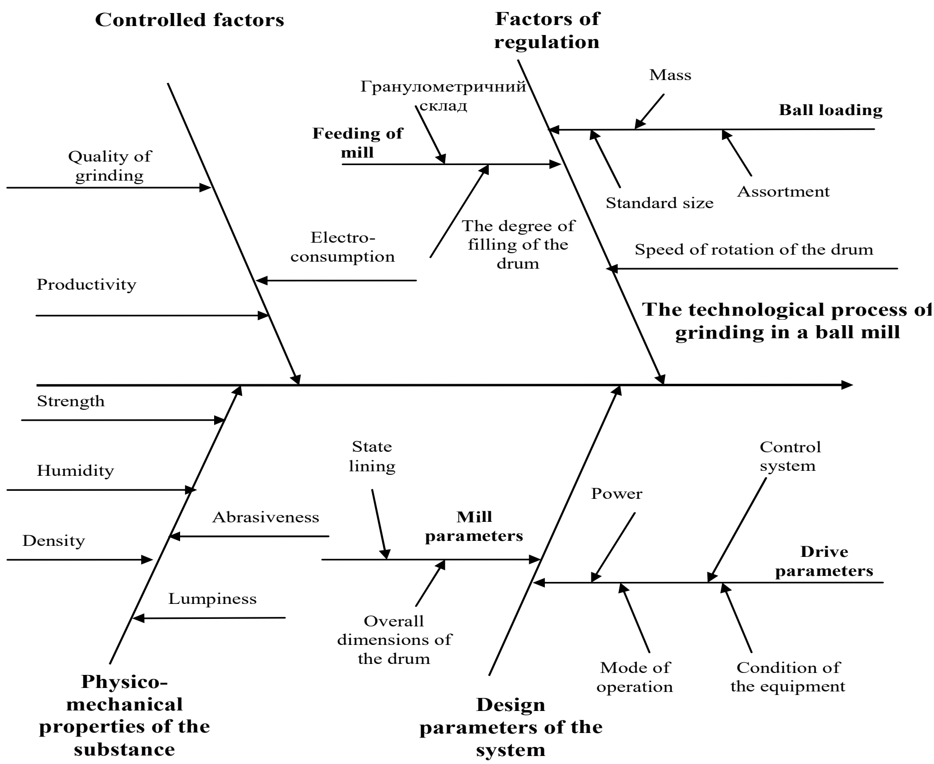

Fig. 1. Factor field of a ball mill

Table 1. The main groups of the factor field of crushing and grinding equipment

Output Vector	Vector of input measurable control variables	Vector of input measured uncontrolled variables	Vector of input non-measurable variables
Electroconsumption (W), productivity (Q), quality of grinding (T)	Ball and raw materials, rotational speed (n) of the working body	Physical and mechanical properties of incoming raw materials	Condition and operating conditions of equipment (lining, balls, drive)

An objective model of the grinding object can be created under the condition of good awareness of the properties of the object under study, the main groups of which are represented in the factor field.

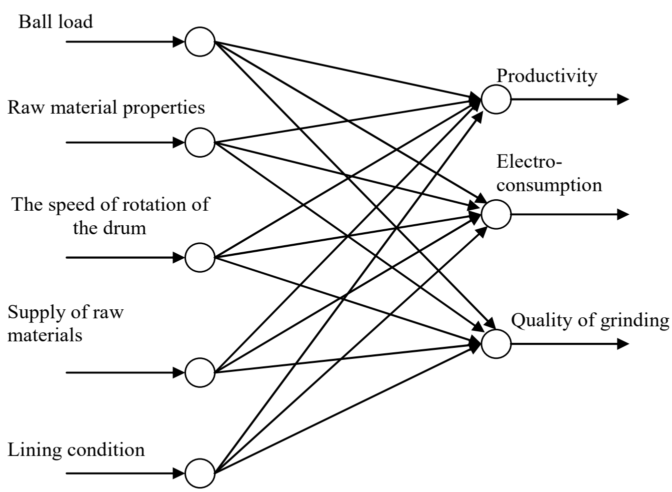

Fig. 2. The grinding control model

According to the degree of completeness of information about real objects and processes occurring within them, we can distinguish:

- objects with a zero level of information; in this case the object is represented as a "black box", its mathematical model is constructed by statistical tests of a real object on the basis of regression, dispersion and correlation analysis and factorial design of the experiment;
- objects whose behavior has empirical information; when creating models of such objects, physical modeling methods are used; a complete closed model is obtained by methods of experiment planning;

- objects with known basic deterministic regularities; their models are formulated by methods of mathematical modeling; deterministic dependencies are partially complemented by empirical relationships, the values of constants are established from experience.

The objects of the crushing and grinding complex belong to the first group. The power consumed by the mill depends on its load and the speed of rotation, so the mill's power consumption model can be represented in the form of two interacting components: the speed n and intra-milling filling (IF). The speed component is unambiguous, not below a certain value at which grinding is generally possible and is easily controlled by means of an adjustable drive.

On the other hand, intramural filling is a function of many variables. First of all, this value is determined by the set productivity and quality, then it must take into account as much as possible the number of perturbations and, in addition, be a function of time – to perform the functions of the predictor (PR) – to determine the influence of the previous values of the factors on their current values. Such a notion of intramelic filling will allow to take into account the multifactority of the object and eliminate the influence of its inertia.

Separately, it should be noted systems consisting of several working together crushers or mills. In a sense, they are a model of a single multi-chamber mill (in operation in series), which makes it possible to optimize their operating mode not only by regulating the rotational speed, but also by regulating the stage of grinding.

The considered model of the mill as a component element is included in the multi-stage grinding scheme: successive operation of two objects. In this case, we have a system of two power consuming objects and the task will be to select a combination of speeds that ensure minimum power consumption.

In this case, the first mill will perform for the second function of the feeder, but in addition to the productivity there will be the possibility of regulating the fineness of grinding and there is an additional condition: selection of the degree of grinding by the first mill for optimal system operation (Fig. 3). That is, if in the case of single work speed was a regulating parameter, and productivity and quality of grinding are internally calculated, then when working together, all three variables for the first mill become adjustable.

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Let the crushing complex consist of several grinding aggregates, included in the sequential work (Fig. 4). Each unit that is part of the complex is characterized by a certain amount of power consumption or power consumption per ton of ground material, the value of which depends on a number of factors (we take into consideration such factors as the mass of grinding bodies M, the productivity of the aggregate Q and the size of the raw material T) and size of the finished product. The size of the finished product is determined by the mode of operation of the unit and the grinding time, which affects the amount of power consumed).

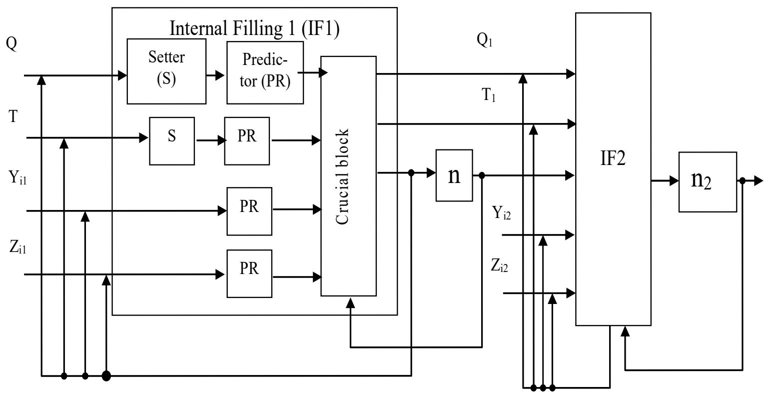

Fig. 3. Simulation of the joint work of mills

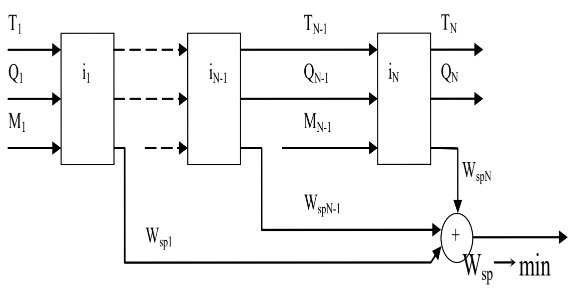

Fig. 4. Model of crushing and grinding complex

The ratio of the size of the product at the inlet to the size of the product at the outlet determines the degree of crushing of the product i. For N consecutive objects, the total degree of grinding is determined by multiplying the degrees of grinding at each stage (Rosen 2015).

$$i = \prod_{K=1}^{N} i_K \tag{1}$$

The value of the power consumption for the complex consists of the sum of the power consumption of individual units

$$W = \sum_{K=1}^{N} w_K \tag{2}$$

Using the specific power consumption as an optimization function, it should be taken into account that this value is determined not only by the value of the received power, but also by the productivity. Summation of specific power consumption is possible only for quantities characterizing the same mode of operation of the complex. Then the total specific power consumption of a group of objects (for a material flow that does not vary from an object to an object-the condition for the joint operation of the elements of the complex included in series) is determined by summing the specific power consumption of each stage.

$$W_{sp} = \sum_{K=1}^{N} w_{sp\_K} \tag{3}$$

Then, the optimization problem for a crushing complex with a performance varying in a narrow range will be written in the form

$$\begin{gathered} W_{y\partial}(Q, i, k_N) \to \min \\ \begin{cases} Q = const \in [Q_{\min}, Q_{\max}] \\ i \geq i_{\partial on} \end{cases} \end{gathered} \tag{4}$$

With this representation of the complex, the specific power consumption is represented by a nonlinear function determined by the state of each element of the complex, each of which in turn is a function of many variables. Two possible solutions are possible here: the first is the reduction of all variables to one, artificially introduced (the expression of all variables through one of them) and the second is the numerical solution of the problem, by sequentially supplying to the inputs of the model possible states of the system. The second option is more labor – intensive, however, its accuracy will be determined by the accuracy of its models. At the initial stage of solving the problem with the help of a numerical model, it is sufficient to identify zones of local minima of a function with the aim of more detailed investigation of them in the future, since each of them can be a minimum in one of the incoming variables and characterize only certain operating modes. Since the objects of the crushing complex are inertial and multi-variable, there may be some discrepancy between the calculated optimal mode and the "real" optimal mode, therefore, one must take into account the accuracy constraints imposed by the properties of the object. In addition, depending on the selected priorities, preference can be given to a particular local minimum.

To implement the monitoring and management system, it is advisable to use neural networks with the help of which it is possible to implement a model of the system and regulator. Neural networks are trained, designed to work with a large number of variables, successfully perform predictions. The task of grinding control using neural networks is implemented as follows (Fig. 5).

Each input of the network corresponds to one of the factors. The network outputs correspond to performance, subtlety and power consumption. Network weights determine the significance of factors. In addition to identifying the factors, the network can detect the forecasted state of the system based on the available data and optimize the work for a given parameter. As optimization parameters, we can take T, W and Q, or the introduced generalizing indicator that reflects all three criteria, depending on their significance.

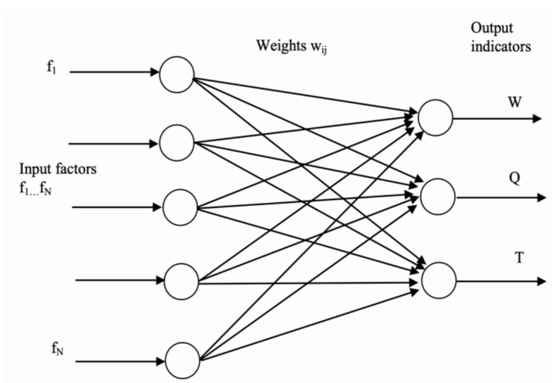

Fig. 5. Neural network model for grinding control

System control using neural networks provide an alternative to the control systems, constructed according to the classical methods of management. This possibility is based on the fact that a neural network consisting of two layers and containing in the hidden layer is arbitrarily large number of nodes can approximate any function of real numbers with a given degree of accuracy (Callan 2000, Medvedev 2002).

To ensure monitoring system with the prediction function, it is necessary to build a neural network model of the form (5) (Medvedev 2002).

$$y(k+d) = N\begin{bmatrix} y(k), y(k-1),..., y(k-n+1), u(k), \\ u(k-1),..., u(k-n+1) \end{bmatrix} \tag{5}$$

where *y (k)* is the output of the model; *d* is the number of prediction cycles; *u (k)* is the output of the model.

To design a tracking system that provides a given trajectory of the form

$$y(k+d) = y_r(k+d)\ . \tag{6}$$

it is necessary to design a nonlinear controller of the following general form

$$u(k) = G\begin{bmatrix} y(k), y(k-1),..., y(k-n+1), \\ y_r(k+d), u(k-1),..., u(k-m+1) \end{bmatrix} \tag{7}$$

In Fig. 6 shows the structure of the corresponding controller in the form of a neural network. Here we should pay attention to the sections of the network that performs the approximation of non-linear operators g and f in outputs $\hat{g} = a_2(t)$ and $\hat{f} = a_4(t)$

The controller outputs are the signals y(t+1) and u(t+1), the latter is implemented as a feedback and a reference signal y(t+2). The delay units include remembering the relevant entry and exit, and then used a two-layer neural networks, which form estimates of the nonlinear operators and compute the control signals.

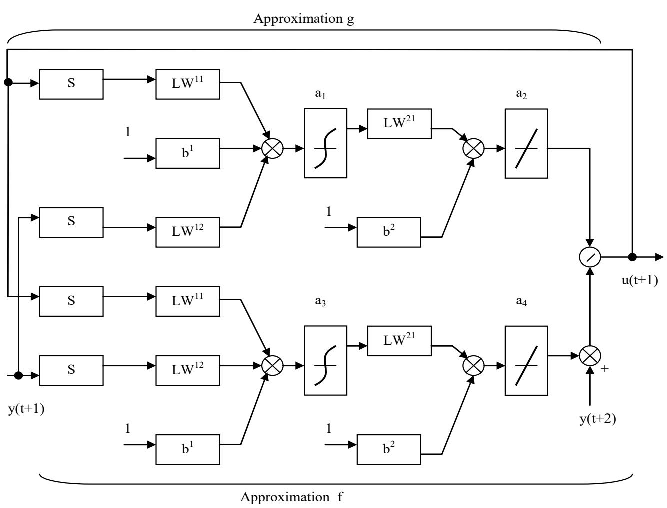

Fig. 6. Model of the neural network controller

The result of the operation of the system with a trained controller is shown in Fig. 7, where curve 1 shows the input stimulus; and curve 2 is the output signal.

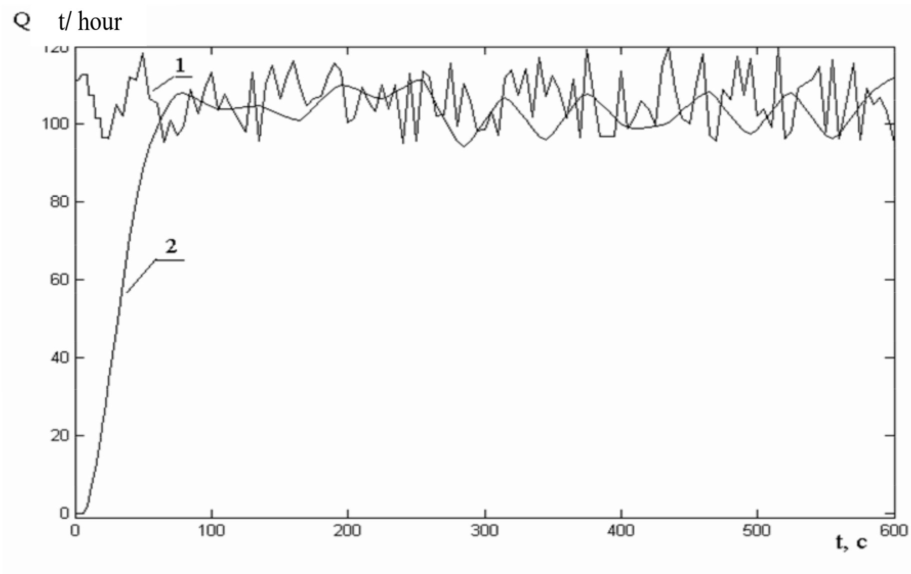

Fig. 7. Learning outcomes of the neuromodel

Comparison charts of the input (random) signal and output of the system shows that the use of the controller allows to achieve a more stable work area for the output product, in case of random changes of the input traffic.

4. Conclusions

The technological process at the enterprises of the crushing and grinding complex is a sequence of operations, each of which changes the physical state of the substance and increases the amount of energy consumed by the complex. Qualitative indicators of the change in the state of a substance and the amount of energy expended on it are determined by factors whose totality forms the factor field of the object. The factor field of the complex includes four groups of factors: controlled, regulating, equipment characteristics and substance characteristics.

The proposed new model of the crushing and grinding complex, which takes into account multi-factor field of the system and displays its internal links based on the mathematical apparatus of artificial neural networks lies in accounting for the formation of the objective function components that determine energy consumption and other technical and economic indicators of the complex "crusher mill" that allows you to increase the energy efficiency of the system by ensuring operation at the optimum power consumption mode.

The energy-saving effect in crushing and grinding complex is achieved by optimal power consumption mode, which is characterized by the calculated grinding fineness at which the transition from grinding from one grinding stage to the next (thinner) is carried out.

The developed model of crushing and grinding complex, which consists of several crushing units, which operate sequentially to determine the optimal parameters for a given criterion the operation mode of the complex, which reduces the power consumption of the complex by selecting an optimal mode for reducing the substance.

Application of neural networks in the implementation of the algorithm for finding the optimal operating mode.

References

Callan, R. (2000). Neural networks Per. from English - M.: Hot line - Telecom. 280.

Dreyfus, G. (2005). Neural Networks. Springer, 386.

Haykin, S. (1999). Neural Networks: A Comprehensive Foundation, 2nd Edition, Prentice-Hall.

Kyrychenko, V. (2014). Concerning CAE development of hydraulic hoists within ship mining complexes // V. Kyrychenko, E. Kyrychenko, V. Samusya, Antonenko A. / Annual collection of scientific-technical papers "Progressive Technologies of Coal, Coalbed Methane, and Ores mining". *Taylor & Francis group*, London, UK, 451-456.

Medvedev, V. (2002). Neural networks. MATLAB 6: Textbook / Medvedev V.S. under. total ed. Potemkin V.G. - M .: DIALOGUE-MIFI, 496.

Meyta, A. (2010). Monitoring and control system of crushing and grinding complex: Dis. ... Cand. tech. Sciences: 05.09.03 Kiev.

Meyta, A. (2016). Investigation of the Factor Field of a Ball Mill // Meyta A/ Energy: Economics, Technology, Ecology, 1, 96-101.

Picton, P. (2000). Neural networks. New York: Palgrave, 195.

Pivniak, G. (2014). Parameters optimization of heat pumps units in mining enterprises // Pivniak G., Samusya V., Oksen Y, Radiuk M. / Annual collection of scientific-technical papers "Progressive Technologies of Coal, Coalbed Methane, and Ores mining": Taylor & Francis group, London, UK, 19-24.

Rosen, V. (2015). Optimization of power consumption of the grinding and grinding complex // Rosen V., Kalinchik V., Meyta A., Skosirev V. / Energy: Economics, Technology, Ecology, 1, 43-47.

Samusya, V. The choice of rational parameters of the heat pump installation for the utilization of low-potential heat of mine water / Samusya V., Oksen Y., O. Huk // Metallurgical and mining industry / Science and Technology and production magazine. 1(92). 126-131.

Titterington, M. (2009). Neural networks. *WIREs Computational Statistics. 2*(1). 1-8.

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Forecasting the Energy Consumption of an Industrial Enterprise Based on the Neural Network Model

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Abstract: This research paper investigates the application of neural network models for forecasting in energy. The results of forecasting the weekly energy consumption of the enterprise according to the model of a multilayer perceptron at different values of neurons and training algorithms are given. The estimation and comparative analysis of models depending on model parameters is made.

Keywords: electrical loads, daily schedule, modelling, neural network, multilayer perceptron, MLP

1. Introduction

In the presence of the electricity market, the need to obtain forecast values of energy consumption is due to economic and technological reasons. Improving the accuracy of the forecast of electric loads allows to avoid overloading of generating capacities, to improve the quality of electricity, and to minimize its losses. Moreover, the projected loads significantly affect the market value of electricity, which is important both at the level of the individual industrial consumer planning its application for electricity, and at the level of the entire power system. High-level accuracy of power system planning allows to optimize the use of energy, distribute electrical loads between network facilities and meet the requirements for reliability and quality of electricity supply. This points to a great relevance and importance of the tasks related to modelling and forecasting of electrical loads for planning the optimal modes of operation of electricity consumers and power supply systems.

2. Analysis of recent research and publications

The quality and accuracy of the forecast depends on the chosen mathematical model. There are a large number of models and methods for loads prediction, which are usually based on the retrospective dynamics of power consumption and the factors that affect it, to identify a statistical relationship between model parameters and process characteristics. Ukrainian and foreign scientists, including V. Vynoslavsky, A. Prakhovnyk, V. Rozen, A. Voloshko, P. Chernenko, worked on the development of mathematical modelling and forecasting of electric loads (Vinoslavsky et al. 1974, Prakhovnik et al. 1985, Kalinchik et al. 2013, Voloshko et al. 2012, Chernenko et al. 2016).

In recent decades, the mathematical apparatus of artificial neural networks (ANN) has been successfully used for prediction, models based on which can establish a relationship between the output characteristics of the system and input factors using the learning procedure. The use of artificial neural networks allows to achieve forecast accuracy up to 96-97%, which will have a significant impact on the management of electrical loads. The choice of network type and its configuration depends on the specific task, available data and their volume.

At present, there are a significant number of classes of forecasting models (Tikhonov 2006). Moreover, some models and relevant methods relate to individual approaches to forecasting.

Speaking of the scientific works studying to the use of ANN in forecasting processes, we should mention the works by Yu. Zaigraieva, G. Shumilova, I. Chuchueva and others (Zaigraeva 2008, Sukhbaataryn 2004, Shumilova et al. 2008, Chuchueva 2012).

The principles of operation and options for the use of ANN were considered by the authors Haykin, Titterington, Picton, Dreyfus (Haykin 1999, Titterington 2009, Picton 2000, Dreyfus 2005).

The main requirements for forecast models include: sufficiently high accuracy of forecasting and simplicity of algorithms, which allows to minimise the decision time and volume of system memory; work in conditions of uncertain and insufficient information; ensuring the sustainability of management.

3. The goal of this paper

Is to develop a model for forecasting the electricity consumption of an enterprise using artificial neural networks to improve the accuracy of planning the operating mode and increase the reliability of the enterprise's estimates in making technical and economic decisions.

To achieve this goal, the following objectives are addressed in the paper:

- Building a structure and developing a mathematical model of ANN for power consumption forecasting.
- Investigation of neuromodels with different numbers of neurons to assess the effect of ANN configuration on prediction accuracy.

4. Presentation of the main research material

Interconnected neurons form a neural network. Network configuration is determined for each separate task. To solve some individual types of problems, there are already optimal configurations described in the academic literature on the construction and operation of neural networks (Komashinsky et al. 2002, Medvedev et al. 2002, Kruglov et al. 2002, Neural networks 2000, Haykin 2006).

On each cycle, all training observations are sequentially fed to the network input, the initial values are compared with the target values, and the error function is calculated. The values of the error function, as well as its gradient, are used to adjust the weights and offsets, after which all steps are repeated. The initial values of the ratios and biases of the network are chosen randomly. The learning process is terminated either after a certain number of cycles, or when the error decreases to a sufficiently small level or ceases to decrease.

Suppose a given multilayer perceptron with a smooth activation function (Surovtsev at al. 1994) (Fig. 1).

Its work is set by the equations:

$$NET_{ijl} = \Sigma w_{ijl} \cdot x_{ijl} - \Theta \tag{1}$$

$$OUT_{jl} = F(NET_{jl}) \tag{2}$$

$$X_{ij(l+1)} = OUT_{il} \tag{3}$$

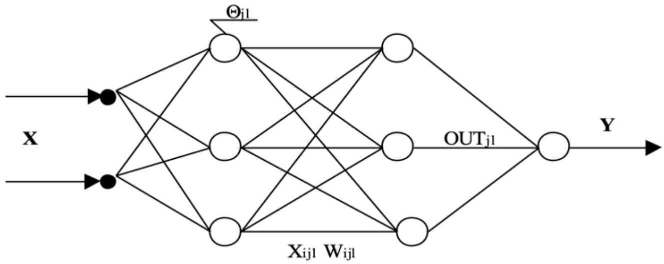

Fig. 1. Multilayer perceptron

We accept the total quadratic error as the objective function:

$$E = \frac{1}{2} \cdot \sum_j \sum_s \left(y_j^s - d_j^s\right)^2. \tag{4}$$

The network is defined by its parameter vector – a set of weights and threshold levels of

$$P = \binom{W}{\Theta}. \tag{5}$$

where W is a vector, the components of which are the weights of the network, Θ is the vector of network threshold levels.

Therefore, if we consider the training set as given, the network error depends only on the vector of parameters:

$$E = E(P) \tag{6}$$

During training on each iteration, the parameters in the direction of antigradient E will be adjusted:

$$\Delta P = -\varepsilon \cdot \nabla E(P). \tag{7}$$

The model of the object of research is realized on the basis of ANN. Preliminary preparation of the input data vector reduces the duration of the learning process, which is important for large amounts of data in the case of multicomponent systems. The mathematical apparatus of the ANN for the implementation of the model is selected based on the fact that the network of such a structure can simulate a function of almost any degree of complexity, and the number of layers and the number of elements in each layer determine the complexity of the function. MLP network has the ability to extrapolate data and high performance after training (Kalinchik et al. 2016).

The paper predicts the schedule of active power consumption for the day ahead on the basis of data on electricity consumption for the previous days. The total sampling consists of 168 observations (24 hourly observations per day during a week) and is provided in the form of a table and graph (Fig. 2). To verify the accuracy of the forecast, the forecast will be based on 144 observations, and the data of the last day will serve as a control sequence. The accuracy of the model will be assessed by the average value of the relative error in the control sequence and the value of the relative error in determining the daily power consumption.

A multilayer perceptron was adopted as a model for prediction. The number of perceptron inputs is determined by the length of the load schedule (24 observations per day). To obtain the predicted value, one source element is sufficient. The number of neurons in the hidden layer is set from 2 to 20 and will be adjusted depending on the accuracy of the model, which will be determined by the performance on the training and test sequences. Threshold activation functions may take linear, hyperbolic, exponential values. Network learning algorithm is BFGS.

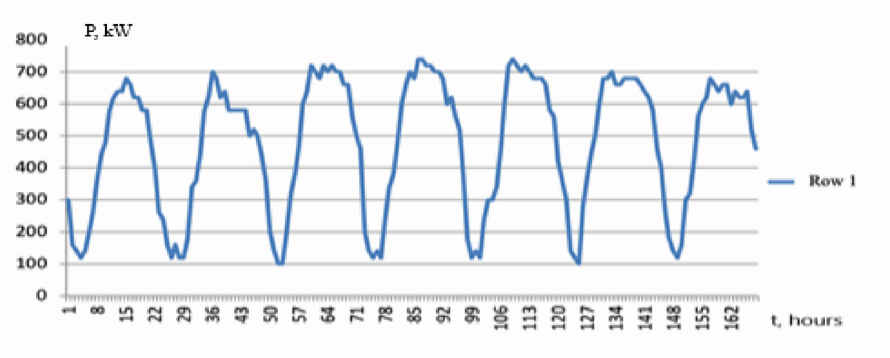

Fig. 2. Weekly schedule of energy consumption of an enterprise

When training networks under given conditions, the best 2 results out of 50 options have the characteristics shown in Table 1. The two networks with the best performance (the smallest absolute error in the training and control sequence) were used to build forecasts for the day ahead (Fig. 3). The quality of the models was assessed by relative error indicators for the predicted values of electricity consumption and the total amount of electricity consumed in Table 2. The average error in forecasting the current values of active power consumption for MLP 24-16-1, MLP-24-14-1 and MLP 24-1-1 networks was 9.7%, 9.9% and 9.5%, respectively. When estimating the total amount of energy consumed, the error was 1.8%, 1.6% and 4.1%.

Table 1. Characteristics networks

№	Net	Training perf.	Test perf.	Training error	Test error	Training algorithm	Hidden activation	Output activation
1	MLP 24-20-1	0.960162	0.981960	1319.822	708.0249	BFGS 5	Identity	Identity
2	**MLP 24-14-1**	**0.974301**	**0.983437**	**804.850**	**646.3876**	**BFGS 12**	**Logistic**	**Identity**
3	MLP 24-14-1	0.973262	0.982999	836.882	763.7459	BFGS 13	Tanh	Exponential
4	MLP 24-20-1	0.962599	0.982751	1210.119	872.7152	BFGS 8	Exponential	Exponential
5	MLP 24-14-1	0.974809	0.982893	789.723	750.9171	BFGS 11	Identity	Logistic
6	MLP 24-2-1	0.968802	0.982306	1004.553	735.2150	BFGS 12	Sine	Sine
7	MLP 24-4-1	0.961010	0.982408	1279.481	715.6567	BFGS 7	Identity	Identity
8	MLP 24-5-1	0.965437	0.982536	1113.829	703.7486	BFGS 29	Sine	Sine
9	**MLP 24-16-1**	**0.975561**	**0.982711**	**752.883**	**740.1567**	**BFGS 11**	**Identity**	**Logistic**
10	MLP 24-11-1	0.973378	0.982453	826.363	758.3667	BFGS 12	Identity	Logistic

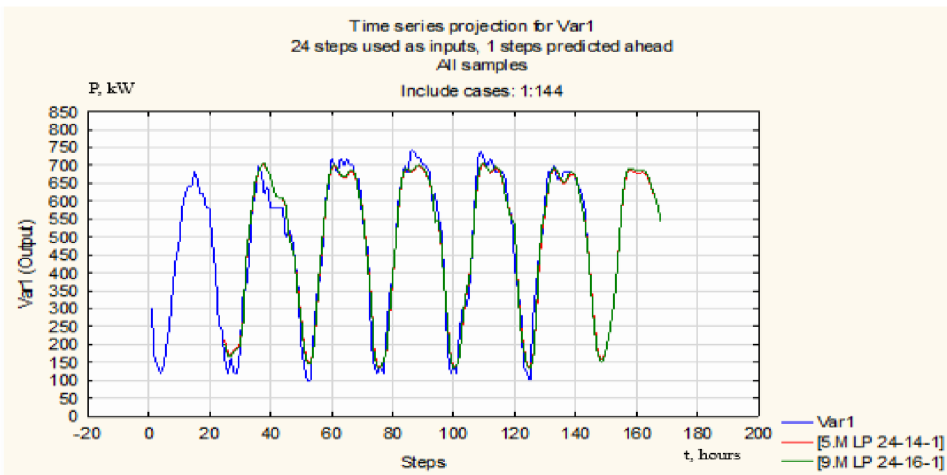

Fig. 3. Graphs of energy consumption by the original sequence and ANN models

Table 2. Estimation of accuracy of models

	Dimen-sion W	24"16"1	24"14"1	Error	Error	24"1"1	Error
1:00	400	364.8682	369.8831	0.08783	0.075292	347.7334	0.130666
2:00	260	263.5233	271.1761	0.013551	0.042985	249.8743	0.038945
3:00	180	184.6158	191.9261	0.025644	0.066256	170.9807	0.050107
4:00	140	153.2481	159.4724	0.094629	0.139089	147.3600	0.052571
5:00	120	153.0187	157.3944	0.275156	0.311620	167.1893	0.393244
6:00	160	186.0898	188.3890	0.163061	0.177431	237.1377	0.482111
7:00	300	228.1412	228.5293	0.239529	0.238236	313.9695	0.046565
8:00	320	281.0085	281.0490	0.121849	0.121722	404.3978	0.263743
9:00	420	350.9698	352.1839	0.164358	0.161467	495.7506	0.180358
10:00	560	456.1922	456.8315	0.185371	0.18423	577.6940	0.031596
11:00	600	575.1257	572.1859	0.041457	0.046357	633.2087	0.055348
12:00	620	654.7844	648.0695	0.056104	0.045273	656.2832	0.058521
13:00	680	687.5770	680.9111	0.011143	0.00134	661.0392	0.027883
14:00	660	690.9127	684.9339	0.046837	0.037779	649.6118	0.015740
15:00	640	687.9962	682.8616	0.074994	0.066971	642.9487	0.004607
16:00	660	684.3566	679.8348	0.036904	0.030053	642.3883	0.026684
17:00	660	683.8430	678.9896	0.036126	0.028772	646.9048	0.019841
18:00	600	686.2046	680.1743	0.143674	0.133624	658.9881	0.098313
19:00	640	681.8390	675.1215	0.065373	0.054877	671.7496	0.049609
20:00	620	664.0817	658.0634	0.071100	0.061393	675.4060	0.089365
21:00	620	637.2844	633.5488	0.027878	0.021853	663.2066	0.069688
22:00	640	611.4985	610.2385	0.044534	0.046502	625.3585	0.022877
23:00	520	584.7224	584.8978	0.124466	0.124803	556.1733	0.069564
24:00	460	541.7731	542.5004	0.177768	0.179349	458.3088	0.003676
	Amoun W	**Amoun W**	**Amoun W**	**Error**	**Error**	**Amoun W**	**Error**
	11480	11694	11669	0.018612	0.016478	11953	0.0412598

5. Conclusions

Operation of the enterprise has a cyclical change of loads, repeated daily during the week. Operation of the enterprise is characterized by hours of minimum load (from 0 to 8 hours) and hours of work with a nominal load of 600 to 700 kW. To build a mathematical model of the function of changing the electrical load, it is advisable to use a multilayer perceptron.

The daily load schedule with hourly data recording determines the observation period and the required number of neurons (24) in the input layer, because predicting a decrease in the number of neurons will worsen the quality of the model due to period mismatch, and increase will complicate the model.

For the proposed prediction model, a network with one hidden neuron provides a more accurate prediction for individual observations, but for predicting total power consumption over a set period, networks with more hidden neurons are more accurate. The biggest forecasting errors are observed at the time of changing the operating mode.

The error of the forecast values for operation at rated mode from 10 to 17 hours (minimum value 0.4%, maximum value 5.8%) and 4.1% error of forecast daily consumption indicates sufficient accuracy of the ANN model applied for forecasting daily loads of the enterprise.

The capability of processing large data sets, self-learning based on the given data sequences, and the high accuracy of the models confirm the feasibility of using artificial neural networks to solve problems of forecasting electrical loads.

References

Chernenko, P.O. (2016). Peculiarities of short-term forecasting of electric load of power system with essential component of industrial power consumption / P.O. Chernenko, O.V. Martyniuk, V.O. Miroshnyk // Proceedings of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine. 43. 24-31.

Chuchueva, I.A. (2012). Model for forecasting time series based on a sample of maximum similarity: dissertation of the PhD: 05.13.18 / Chuchueva I.A. Moscow, 153.

Dreyfus, G. (2005). Neural Networks. *Springer*, 386.

Haykin, S. (1999). Neural Networks: A Comprehensive Foundation, 2nd Edition, Prentice-Hall.

Kalinchik, V.P. (2013). Forecasting of indicators of energy consumption, generation and cost of the received energy / Kalinchik V.P., Kokorina M.T.: NTUU "KPI" N.-i. Institute of Automation and Power Engineering "Energy". Kiev, 14: bibliographic illustrations: 7 – deposit in SSTLU Ukraine 22.07.13, 35 Uk.

Kalinchik, V.P. (2016). Energy-efficient control of the "crusher-mill" mechatronic complex using artificial neural networks / Kalinchik V.P., Rosen V.P., Shevchuk S.P., Meita A.V. // Energy: economics, technology, ecology, 3, 45-50.

Komashinsky, V.I., Smirnov, D.A. (2002). Neural networks and their application in control and communication systems: Moscow: Hotline – Telecom, 94.

Kruglov, V.V., Borisov, V.V. (2002). Artificial neural networks. Theory and practice. Moscow. Hotline – Telecom. 382.

Medvedev, V.S., Potemkin, V.G. (2002). Neural networks. MATLAB 6. – Moscow: Dialogue, MIFE, 496.

Neural networks. (2000). STATISTICA Neural Networks. – Moscow: Hotline – Telecom. 182.

Picton, P. (2000). Neural networks. *New York: Palgrave, 195*.

Prakhovnik, A.V. (1985). Energy-saving modes of power supply of mining enterprises / A.V. Prahovnik, V.P. Rosen, V.V. Degtyarev. – Moscow: Bosom, 232.

Shumilova, G.P. (2008). Prediction of electrical loads in the operational control of electric power systems based on neural network structures / G.P. Shumilova, N.E. Gotman, T.B. Startseva. *Syktyvkar: RAS, 78*.

Sukhbaataryn Munkhzhargal. (2004). Development and research of neural network algorithms for short-term forecasting of the load of the central electric power system of Mongolia: dissertation of the PhD: 05.14.02 / Sukhbaataryn Munkhzha. – Novosibirsk, 177.

Surovtsev, I.S., Klyukin, V.I., Pivovarova, R.P. (1994). Neural networks. *Voronezh: HSU, 224*.

Tikhonov, E.E. (2006). Forecasting methods in market conditions: textbook / E.E. Tikhonov – Nevinnomyssk: North Caucasian GTU, 221. ISBN 5895710778.

Titterington, M. (2009). Neural networks. *WIREs Computational Statistics, 2*(1). 1-8.

Vinoslavsky, V.N. (1974). Forecasting the power consumption of industrial facilities / V.N. Vinoslavsky, A.V. Prakhovnik, A.F. Bondarenko // *Energy and electrification, 5*, 30-31.

Voloshko, A.V., Lutchin, T.M., Kladko, O.M. (2012). Short-term forecasting of electric load graphs based on wavelet transforms. Energosberezhenie, vol. Energy. *Energy audit., 6*. 35-42.

Zaigraeva, Yu. B. (2008). Neural network models for assessing and planning energy losses in electrical systems: author. dis. for a job. scientific. degree of Cand. those. Sciences: spec. 05.14.02 "Power Plants and Electric Power Systems" / Zaigraeva Yulia Borisovna; Novosibirsk state technical university – Novosibirsk, 20.

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Integration of Heat Storage Technologies in District Heating Systems

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Abstract: Global trends in the efficiency, safety of energy systems and energy conservation actualize the task of developing new technologies for energy storage and transportation. The article considers current technologies of storage and accumulation of thermal energy, which can be used in central heating systems, and draws conclusions about the feasibility of their use. Also, the classification of energy storage systems is presented. The most perspective thermal energy storage, which can be used to equalize the load on the energy source to ensure the peak demand for heat with a high coefficient of utilization of the equipment capacity, is noted.

Keywords: thermal energy storage, district heating system, mobile thermal energy storage

1. Introduction

Improving the efficiency of heat supply contributes to overall energy savings at the national level. The heat supply is carried out mainly by a branched pipeline infrastructure – a network of district heating (DH) and cooling. Consumers remain apartment buildings. Partially, the private sector and industrial enterprises. In the European Union, the residential sector uses about 26.1% of final energy consumption (European Commission 2019). In Ukraine, 1.6 times more primary energy is used for heat production than for electricity. Electricity production accounts for 39%, while high-potential (T > 100°C) heat production consumes 21% and low-potential (T < 100°C) 40%. Therefore, increasing the efficiency of the DH system can contribute to overall energy savings.

The main advantages of DH system are the possibility to provide a large number of consumers with heat at the same time, the use of various local fuels and energy sources which makes it possible to reduce the cost of heat. In DH-systems there is possibility of centralized regulation of the heat-carrier temperature, allows to minimize heat losses. There is also the possibility to control the DH work remotely, which ensures high reliability and easy use of the system.

But the significant disadvantages of the system, level out the listed advantages – there are significant losses during transportation, lack of quantitative regulation and violation of the temperature regime during peak loads. Currently, the state of heating networks does not meet the current technical requirements. For example, in the EU countries up to 11% of heating systems are inefficient (European Commission 2016), in Ukraine from 22.3% to 17%. This is due to the difficult technical condition of the pipeline, insulation, distribution systems.

The use of thermal energy storage systems (TES) allows to stabilize the DH system operation during the peak period of heat consumption, significantly reduce harmful emissions into the environment. And also, to ensure the systematic operation of boiler equipment with the highest possible high efficiency, to reduce the consumption of electricity and fossil fuels and to attract to the multipower balance of renewable energy systems and secondary energy resources.

These tasks are especially relevant nowadays, to ensure energy security and flexibility of DH systems, decarbonization of generation, reduction of the cost of transport and distribution of thermal energy and the prospects for transition to the new advanced technologies of the fourth generation. DH systems of the fourth generation is a modern trend of heat supply, actively implemented in the EU, the U.S. and China. In particular, their introduction allows to solve ecological problems, so the European Union announced the "green agreement" aimed at reducing of greenhouse gas emissions by 50% by 2030 in comparison with 1990 (Union European 2020).

2. Purpose and objectives of the work

The purpose of this work is to investigate the integration of heat storage technologies in central heating systems.

According to the set goal, the following tasks are formulated:

- determine the promising directions of development of central heating,
- to review modern technologies of heat storage and identify promising options for their use in DH systems.

3. Directions for development of district heating

Modernization of the central heating system makes it possible to level out the divergence of priorities between district heating companies and consumers. The conducted analysis indicates convergence of priorities at the level of installation of heat regulation systems and reduction of heat losses for technological needs. Consumers are interested in reducing the cost of heat supply services, and heat suppliers are interested only in the transition to the multi-parallel balance and reducing the cost of heat production.

In order to improve the efficiency of district heating, there is a decrease in operating temperatures in heating networks. Low temperatures in the network allow to reduce heat losses and to integrate low-grade waste heat and renewable energy sources.

Due to changing climatic conditions, the demand for heating is expected to decrease, as opposed to the demand for cooling increasing significantly. The task of an emission-free supply of heating and cooling energy is a challenge, especially in urban areas. Therefore, energy supply from decentralized sources of supply is not feasible. On the other hand, district heating and cooling (DHS) is gaining in importance.

It should be noted, the general trend according to the stages of development of heating networks of industrial development. DHS systems of the 1st generation emerged in the first half of the last century. This system is characterized by separate production of heat and electric energy and use of fossil fuels and oil products. DHS of the 1st generation is characterized by high temperature of the heat carrier >150°C and low efficiency of ≈ 50%.

DHS heating and hot water generation 2 developed from the 1940s to the 1990s. This period is marked by the active use of natural and liquefied gas, secondary energy resources in the fuel mix. Generation of heat and electric energy is compatible. The temperature of the heat carrier is reduced to 115-70°C, while the efficiency of the system is increased up to 60%. TES start to be used on heat generation sources.

Generation 3 DHS unfolded in Western Europe and the U.S. from the early 2000s to 2020, and is characterized by the cogeneration of heat and electricity and the use of renewable energy sources (RES), alternative and biological fuels. There is a gradual abandonment of the use of fossil fossil fuels. Heat-carrier temperature is reduced to 90-70°C, and the efficiency of the system increases up to 70%. Widespread use of RES leads to the spread of heat storage technologies. Today, most energy comes from such sources as oil, coal, natural gas and uranium, causes emissions into the environment, global warming and associated climate change. Countering these phenomena is one of the main challenges for modern science and economy. Therefore, it is necessary to conduct research on the widespread use of available renewable energy sources. It should be noted that the high potential for the use of heat from solar energy, due to the high efficiency of the accumulation and conversion of this energy. The main elements used in this area are solar collectors and heat storage systems.

Intensive use of RES and TES systems has led to a transition to DHS 4th generation systems. Now the EU is implementing a project for a new generation of heating, hot water and cooling systems by 2050. It covers the development and use of new energy sources and the rejection of fossil fuels. The coolant temperature of such a system is in the range of 70 to 50°C. And the overall efficiency of the system is higher than 70%. The focus is on energy accumulation and storage systems. Scientific research carried out in recent years is aimed at developing new storage technologies and battery designs that will allow for efficient and safe energy storage.

Among the various methods of heat storage are direct heat storage, latent heat storage and thermochemical energy storage. The efficiency of TES depends on the properties of the selected heat storage materials, on the conditions in which these devices are used, and on the purpose for which they are used.

4. Classification of heat storage technologies

Modern TES technologies provide the ability to store heat or cold for hours, days, or even months. Global trends in efficiency, energy savings and security of energy systems are based on the principle of energy storage. Depending on how energy is stored, heat storage technologies are divided into:

1. Technologies for transforming mechanical energy into thermal energy, such as hydroelectric power plants, steam turbines, Stirling engine. They are widespread, but are characterized by low efficiency, about 30%. Because there are thermodynamic limitations of power generation at temperatures below 340°C, so they are not used in DHS systems.
2. Low-temperature heat technologies. A considerable amount of heat is available in the temperature range from 40 to 200°C, but there are difficulties in its use, which require a separate and in-depth study. Because low-temperature heat involves a smaller temperature gradient between two fluid streams, large heat transfer surfaces are required for heat transfer. This limits the economic feasibility of their use, since it requires the use of a heat pump to increase the temperature of the coolant. TES based on single-phase capacitive accumulation for seasonal or short-term accumulation of thermal energy allows the use of heat or cold from natural sources and secondary energy resources. Thermal accumulation is carried out by solid or liquid substances due to the heat capacity of the material. The capacity of heat storage in such accumulator's ranges from 100 kW to hundreds of MW.
3. Latent heat is the accumulation of thermal energy in the so-called latent TES systems, based on the use of materials with a phase transition. Phase-transition materials can be of organic (high molecular weight paraffins, waxes and glycols) or inorganic origin (crystalline hydrates, salt hydrates and eutectic water-salt solutions). Such materials have a high latent heat capacity. The limited use of thermal accumulators with phase transition can be explained by the low coefficient of thermal conductivity and excessive corro-

siveness of inorganic materials, as well as the change in volume during melting of materials of organic origin.

4. Hidden chemical energy utilization technologies based on adsorption processes. Equipment for heat recovery from gas for low and medium temperatures, using zeolites and silica gel as the working body. The heat transfer medium is air. Thermal energy storage can be daily, weekly, monthly or even seasonal.
5. TES, the principle of operation of which is based on photochemical and thermochemical, thermoelectric reactions. Such TES have not found wide application and are currently at the stage of scientific research. However, new technologies are being developed that can produce electricity directly from heat, such as thermoelectric and piezoelectric generation with subsequent storage and application for heat carrier heating.

5. Application of heat storage technologies in central heating systems

In TES that in the future will be used in DHS systems include – main pipelines, heat pumps, stationary and mobile thermal storage.

Central heating and hot water supply has a great potential for the use of main pipelines as TES, which is allowed by the current regulatory documents (Thermal networks 2009). While in Western Europe occupies about 10% of the total heating market, in Ukraine it reaches 70% (Poredos et al. 2011). Our research shows that the use of heat supply networks as heat storage and optimization of DHS system can reduce the total cost of primary energy up to 5%.

In promising technologies of heat storage in central heating systems, also include heat pumps. However, investment in electric heat pumps is not attractive due to lack of support at the state level. Large capacity heat pumps for DHS are considered as an economic and energy efficient solution (David et al. 2017).

Widespread stationary heat accumulators are used both in homes and in combination with thermal power plants, boilers and heat pumps in DHS. TES enables optimal management of the boiler load, reducing the consumption of fuel and energy resources and harmful emissions into the environment.

Mobile thermal storage (M-TES) can be successfully used to combine several sources of thermal energy, combined into a single system. This is of particular importance, given the increasing use of renewable and secondary energy sources (Demchenko et al. 2020, Demchenko et al. 2020 september). Abroad, research work on mobile thermal energy storage for the utilization and utilization of industrial waste and excess heat for distributed users is underway, and the first commercial projects have been implemented. In Germany, for example, Marco Deckert et al., has tested a system of two 20-foot tanks filled with sodium acetate trihydrate. The tested M-TES stores up to 2.0 MWh of heat. And Andreas Krönauer et al., presented the results of a year-long test, in which M-

TES in a tank filled with 14.0 tons of zeolite, and has a heat storage capacity of 2.3 MWh.

Weilong Wang (Taiwan) investigated water storage tanks of direct and indirect heating filled with erythritol, which has a melting point of 118°C.

The author's collective of laboratory "Processes and Technologies of Heat Supply" of ISTP of NAS of Ukraine created the prototype of mobile heat storage with heat productivity 1200 kW/H, Fig. 1.

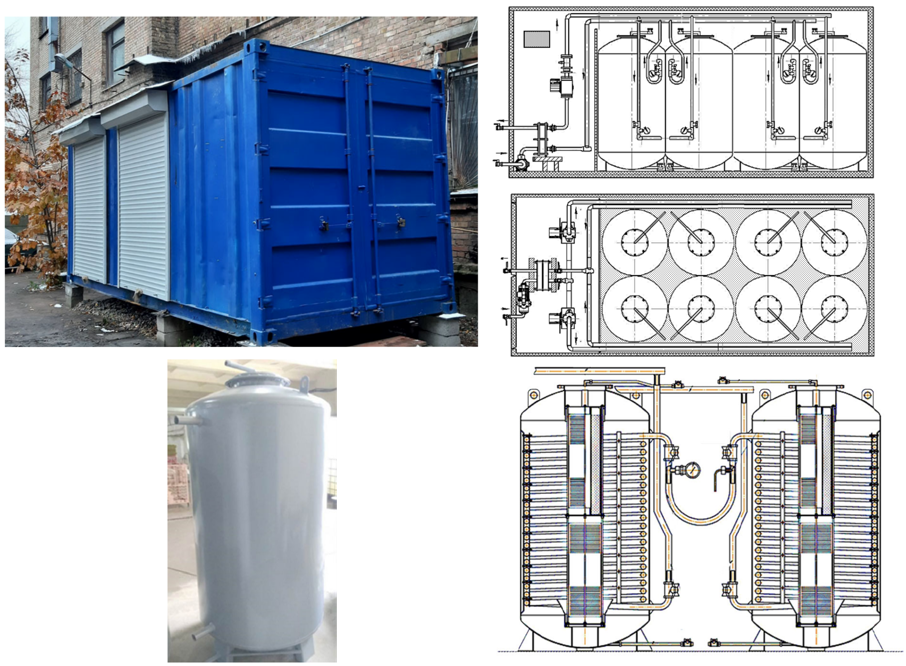

Fig. 1. Mobile thermal storage M-TES-0,5 MW

Charging time is 4 – 6:00, discharging time is 10 – 12:00, the heat storage capacity is 200 kWh, the average load power is 120 kW, the average discharge power is 90 kW. Mobile container-type M-TES is equipped with a block heat point and heat storage tanks.

For the first time in order to solve this problem a design of a mobile heat accumulator is proposed which consists of a dry cargo container in which an individual heat point is mounted and the accumulators are filled with a combination of a material with a phase transition and hydrogels.

The basic technological scheme of integration of heat accumulators into the heat supply system is shown in Fig. 2.

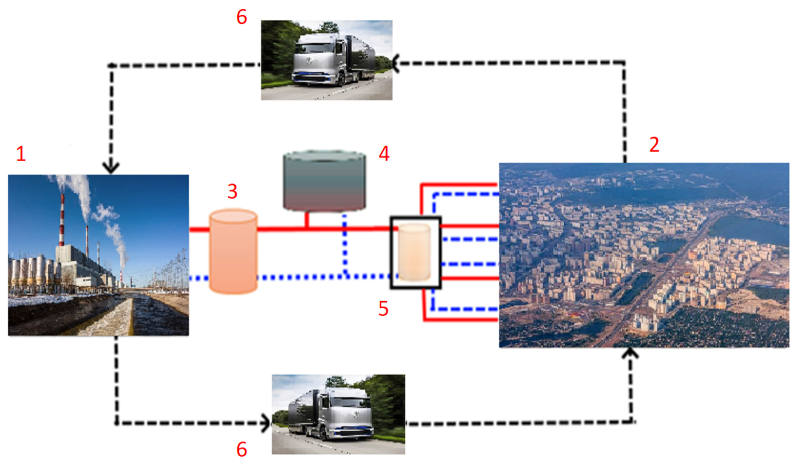

Fig. 2. Schematic flowchart of the integration of thermal accumulators in the heat supply system, where: 1 – TES an energy source, 2 – TES is a user 3 – TES of direct action, 4 – TES of transport network, 5 – TES of indirect influence on the distribution network, 6 – M-TES

Demand-side management using heat accumulators is an effective method of managing district heating, which has investment attractiveness and contributes to decarbonization. Using TES, it is possible to reduce peak loads by up to 30% and reduce emissions and fuel consumption by up to 10%.

Comparative characteristics of functional properties of modern energy system and the system based on the concept of Smart Grid demonstrates that the introduction of Smart Grid means the creation of intelligent distribution network (Demchenko et al. 2019). This allows to achieve an increase in profitability, reliability and failure-free operation with reduction of heat and coolant losses in networks. These systems are aimed at improving operational efficiency, optimizing the distribution of load on the heating network. Implementation of the concept of Smart Grid is innovative in nature and reflects the transition to a new technological paradigm in the energy sector and the economy, will have a positive impact on energy independence.

Fig. 3 shows the proposal of energy-saving innovations for district heating companies. So, at the level of use of fuel and energy resources is the transition to a multifuel balance. At the level of generation of heat, cold and electricity – it is proposed to widely use alternative and renewable sources. When transporting coolant – it is proposed to use accumulators for targeted dosed supply of heat or cold to the consumer with the help of mobile heat accumulators.

When distributing heat – it is a quantitative-qualitative regulation, the use of a new method of transporting coolant by coaxial pipelines, developed in the laboratory of heat processes and technologies of the ITTF of the NASU.

It is supposed that the pipeline of the consumer coolant supply is located inside another pipeline (Demchenko et al. 2016)

Coaxial pipelines proposed for implementation can reduce heat losses almost 2 times.

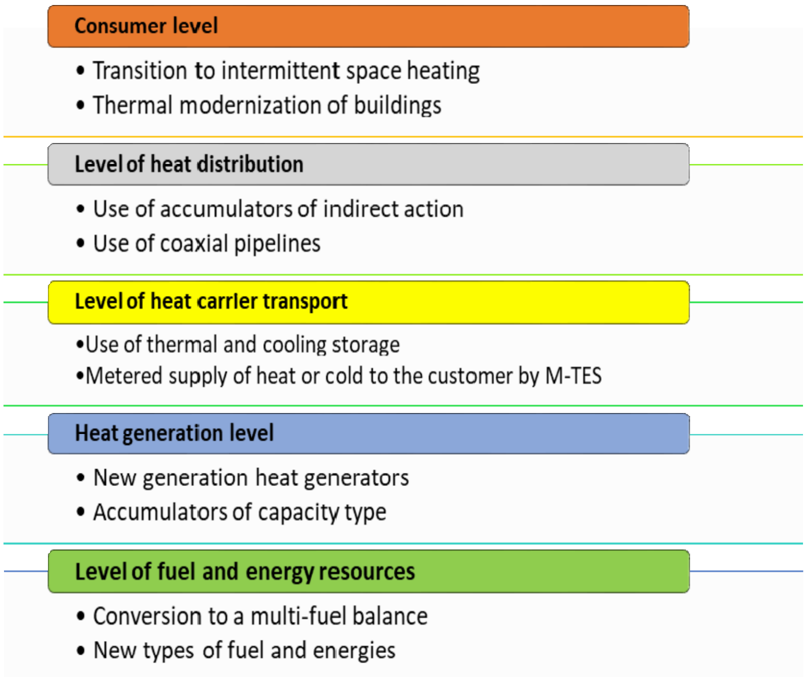

Fig. 3. Suggestions for energysaving innovations for district heating companies

Advantages of a new way of a heatcarrier transportation consist in essential reduction of means for construction of a heating network, possibility of use of existing pipelines at modernization of networks, reduction of a thickness of a layer of isolation. The length is less due to the reduction of the number or lack of expansion joints, the hydraulic stability of the operation, reducing the temperature drop and pressure in the network.

At the consumer level, in addition to the thermomodernization of buildings, the transition to intermittent space heating, that is, heating only during the permanent stay of people in them and reducing the temperature during absence.

6. Conculusions and further reserche

As a result of the analysis of existing district heating systems and the literature regarding new research on TES, the most promising proposals for energysaving innovations for district heating companies, according to the authors, are:
- The search for new energy sources and the transition to a multifuel balance,
- wide use of alternative and renewable sources and combination of TES,
- use of accumulators for heat transportation, for targeted dosage delivery of heat or cold to the consumers by M-TES – quantitative and qualitative regulation during heat distribution, use of new method of heat carrier transportation by coaxial pipelines,
- in addition to the thermal modernization of buildings, a transition to the intermittent heating of rooms, that is, heating only during the continuous stay of people in them at a comfortable temperature, followed by its reduction in their absence, is proposed.

Prospective is the search for new discrete ways of heating with the help of mobile heat storages, allow to build a flexible heating system and minimize heat losses during transportation. Creation of new materials and application of natural materials with phase transition deserve special attention.

References

David, A., Mathiesen, V., Averfalk, H., Werner, S. & Lund, H. (2017). Heat Roadmap Europe: Largescale electric heat pumps in district heating systems, *Energies, Review 10*(4). DOI: https://doi.org/10.3390/en10040578

Demchenko, V., Konyk, A. (2020). The main aspects of the processes of heat-akumulation Scientific Works, 84(1), 48-53. [Demchenko V.G., Konyk A.V., Main aspects of heat-acumulation processes, Odessa National University of Food Technologies, Collection "Scientific Proceedings", 84(1), 48-53]. DOI: https://doi.org/10.15673/swonaft.v84i1.1868.

Demchenko, V. (2019). "SMART GRID" subsystem of thermal energy storage, "Thermophysics and thermal energy", 41(5), 120-121 [V.G. Demchenko, "SMART GRID" subsystem of thermal energy accumulation, "Thermophysics and Thermal Power Engineering", 41(5), 120-121].

Demchenko, V.G., Dunyak, A.V., Yevtushenko, A.V. (2016). Comparative assessment of the efficiency of the heat carrier transportation system based on coaxial pipes. *Industrial Heat Engineering, 38*(5), 39-47. DOI: https://doi.org/10.31472/ihe.5.2016.07.

Demchenko, V.G., Konyk, A.V. (2020). Application of special multifunctional transportable batteries of capacitive type, Collection of abstracts of XX scientific-technical conference, Chernigov. Chernigov 03-04 September 2020 "Creation and modernization of weapons and military equipment in modern conditions", 74-75.

European Commission. The European green deal: communication from the commission to the European Parliament. the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions; 2019. URL, https://eurlex.europa.eu/legalcontent/EN/TXT/ uri¼CELEX:52019DC0640.

European Commission, "An EU Strategy on Heating and Cooling," Brussels 2016, Available: https://ec.europa.eu/transparency/regdoc/rep/1/2016/EN/1-2016-51-EN-F1-1.PDF.

Poredos, A. & Kitanovski, A. (2011). *District heating and cooling for efficient energy supply*. DOI: 10.1109 / ICECENG.2011.6058201.

Thermal networks (2008), DBN B.2.5-39: 2008, Valid from 2009-01-07 [Heating networks, DBN B.2.5-39: 2008, in force since 2009-01-07].

Union European. EU Energy in figures: Statistical pocketbook 2020. 2020. URL, https://op.europa.eu/s/oIDP. DOI: 10.2833/75283.

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Numerical Modeling of Solid and Gaseous Fuel Combustion in the TP-14A Boiler Furnace to Reduce PCDD/F and Greenhouse Gas Emissions

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Abstract: The issues related to the emission of atmospheric pollutants during the provision of energy supply services and the circulation of household waste in settlements are considered. The ways of air pollution by toxic compounds and the formation of greenhouse gases with existing methods of waste heat treatment are analyzed. The issues of reducing the content of toxic emissions in combustion products are studied on the basis of a numerical experiment by means of computational fluid dynamics (CFD). The combustion processes in the power boiler TP-14A (E 220/100) are considered and adequate boundary conditions for the processes of aerodynamics, heat transfer and combustion of gas fuel are determined. The temperature, velocity and concentration fields in the furnace of the investigated boiler have been determined. According to the results of the calculations performed, the formation of chemical underburning and nitrogen oxides is predicted.

Keywords: atmospheric pollution, combustion, nitrogen oxides, dioxins and furans, numerical modeling, computational fluid dynamics, pressurization mode, normative method

1. Introduction

Urban air pollution is a major risk factor for public health. The negative impact on the state of atmospheric air is the result of the constant interaction of people with the environment. A wide variety of sources contributes to the loss of air quality. These are transport, energy, industry and the entire complex of housing and communal services – residential complexes and consumer services for the population, down to the smallest. It is believed that from stationary sources objects of large energy and municipal infrastructure (sewage treatment plants and MSW landfills) of the given settlement make the largest contribution to urban air pollution. The main pollutants in terms of mass emission (excluding greenhouse gases) are sulfur dioxide SO_2, nitrogen oxides NO_x and carbon monoxide CO. They account for up to 80%, the share of other homogeneous pollutants is less than 10%, the rest is solid suspended particles.

With this traditional approach to considering the problem of cleanliness of the urban air environment, which is most important for the state of national health, the aspect of the toxicity of the pollutants emitted does not fall into the field of vision. Approaching the problem from this position, one can find the exaggeration of the influence of large energy facilities on the city air. The constant replacement of large emission sources with many small-dispersed ones – from mini-CHPs and block boiler houses to individual heat generators in apartment buildings, has led to a decrease in the dominant role of centralized generation in air pollution. Now in Russia, the ratio of centralized and decentralized heat supply can be estimated as 2: 1, and in terms of heat supply to the population, it is approaching parity. Note that NO_x and CO represents toxic compounds of emissions from gas power generation, which belong to the class of moderately hazardous substances. This also leads to the equalization of the influence of the centralized and decentralized energy sectors on the formation of urban air pollution. At the same time, the issues of reducing the emission of nitrogen oxides in large-scale power engineering have been considered for more than half a century, and at present, the main methods are quite deeply worked out and are widely used. The progress of individual heat generators, especially the widely used condensing household boilers, has recently proceeded mainly along the line of increasing the fuel utilization factor, which, as is known, is achieved by methods directly opposite to the methods of reducing the generation of nitrogen oxides during gas combustion. In addition, large energy facilities have high-rise pipes designed to dilute pollutants and remove them from the settlement, while emissions from small boiler houses and individual boilers remain in the immediate vicinity of their generating device.

Calculations of the numerical ratings of emission sources, taking into account the toxicity of pollutants (Ziganshin 2019), also allow us to find that in terms of air pollution in cities, centralized and decentralized generating facilities and devices, taken together, are not ahead of housing and communal services enterprises dealing with the circulation of solid and liquid household waste. For example, at landfills of solid waste, the so-called «landfill» gas is formed anaerobically, the composition of which is only very rough information. At a large landfill, its output can be in the range of 2-5 thousand m^3/h, which is 3 orders of magnitude lower than the emission of flue gases from a thermal power plant. The main components (90% and more) of «landfill» gas can be, depending on the storage period of solid waste, carbon dioxide, ammonia, methane. At the same time, the concentration of the latter can at times exceed the lower flammable limit, which in the USA and the EU has led to its use for power generation. However, the rest of its pollutants are represented by a variety of classes of chemical compounds, including furans and dioxins. For example, the analysis of landfill gas at the Kuchino landfill (Moscow region) made it possible to identify 157 names of substances. Among them there are the following classes of chemical compounds: hydrocarbons (saturated, unsaturated, cyclic non-aromatic, terpene, aromatic, polycyclic aromatic) – 74 names, total concentration from 61 to 80 mg/m^3; oxygen-containing (alcohols, ketones, ethers and esters, organic acids) – 53 items, total concentration from 24 to 44 mg/m^3; sulfur-containing (sulfides, thiols, etc.) – 22 items, total concentration from 6 to 11 mg/m^3; nitrogen-containing – 2 items, total concentration up to 0.6 mg/m^3; chlorine – 3 items, total concentration from 0.18 to 2.1 mg/m^3; furans and piranas – 2 names, total concentration from 0.17 to 1.2 mg/m^3. Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) are chemically stable organic compounds. These are highly toxic pollutants that can accumulate in the tissues of organisms. Some of them (for example, 2,3,7,8-tetrachloro-p-dibenzodioxin) are extremely toxic, carcinogenic, cause hormonal disorders and damage to the immune system, which is especially dangerous in the context of a coronavirus pandemic (Bilalov et al. 2019, Feng et al. 2018, Rigang et al. 2020). Therefore, the MPC for PCDD/F is an order of magnitude lower than the MPC for chemical warfare agents and is 7-8 orders of magnitude lower than the MPC for NO_x and CO, and the emission of 1 mg of dioxin is commensurate with the emission of 10 tons of NO_x.

This means that the emission of 10 m^3/h of «landfill» gas with a dioxin concentration of 1.2 mg/m^3 in toxicity is equivalent to the emission of 400 thousand m^3/h of flue gases with a concentration of 300 mg/m^3 NO_x, which corresponds to the operating parameters of one boiler at a TPP.

The transformation of garbage in the furnaces of the steam generators of «garbage» TPPs takes place in an oxidizing mode. In this case, sulfur-, nitrogen- and phosphorus-containing chemical compounds of various toxicity are formed, up to chemical warfare agents, furans, and dioxins that exceed them in toxicity. Waste incinerators, including the most dangerous of them (medical waste incinerators) are the main sources of supply of polychlorinated dibenzo-n-dioxins and dibenzofurans to the atmosphere. In such conditions, in order to reduce damage, it is possible to organize preliminary waste treatment to the high-temperature zone with the removal of chlorine compounds (Ziganshin et al. 2009).

However, unauthorized fires in the places of collection and storage of solid waste, where preliminary processing is impossible, are also very dangerous sources. At the same time, incinerators and landfills are placed, as a rule, away from housing, while approximately the same set of chemical compounds is emitted directly into the air of a residential area during fires and arson at sites for temporary storage of household waste.

To reduce the formation of toxic compounds both when burning traditional fuel and when burning garbage, it is especially important to establish a sequence of elementary stages of transformation of the initial components in the thermo-oxidizing zone. Since during incineration the specific initial composition of the fuel is unknown, and when using household waste it is unstable, it is possible to establish a set of elementary stages of the radical chain mechanism of thermal oxidation only empirically. The data available in the literature on the kinetics of reactions during waste incineration are insufficiently complete and sometimes contradictory.

Recently, a lot of research has been carried out on the production of hydrogen from recycled plastic. Plastic waste from the city's waste collection system is decomposed by thermal gasification. In this case, the organic part of the waste is converted into hydrogen, and carbon monoxide is also released. Carbon monoxide from this process is used to make carbon-based products. Hydrogen goes to the production of ammonia, goes to hydrogen gas stations, and is also used to generate electricity.

Hydrogen is poised to decarbonize many sectors of our economy. It can be directly used in fuel cells for carbon-free power, or in gas turbines where its high energy density, higher auto-ignition temperatures and ability to lean-burn are favored.

Simulating the combustion of hydrogen fuels with the ANSYS Fluent software can help the energy and aviation sectors achieve the low-carbon faster while saving costs.

When burning waste with a temperature above 1200-1300°C, thermal oxidation of organic and organochlorine components of MSW in the presence of metals can occur together with the reduction of their oxides. In this case, in some cases, it is possible to create conditions for the joint thermal neutralization of toxic compounds, for example, for the reduction of hexavalent chromium compounds to trivalent (Bilalov & Ziganshin 2019). The intermediate products formed in the high-temperature zone react with each other to the final products upon cooling the zone itself, and PCDD/F are formed in the range from 650°C to 250°C (Tugov eta al. 2018). It is believed that their main part is condensed on ash suspended in combustion products, in connection with which it becomes especially important to use technologies with a high degree of purification of flue gases from suspensions (Belyaeva et al. 2019). In general, the scheme for the formation of PCDD/Fs is not fully known. Full-scale and numerical studies on the kinetics of reactions were carried out for a limited number of starting components (Hongting et al. 2018, Min et al. 2018).

The presence of SO_2 in the high-temperature zone of sulfur dioxide ultimately leads to a decrease in the concentration of PCDD/F in the combustion products. However, on the whole, the picture of their formation is not yet clear enough. Recommendations for reducing the generation of PCDD/F so far boil down to the following: the temperature in the combustion zone should be above 1200-1300°C, with the residence time of gaseous products of the reactions of thermal destruction and oxidation of solid waste in the high-temperature zone for at least 2-4 s, followed by sharp cooling («Hardening») of combustion products up to 200°C.

2. Methods

The paper considers the results of numerical modeling of the furnaces of a steam boiler E-220/100 (TP-14A, manufactured by JSC TKZ «Krasny Kotelshchik») with a steam capacity of 220 t/h. Geometric modeling of the TP-14A furnace for studying the combustion of low-grade fuel and waste was carried out using the Gambit software product with the Exceed emulation environment. Firstly, a geometrically accurate 3D model of the furnace with a cold funnel and all burners was performed (Fig. 1).

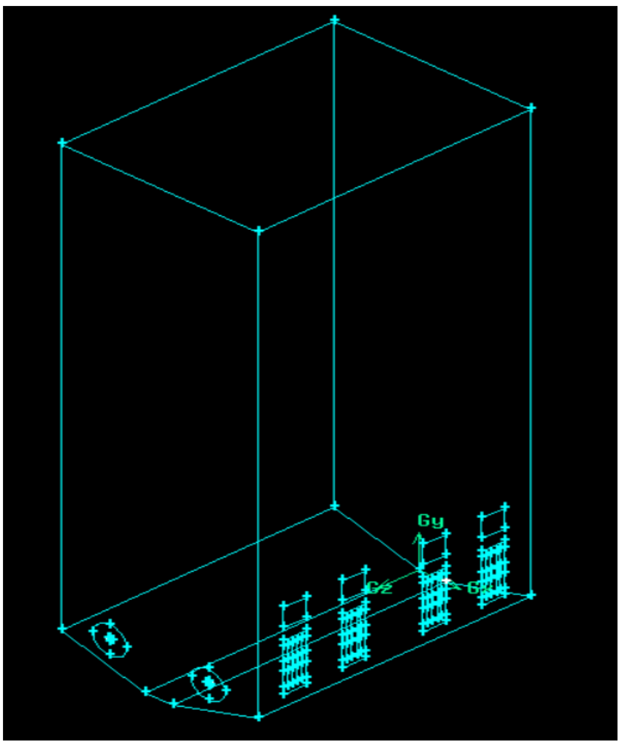

Fig. 1. Construction of a 3D model of the TP-14A boiler combustion chamber in the Gambit program, geometrically accurate model of the TP-14A boiler combustion chamber

But due to difficulties in generating the grid using Gambit software, a simplified model of the combustion chamber was built, in which an unstructured hexahedral grid was generated (Fig. 2).

The model was transferred to the Ansys Fluent processor. The movement of flows in the furnace was calculated on the basis of the Navier-Stokes relations (RANS), the convergence of the relations according to the two-parameter k-ε model. The task is non-isothermal, using the energy equation («Energy Equation») and the P1 radiation model. For combustion of coal dust and garbage particles in the TP 14A furnace, a compositional transport model based on the probability density function (PDF) – Composition PDF Transport. The average reaction rate is modeled using the Eddy-Dissipation model. The combustion model is adopted as the transfer of combustible reagents «Species Transport», the model of mixing the reaction components, as for the TP 14A furnace – vortex dissipation «Eddy-Dissipation».

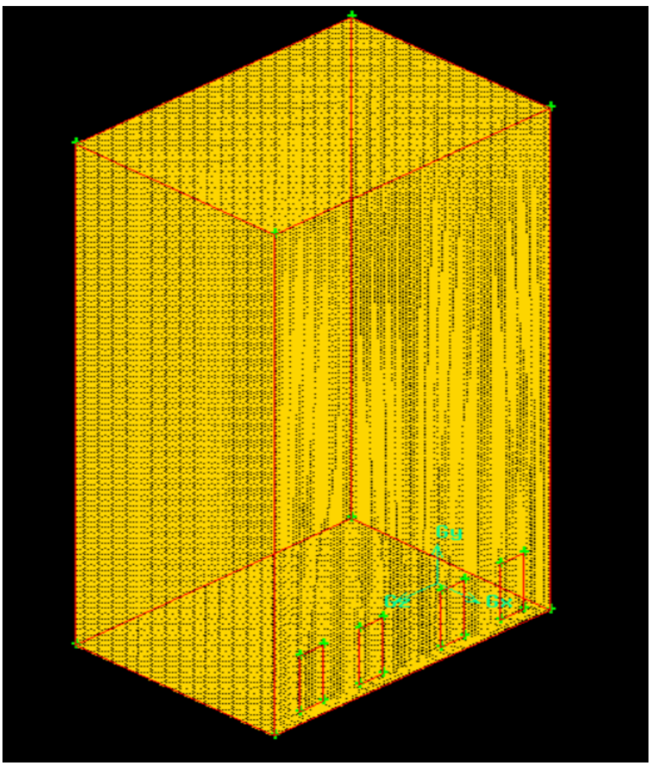

Fig. 2. Construction of a 3D model of the TP-14A boiler combustion chamber in the Gambit program, a simplified model with a generated computational grid

3. Simulation results

Numerical modeling requires verification and validation using reliable experimental data. The type of steam generator for modeling was selected from the condition of the possibility of verifying the results of modeling according to the data of (Kaverin 2017), where the test results of a similar steam generator at the Kumertau CHPP (Kaverin 2017) are considered. The physical adequacy of the created model in hydrodynamics is confirmed by the results of calculations of the pressure in the furnace, the values of which are close to atmospheric (Fig. 3a), and the absence of reverse currents. The adequacy of the calculations of combustion processes is confirmed by the fact that the maximum yield of volatiles and their most complete afterburning to CO_2 occur above the level of the location of the burners (Fig. 3b, 3c).

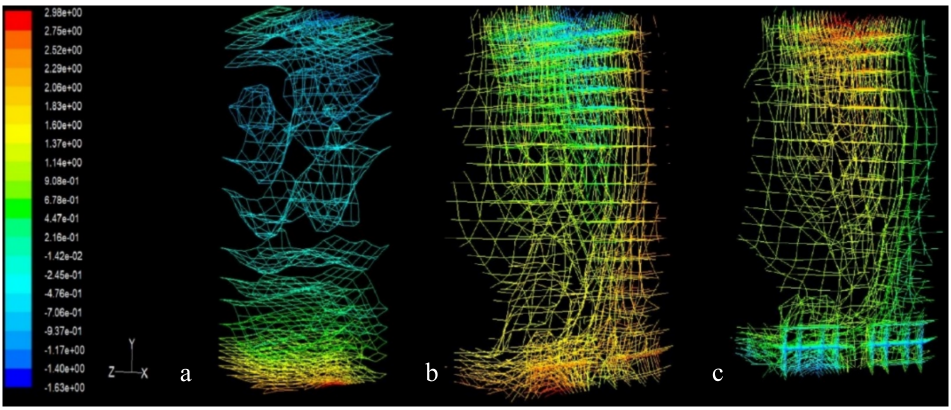

Fig. 3. Distribution of static pressure and content of volatile fuels and CO_2 in the TP-14A boiler furnace: a – calculated data on the distribution of static pressure in the boiler furnace, b – calculation results for the release of volatile fuels, c – the results of calculations on the afterburning of volatile fuels to CO_2

In recent decades, the ISAT (in situ adaptive tabulation) algorithm of adaptive tabulation of reactions has been practiced to study models of the combustion process of domestic boilers operating on gas fuel, which has now been made a number of improvements to increase its stability and speed without reducing the level of accuracy (Xie et al. 2018a, Xie et al. 2018b). However, they are adapted to internal combustion engines and need to be validated in the transition to boilers.

Recent versions of ANSYS include redesigned Chemkin combustion kinetics code in the ANSYS Chemkin-Pro software package to simulate pollutant emissions with detailed and accurate descriptions of combustion processes, taking into account the various properties of the fuel. Separate studies using Chemkin-Pro are available in the field of dioxin formation during combustion of halogen-containing compounds. They used 45- and 71-stage models of the formation of 1,3,6,8- and 1,3,7,9-TCDD (tetrachlorodibenzo-para-dioxins) from one starting compound 2,4,6-trichlorophenol.

ANSYS Chemkin-Pro software is designed for detailed kinetic modeling of chemical mechanisms. The program is a set of tools for solving a wide range of tasks. With the help of this product, equations of state are solved, thermophysical properties and reaction rates are determined (Recording… 2019).

To gain a deeper understanding of kinetic mechanisms, ANSYS Chemkin provides a Reaction Path Analyzer.

Having a visual display of kinetic mechanisms when using the Reaction Path Analyzer tool gives an accurate understanding of the prevailing pathways of reactions.

The ANSYS Chemkin Extinction Model provides fast and accurate calculations of flame decay rates to determine combustion stability. Attenuation is especially important to consider in premixed and low NO_x combustion systems.

ANSYS Chemkin's innovative particle tracing technology simulates particle nucleation, growth, aggregation and oxidation. Two independent tracing methods predict the average particle size and particle diameter distribution, which in turn can be used to predict the formation of soot or to optimize the particle production process.

Many combustion system designers use combustion models that are based on Flamelet libraries. ANSYS Chemkin provides a robust and fast method for generating Flamelet libraries as input to CFD models.

Combustion chamber modeling requires the resolution of complex geometry, turbulent flow, heat transfer, and detailed chemistry. Typical CFD analysis is used to model chemical kinetics on detailed geometry, but with simplified chemical reaction models that do not accurately predict emissions and product stability. The simplified formulation used in CFD modeling chemical kinetics cannot fully resolve the release of harmful substances such as NO_x, CO and unburned hydrocarbons. To allow the formation of these substances, it is necessary to use detailed kinetic mechanisms with hundreds of components and thousands of reactions.

The Energico software module allows you to superimpose idealized chemical reactors on the flow field, which makes it possible to effectively apply detailed chemistry of combustion processes to accurately determine the formation and destruction of components present in negligible concentrations. The use of equivalent reactor circuits makes it possible to represent the flow field in the form of a set of ideal mixing and ideal displacement reactors with appropriate gas inlets and outlets. Energico directly transmits the results of the gas dynamic calculation into an equivalent circuit that describes the prevailing flow distribution and recirculation zones. For each calculation step, Energico contains automated templates, as well as many additional parameters for fine-tuning.

4. Conclusions

Analysis of the ways of air pollution in the residential area shows that the negative role of large-scale energy storage in this issue is exaggerated. In connection with the continuing decentralization of heat supply to the housing stock, the contributions of large-scale energy and decentralized sources to the deterioration of the atmosphere are converging, and in aggregate they do not exceed the impact on the urban air environment of emissions generated during the handling of household waste, due to their toxicity.

The developed numerical model of the combustion device of the TP-14A steam boiler, despite some simplifications of geometry, showed physical adequacy and can be used for numerical studies of furnaces of heat sources with the constructive know-how of modern manufacturers, provided that solid fuel with characteristics close to standard is burned.

With their significant deviation, it is difficult to predict the adequacy of modeling by the kinetics of thermal oxidation reactions, since at present there are no robust algorithms that provide acceptable accuracy of results when processing models with a sufficient number of initial fuel components, and validated for steam generator furnaces.

The use of professional ANSYS Chemkin software tools for solving combustion problems and flows with chemical reactions in the design of boilers allows us to understand and predict the chemical processes occurring in the system, which is of key importance in the development and calculations of thermal power plants. In addition, the emission of pollutants must be minimized. It is very costly to carry out only field tests to accurately assess performance, given the complexity of the structures and the shortened design time. Detailed chemical simulations are often critical to the cost-effective design of low-emission systems.

References

Belyaeva, G. I., Ziganshin, M. G. & Sukhov, R. D. (2019). *Experimental and numerical studies in elaboration the multi-cyclone with filter cells to processing of flue-gases of coal-fired and incineration power Plants*. IOP Conference Series: Earth and Environmental Science, (288), 0120771-0120777. DOI: https://doi.org/10.1088/1755-1315/ 288/1/012077

Bilalov, M.I. & Ziganshin, M.G. (2019). *Estimates of the influence of the solar irradiation spectrum energy on the intensity of heat treatment of solid waste with hexavalent chromium*. IOP Conf. Series: Materials Science and Engineering, (481), 012044. DOI: https://doi.org/10.1088/1757-899X/481/1/012044

Feng, Z., Xiaofei, L., Jia-Wei, L., Jing, H., Jieru, Z., Bing, X. & Chengyang, H. (2018). Emission characteristics of PCDD/Fs in stack gas from municipal solid waste incineration plants in Northern China. *Chemosphere, (200)*, 23-29. DOI: https://doi.org/10.1016/j.chemosphere.2018.02.092

Hongting, Ma, Na, Du, Xueyin, Lin, Chaofan, Liu, Jingyu, Zhang & Zhuangzhuang, Miao. (2018). Inhibition of element sulfur and calcium oxide on the formation of PCDD/Fs during co-combustion experiment of municipal solid waste. *Science of the Total Environment, (633)*, 1263-1271. DOI: https://doi.org/10.1016/j.scitotenv.2018.03.282

Kaverin, A. (2017). Investigation of flare combustion of low-grade coarse-grained solid fuel in a system of direct-flow turbulent jets. Moscow: FAEI of HE «RI MPEI»

Min, Y., Liu, C.J., Shi, P.Y., Qin, C.D., Feng, Y.T. & Liu, B.C. (2018). Effects of the addition of municipal solid waste incineration fly ash on the behavior of polychlorinated dibenzo-p-dioxins and furans in the iron ore sintering process. *Waste Manage, (77)*, 287-293. DOI: https://doi.org/10. 1016/j.wasman.2018.04.011

Recording of the webinar «ANSYS Chemkin-Pro and Energico». (2019). Reaction Design Product Overview Retrieved from: https://www.plm-ural.ru/videos/zapis-vebinara-ansys-chemkin-pro-i-energico-obzor-produktov-reaction-design

Rigang, Z., Chen, W., Zuotai, Z., Qingcai, L. & Zongwei, C. (2020). PCDD/F levels and phase distributions in a full-scale municipal solid waste incinerator with co-incinerating sewage sludge. *Waste Management, (106)*, 110-119. DOI: https://doi.org/10. 1016/j.wasman.2020.03.020

Tugov, A.N., Ryabov, G.A., Shtegman, A.V. & Maidanik, M.N. (2018). Development experience of modern made in russia boiler installations. *Power engineering: research, equipment, technology, 20*(7-8), 87-98. DOI: https://doi.org/10.30724/1998-9903-2018-20-7-8-87-98

Xie, W., Lu, Z., Ren, Z. & Goldin, G.M. (2018a). Dynamic adaptive acceleration of chemical kinetics with consistent error control. *Combustion and Flame, (197)*, 389-399. DOI: https://doi.org/10.1016/J.COMBUSTFLAME.2018.08.018

Xie, W., Lu, Z. & Ren, Z. (2018b). Rate-controlled constrained equilibrium for large hydrocarbon fuels with NTC. *Combustion Theory and Modelling, 23*, 226-244. DOI: https://doi.org/10.1080/13647830.2018.1513566

Ziganshin, M.G. (2019). Method of assessment generation efficiency at thermal power plants taking into account emissions of pollutants. *Power engineering: research, equipment, technology, 21*(6), 29-38. DOI: https://doi.org/10.30724/1998-9903-2019-21-6-29-38

Ziganshin, M.G., Ziganshin, A.M. & Dmitriev, A.V. (2009). Equipment and working conditions for comprehensive treatment of discharges containing halogen-bearing pollutants. *Chemical and Petroleum Engineering, (45*), 230-235. DOI: https://doi.org/10.1007/s10556-009-9153-8

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Heavy Metals and Metalloids Leachability from Composite Ground Materials Peat – Fly Ash – Lime

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Abstract: This publication presents the test results of heavy metals and metalloids leachability from ground composite materials. The components of the obtained composites are peat and stabilizing binders in the form of fly ash and hydrated lime. The composites were designed to be used to stabilize low-bearing organic soil in the Lake Druzno basin in the area of Żuławy Elbląskie. The results of the leachability studies show that as the lime hydrated in the composition of the composite increases, the leachability of heavy metals and metalloids decreases. The decrease in the leachability of these elements is also influenced by the increase in the pH value. The results of heavy metals and metalloids leachability from composites as well as the obtained pH values make it possible to conclude that they are neutral to the ground environment and can be used in engineering practice under specific conditions in the area of Żuławy Elbląskie.

Keywords: Leachability, heavy metals, metalloids, peat, fly ash, hydrated lime, pH value

1. Introduction

Heavy metals play a major role in pollution and environmental degradation. The type, concentration and distribution of them in the soil depends on many natural factors such as granulometric composition, hydrogen ion content, organic matter content, soil type as well as geological and soil processes (Kończak-Konarkowska & Kuziak 2000). Environment is also affected by anthropogenic factors such as industrial contaminants and agrotechnical activities (Baran 2000, Kanakaraju et al. 2019, Skwaryło-Bednarz et al. 2014, Zorluer 2020).

Reinforcing the substrate with various stabilizers can increase the content of heavy metals in the ground. The ground composite material stabilizing the substrate should be selected so that it has established physical and mechanical properties. It is a common practice to use easily available materials in the vicinity of the construction site as components of composites. Cement, lime and gypsum, blast furnace slag, fly ash or mixtures of these materials are used as binders (Hayashi et al. 2005, Rathore et al. 2018, Timoney et al. 2012). This has a direct impact on the technologies of execution and, above all, on the economic effect (Afrin 2017, Al-Tabbaa 2005, Cortellazzo et al. 1999).

The purpose of the research is to select the optimal stabilizer in such a way that the resulting ground composite material has the assumed physical and mechanical properties.

The basic criterion for the applicability of composites should be their neutral environmental impact. This is particularly important in areas that are protected e.g., under EU or national programmes and in areas bordering national or landscape parks.

Important factors influencing solubility, adsorption and the presence of heavy metals in the porous solution are the content of hydrogen ions and organic matter. As the pH value decreases, their mobility increases (Wójcik 2009). Therefore, it is important to choose a stabilizer that will simultaneously stabilize the soil and increase its pH value (Jonczy et al. 2014, Kopańska & Dudziak 2015, Sybilski & Kraszewski 2004).

The purpose of the work is to assess the possibility of using ground composite materials, peat – fly ash – lime, in the basin of Lake Druzno in the area of Żuławy Elbląskie in terms of the content of heavy metals and metalloids and assessing their impact on environmental pollution.

The parameter assessing the degree of risk will be the leachability of heavy metals and metalloids from ground composite materials.

The phenomenon of leachability is the process by which soluble components change from solid material to liquid as a result of percolation or diffusion (Makowska et al. 2018).

2. Methods and materials

Composites made from the base material in the form of peat taken from the basin of Lake Druzno, Żuławy Elbląskie, and stabilizing materials in the form of fly ash and hydrated lime, were used for the study.

The selection of stabilizing binders was carried out on the basis of preliminary tests aimed at determining the amount of stabilizer in terms of binding properties and with a view to economic viability.

Peat (P) was taken by means of a drill from the depth of 0-2 m and additionally with mechanical equipment directly at the site of the excavation. The collected peat was mixed and then subjected to detailed laboratory tests.

A thermogravimetric method with the temperature range 105-650°C was used to determine the organic matter content of the base material. The formulas in PN-88/B-04481 were used to calculate natural humidity, density and porosity. The organic matter content was used to calculate the density of the ground skeleton using empirically established correlation relations (Borys 1993). The potentiometric method determined the concentration of hydrogen ions contained in the peat solution using an Elmetron CX-701 electronic pH meter. The degree of decomposition was determined on the Van Post scale (Post 1922). The results of the tests can be found in Table 1.

Table 1. Physical and chemical properties of peat and organic matter content

Physical and chemical properties	Humidity, W_n [%]	Bulk density, ρ [kg/m^3]	Specific density of the soil skeleton, ρ_s [kg/m^3]	Organic matter content, I_{OM} [%]	pH value	Porosity, n	Degree of decomposition, H
	350.0	$9 \cdot 10^2$	$1.8 \cdot 10^3$	62.9	6.5	0.88	H4-H5

Fly ash (FA) from the Elbląg Power Plant was used to make ground composite materials. It is obtained by gravity using fans blowing it out from under the furnace. Fly ash is formed by burning coal dust of type 32 MIIA in dust boilers. The tests of the chemical composition of fly ash carried out by means of the Thermo iCAP 6500 Duo ICP plasma spectrometer is shown in Table 2. The calculated specific density was 2298.32 kg/m^3 and the specific area was 364.78 m^2/kg. Le Chatelier method and Blaine method (Żygadło & Wozniak 2009) were used in the calculations, respectively. On the basis of the data obtained, the tested fly ash can be classified as silicate ash and the category A due to roasting losses of 3.71%. A radioactivity determination was also made with background radiation of 0.14 μSv/h. The ash showed 0.21 μSv/h, i.e., contains only trace quantities of radioactive elements.

Table 2. Chemical composition of fly ash

Ingredient	SiO_2	Fe_2O_3	Al_2O_3	Mn_3O_4	TiO_2	CaO	MgO	SO_3	P_2O_5	Na_2O	K_2O	BaO	SrO
Quantity [%]	56.5	6.9	18.6	0.12	0.86	4.74	2.81	0.48	0.41	0.72	3.08	0.16	0.07

Dry-slaked hydrated lime (HL), commercially named “Bielik”, was also used to stabilize peat and is referred to as building lime EN 459-1 CL 90-S

(Karta charakterystyki 2018). Hydrated lime consists of CaO – min 92%, MgO – max 1%, SO_3 – max 0.5% and CO_2 – max 2.5%.

15 mixtures were designed, taking the ratio of fly ash mass to peat (FA/P) and hydrated lime to peat (HL/P) as shown in Table 3. The ingredients were mixed using a mechanical mixer which mixed the ground with the stabilizer for about two to three minutes to obtain a homogeneous mass. The mixed ingredients were placed in cubic forms measuring 150x150x150 mm. The formed samples were cured in a tightly closed container with access to water, where the relative vapour pressure $p/po \approx 1$.

Table 3. Composition of ground composite, peat – fly ash – lime hydrate in mass ratio

Composite	FA/P	HL/P
C1	0.25	0.0125
C2	0.25	0.025
C3	0.25	0.0375
C4	0.25	0.05
C5	0.25	0.0625
C6	0.50	0.025
C7	0.50	0.05
C8	0.50	0.075
C9	0.50	0.1
C10	0.50	0.125
C11	0.75	0.0375
C12	0.75	0.075
C13	0.75	0.1125
C14	0.75	0.15
C15	0.75	0.1875

The test of heavy metals leachability from ground composite material and fly ash was carried out in the accredited Laboratory of Advanced Environmental Analysis of the Elbląg Technology Park.

The test material was taken from samples which were cured for 28 days under laboratory conditions in a sealed container with access to water, where the relative vapour pressure $p/po \approx 1$.

According to the instruction, the preparation of the test water extract (RRM 2000) consisted in taking from each sample approximately 1 kg of composite which was dried at 105°C and then sifted through a standard woven sieve with square meshes No. 10. The sample of fly ash was taken and prepared in the same way. 0,1 kg samples were weighed from the sifted mass of composites and ash, placed in a flask and then flooded with distilled water in a mass ratio of 1:10. The tightly closed flask was shaken on the laboratory shaker for 4 hours. After 12 hours, the shaking process was repeated for 4 hours and then the suspension was left for 6 hours. The prepared suspension was filtered through a membrane filter with pores of 0.45 μm using a pressure-reduced filtration apparatus. The obtained (water extract) 10 ml of filtrate was mineralised with 7 ml of nitric acid and 3 ml of hydrogen peroxide. The process of mineralisation was carried out in a 1800 W Milestone Ethos One microwave mineraliser for 20 minutes at 205°C.

The concentration of the following metals and metalloids in the samples was determined: arsenic, cadmium, general chromium, copper, lead, molybdenum, nickel, vanadium, zinc, selenium, cobalt, iron, manganese. The test was performed in accordance with PN-EN ISO 17294-2:2016 by means of a mass spectrometer with inductively aroused plasma ICP-MS Agilent Technologies 7700x. Certified solutions and formulas conforming to the above standard were used during the test.

The prepared water extracts were also used to carry out tests on the hydrogen ion content by means of the Elmetron CX-701 pehameter with a measuring range of 3 to 20 pH and a measurement accuracy of up to 0.001 pH. The electrode used in the test was Elmetron EPP-1 designed to test both pure and contaminated liquids. Before each subsequent test of the individual composites, the device was calibrated using calibration solutions.

3. Test results

Strengthening soil with fly ash can pose a risk of environmental pollution from heavy metals. The permissible content of heavy metals, whether in waste material itself or in surface water, soil and ash itself resulting from the combustion of coal, is regulated by standards and regulations (DSO 1999, RMG 2015, RMOŚZNL 1995, RRM 2016, Sybilski & Kraszewski 2004). Coal-burning ashes are not classified as hazardous waste but, at the same time, due to their heavy metal content, cannot be considered neutral (RRM 2014). Table 5 shows the limit values of heavy metal content for surface water, non-hazardous waste and fly ashes (DSO 1999, RMG 2015, RMOŚZNL 1995, Sybilski & Kraszewski 2004). The test of heavy metal leachability from ground composite materials was carried out twice for each composite and for fly ash, and the obtained results are presented in Table 4 as the arithmetic means.

Table 4. Heavy metals and metalloids content in water extracts from ground composite materials and fly ash

Element / Composite	C 1 [mg/l]	C 2 [mg/l]	C 3 [mg/l]	C 4 [mg/l]	C 5 [mg/l]	C 6 [mg/l]	C 7 [mg/l]	C 8 [mg/l]	C 9 [mg/l]	C 10 [mg/l]	C 11 [mg/l]	C 12 [mg/l]	C 13 [mg/l]	C 14 [mg/l]	C 15 [mg/l]	Fly ash [mg/l]
Total chromium [Cr]	0.1122	0.1147	0.0806	0.0816	0.0826	0.0961	0.0732	0.0384	0.0970	0.0604	0.0731	0.1059	0.0991	0.0773	0.0768	0.2835
Nickel [Ni]	0.0333	0.0425	0.0259	0.0478	0.0694	0.0312	0.0429	0.1078	0.1824	0.1535	0.0276	0.0673	0.0944	0.0931	0.0851	0.0000
Copper [Cu]	0.0759	0.0936	0.0730	0.1714	0.1451	0.1160	0.1055	0.1865	0.2944	0.2963	0.1974	0.2278	0.2484	0.2320	0.2260	0.0122
Zinc [Zn]	0.0214	0.0645	0.0016	0.0706	0.0231	0.0260	0.0000	0.1410	0.0000	0.0000	0.0388	0.0000	0.0000	0.0000	0.0000	0.0000
Arsen [As]	0.0095	0.0162	0.0216	0.0293	0.0305	0.0113	0.0143	0.0267	0.0131	0.0132	0.0122	0.0163	0.0161	0.0145	0.0043	0.0012
Selenium [Se]	0.0150	0.0184	0.0174	0.0214	0.0260	0.0222	0.0276	0.0323	0.0321	0.0284	0.0286	0.0353	0.0317	0.0274	0.0282	0.0195
Molybdenum [Mo]	0.1036	0.1201	0.1008	0.1207	0.1222	0.1110	0.1445	0.1401	0.1661	0.1287	0.1262	0.1514	0.1271	0.1165	0.0965	0.1598
Cadmium [Cd]	0.0002	0.0053	0.0001	0.0002	0.0003	0.0001	0.0003	0.0001	0.0002	0.0001	0.0002	0.0001	0.0001	0.0002	0.0000	0.0001
Antimony [Sb]	0.0049	0.0098	0.0091	0.0107	0.0143	0.0100	0.0136	0.0049	0.0062	0.0013	0.0115	0.0326	0.0032	0.0024	0.0007	0.0002
Barium [Ba]	0.3148	0.3909	0.0944	0.0853	0.0563	0.1250	0.1032	0.1234	0.3722	0.5048	0.1578	0.0964	0.1860	0.4669	0.8899	1.0076
Mercury [Hg]	0.0013	0.0011	0.0009	0.0007	0.0006	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0004	0.0004	0.0003	0.0002	0.0004
Lead [Pb]	0.0122	0.0242	0.0044	0.0051	0.0028	0.0030	0.0044	0.0022	0.0042	0.0007	0.0072	0.0117	0.0016	0.0008	0.0008	0.0004

Table 5. Acceptable concentrations of heavy metals for selected environmental conditions (DSO 1999, RMG 2015, RMOŚZNL 1995, Sybilski & Kraszewski 2004)

Element	Limit value for waste materials (non-hazardous) [mg/l]	Values of surface water pollution indicators (purity classes) [mg/l]			Maximum acceptable content for ashes [mg/l]
		I	II	III	
Total Chromium [Cr]	1	–	–	–	0.1
Nickel [Ni]	1	<1.0			0.1
Copper [Cu]	5	<0.05			1.00
Zinc [Zn]	5	–	–	–	3.0
Arsenic [As]	0.2	<0.05		<0.2	0.1
Selenium [Se]	0.05	<0.01			0.05
Molybdenum [Mo]	1	–	–	–	–
Cadmium [Cd]	0.1	<0.05	<0.05	<0.05	–
Antimony [Sb]	–	–	–	–	–
Barium [Ba]	10	–	–	–	1.00
Mercury [Hg]	0.02	<0.001	<0.05	<0.01	0.005
Lead [Pb]	1	<0.05			0.1

In the test samples of all ground composite materials and fly ash, the content of heavy metals such as cadmium, total chromium, lead, molybdenum, nickel, vanadium, zinc, cobalt, iron and metalloids such as arsenic, selenium and antimony was mostly lower than acceptable concentrations for selected environmental conditions, as shown in Table 4. As research by the Research Institute of Roads and Bridges (Sybilski & Kraszewski 2004) shows, the laboratory conditions in which samples are prepared and experiments conducted are more conducive to leachability than under natural environmental conditions.

The amount of selenium and copper in the composite samples tested slightly exceeds the limit values for surface water contamination indicators. The copper content of the fly ash itself is lower than in the ready-made composites. This might be due to the fact that copper is a compound strongly bonded by an organic substance in the ground (Konarkowska & Kuziak 2000). The same is true of selenium whose larger amounts are found in soils rich in organic matter (Niedzielski et al. 2000).

No nickel and zinc compounds were detected in the fly ash. However, trace amounts of zinc can be found in selected composites. The zinc content, which occurs naturally in the ground, changes together with the organic matter content in the composites, as shown in Table 4. In composites with the smallest amount of organic matter zinc was not detected.

In the all tested composite materials the pH value after 28 days of curing was above 9. The lowest value, i.e., 9.93, was obtained by the C1 composite with the smallest amount of fly ash and hydrated lime. The highest pH value, i.e., 12.88, was obtained by the C15 composite, where the stabilizer content was the highest. The pH value of the tested peat was 6.5, fly ash 12.30 and the hydrated lime 13.02. The increasing pH values are undoubtedly related to the addition of increasing amounts of stabilizer which minimizes the acidic reaction of peat. The pH values of all composites are shown in Table 6.

Table 6. PH values of ground composite material, peat – fly ash – hydrate lime

Composite	pH value
C1	9.93
C2	10.74
C3	11.63
C4	11.97
C5	12.31
C6	12.23
C7	12.50
C8	12.59
C9	12.68
C10	12.81
C11	12.30
C12	12.47
C13	12.69
C14	12.81
C15	12.88

It can be seen that in composites with the highest content of hydrated lime, the content of heavy metals is significantly lower. This fact has been confirmed by the research conducted in the Institute for Road and Bridge Research (Sybilski & Kraszewski 2004). It has shown that adding lime, which increases the pH value, also influences the reduction of heavy metal leachability from fly ash. This is particularly important while building roads where there is a possibility of high hydration of the substrate (Sybilski & Kraszewski 2004).

Based on the results of studies as well as literature of the subject, it can be concluded that the low leachability of heavy metals and metalloids is related to the high pH value (Desfitri et al. 2020, Leelarungroj et al. 2018). The reduction of heavy metals can also be the result of a pucolanic reaction and the formation of the CSH phase and ettryngite (Leelarungroj et al. 2018, Liu et al. 2018).

Therefore, it can be assumed that environmental pollution while strengthening organic soil with fly ash and lime, in the area of Elbląg Żuławy, and the Druzno Lake Basin in particular, might be of no practical importance. The use of these stabilising materials does not pose any threat to the environment, cultivated soils and humans. As a result, they can be used to strengthen organic soil (Filipiak 2013) for road construction and low volume structures in the area.

4. Conclusions

On the basis of the presented results of the studies, the following conclusions can be drawn:

- The low heavy metal and metalloids leachability from composites makes it neutral for the ground environment, which is important because these sites are protected under the Nature 2000 Programme (Szablon projektu 2013).
- The amount of leachable heavy metals and metalloids decreases with an increased amount of stabilizer. The smallest amounts of leachable metals and metalloids were obtained for composite C15, which is the optimal ratio of fly ash to peat FA/P = 0.75 and lime hydrated to peat HL/P = 0.1875. This is evident in case of mercury, where its quantity in composite C1 is 0.00129 mg/l and in composite C15 is 0.00023 mg/l.
- The addition of hydrated lime increases the pH value, which is associated with a decrease in the leachability of heavy metals and metalloids.
- The decrease in the amount of heavy metals and metalloids in compo-sites can also be the result of a pucolanic reaction and the formation of the CSH phase as well as ettryngite.
- The use of fly ash for strengthening the organic ground substrate in the area of the Lake Druzno basin might be one of the ways of managing the energy products of coal combustion from the Elbląg Power Plant. It can also contribute to reducing environmental pollution with stored material.
- Further work concerning the analyzed issue should consist in testing the water permeability of composite materials, which might be one of the parameters assessing the flow rate of heavy metals.

References

Afrin, H. (2017). A review on different types soil stabilization techniques. *International Journal of Transportation Engineering and Technology, 3*(2), June 2017, 19-24. DOI: 10.11648/j.ijtet.20170302.12

Al-Tabbaa, A., Evans, W.C. (2005). *Stabilization-Solidification Treatment and Remediation: Part I: Binders and Technologies-Basic Principal*. Proceedings of the International Conference on Stabilization/Solidification Treatment and Remediation. Pages: 367-385. Cambridge, UK: Balkerma. DOI: org/10.1201/9781439833933

Baran, S. (2000). *Ocena stanu degradacji i rekultywacji gleb*. Wyd. AR Lublin, 106-133.

Borys, M. (1993). *Niskie nasypy z miejscowych gruntów organicznych dla potrzeb budownictwa wodno-melioracyjnego*. Rozprawa habilitacyjna. Instytut Melioracji i Użytków Zielonych, Falenty (in Polish).

Cortellazzo, G., Cola, S. (1999). Geotechnical Characteristics of Two Italian Peats Stabilized with Binders. Proceeding of Dry Mix Methods for Deep Soil Stabilization. Pagers 93-100. Stockholm: Balkerma.

Desfitri, E.R., U.M., Hayakawa, Y., Kambara, S. (2020). Effect of additive material on controlling chromium (cr) leaching from coal fly ash. *Minerals 10*(6), 563. DOI: 10.3390/min10060563

Dyrektywa w sprawie Składowania Odpadów (DSO) – Dyrektywa 99/31/WE.

Filipiak, J. (2013). Wykorzystanie ubocznych produktów spalania jako stabilizatora do wzmacniania gruntów organicznych. *Rocznik Ochrona Środowiska, 15*(2). 1153-1163.

Hayashi, H., Nishimoto, S. (2005). Strength Characteristic of Stabilized Peat using Different Types of Binders. *International Conference on Deep Mixing – Best Practice and Recent Advances, Report, 13*(1), 55-62, Stockholm.

Jonczy, I., Huber, M., Lata, L. (2014). *Mineral Resour Manage, 30,* 161-174. DOI: 10. 2478/gospo-2014-0008

Kanakaraju, D., Norfadzila, D., Nori, H., Wahi, R. (2019). Heavy metals leachability in fly ash remediated soil. *Journal of Sustainability Science and Management, 14*(2), 35-45.

Karta charakterystyki. (2018). Wapno budowlane EN 459-1CL 90-S. Wapno hydratyzowane. Trzuskawica S.A.

Kończak-Konarkowska, B., Kuziak, M. (2000). *Stan zanieczyszczenia gleb metalami ciężkimi*. Biblioteka Monitoringu Środowiska, 100-112, Gorzów Wielkopolski.

Kopańska, D., Dudziak, M. (2015). Występowanie metali ciężkich w wybranych gruntach nasypowych. *Proceedings of ECOpole. 9*(1), 237-244. DOI: 10.2429/ proc.2015.9(1)03

Leelarungroj, K., Likitlersuang, S., Chompoorat, T., Janjaroen, D. (2018). Leaching mechanisms of heavy metals from fly ash stabilised soils. *Waste Manag Res., 36*(7), 616-623. DOI: 10.1177/0734242X18775494

Liu, J., Zha, F., Xu, L., Deng, Y., Chu, Ch. (2018). *Engineering properties of heavy metal contaminated soil solidified/Stabilized with high calcium fly ash and soda residue*. In book: Proceedings of GeoShanghai 2018 International Conference: Geoenvironment and Geohazard. 442-449. DOI: 10.1007/978-981-13-0128-5_49

Makowska, D., Świątek, K., Wierońska, F., Strugała, A. (2018). Wymywanie arsenu z odpadów powęglowych: ocena metod badawczych. *Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk, 105,* 157-171. DOI: https://doi.org/10.24425/124378

Niedzielski, P., Siepak, M., Siepak, J. (2000). Występowanie i zawartości arsenu, antymonu i selenu w wodach i innych elementach środowiska. *Rocznik Ochrona Środowiska, 2*, 317-341.

PN-88/B-04481 Grunty budowlane. Badania próbek gruntu.

PN-EN ISO 17294-2:2016 Jakość wody – Zastosowanie spektrometrii mas z plazmą wzbudzoną indukcyjnie.

Post van, L. (1922). Sveriges Geologiska Undersöknings torvinventering och några av dess hittills vunna resultat. *Svenska Mosskulturföreningens Tidskrift*, 1-37, Jönköping.

Rathore, A.P.S., Pathak, D., Sharma, J.K. (2018). Review of soil stabilization using different types of stabilizers. *International Journal of Advance Research in Science & Engineering, 07*(02), 540-544.

Rozporządzenie Ministra Gospodarki (RMG) z dnia 16 lipca 2015 r. W sprawie dopuszczania odpadów do składowania na składowiskach.

Rozporządzenie Ministra Ochrony Środowiska, Zasobów Naturalnych i Leśnictwa (RMOŚZNL) z dnia 5 listopada 1991 r. w sprawie klasyfikacji wód oraz warunków, jakim powinny odpowiadać ścieki wprowadzane do wód lub do ziemi.

Rozporządzenie Rady Ministrów (RRM) z dnia 1 września 2016 r. W sprawie sposobu prowadzenia oceny zanieczyszczenia powierzchni ziemi.

Rozporządzenie Rady Ministrów (RRM) z dnia 27 grudnia 2000 r. zmieniające rozporządzenie w sprawie opłat za składowanie odpadów.

Rozporządzenie Rady Ministrów (RRM) z dnia 9 grudnia 2014. W sprawie katalogu odpadów.

Skwaryło-Bednarz, B., Kwapisz, M., Onuch, J., Krzepiłko, A. (2014). Ocena zawartości metali ciężkich i aktywności katalazy w glebach otuliny Roztoczańskiego Parku Narodowego. *Acta Agrophysica, 21*(3), 351-359.

Sybilski, D., Kraszewski, C. (2004). *Ocena i badania wybranych odpadów przemysłowych do wykorzystania w konstrukcjach drogowych*. Instytut Badawczy Dróg i Mostów w Warszawie, Warszawa. DOI: 10.13140/RG.2.1.4512.8566

Szablon projektu dokumentacji Planu Zadań Ochronnych obszaru o znaczeniu dla Wspólnoty Natura 2000 Ostoja Druzno PLH280028 w województwie warmińsko-mazurskim. (2013). Warszawa.

Timoney, M.J., McCabe, B.A., Bell, A.L. (2012). Experiences of dry soil mixing in highly organic soils. *Proceedings of the Institution of Civil Engineers Ground Improvement, 165*, 3-14. DOI: org/10.1680/grim.2012.165.1.3

Wójcik, R. (2009). *Geologia, 35*, 305-311.

Zorluer, I. (2020). Evaluation of Trace Elements from Used Industrial Waste in Soil improvement. *Earth Sciences, An. Acad. Bras. Cienc., 92*(3). DOI: org/10.1590/0001-3765202020200974

Żygadło, M., Woźniak, M. (2009). Obserwacje zmian właściwości popiołów powęglowych w procesach wietrzeniowych. *Energetyka, 11*, 771-715.

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Variation Between Voivodships in Terms of Forest Area and Silviculture Activities in Polish Forests in 2015-2019

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Abstract: The objective of the study reported here was to compare voivodships in terms of forest area, forest regeneration area, afforested area, thinned forest area and natural forest regeneration area Main Statistical Office data for Polish voivodships was analysed. It included forest area, natural forest regeneration and silviculture activities (forest regeneration, afforestations and thinning) in all forests, state-owned forests and privately-owned forests. Voivodships were compared using the arithmetic mean, the indicator of structure, the average rate of change, principal component analysis and cluster analysis. Principal Component Analysis, revealed that state-owned forest area, forest regeneration in state forests, total forest regeneration, and thinning in state-owned forests had the greatest share in the multivariate variation among voivodships analysed in terms of forestry. Cluster analysis yielded two groups of voivodships. The voivodships in the first group had a higher average total forest area, area of state-owned forests, total area of forest regeneration and forest regeneration in state-owned forests, area of natural forest regeneration and thinning in state-owned forests. On average, forests of voivodships which formed group 2 included less privately-owned forests in which fewer forest regeneration and afforestation activities had been conducted. Opolskie and Śląskie Voivodships as well as Łódzkie and Świętokrzyskie Voivodships were the most similar in terms of all the analysed characteristics.

Keywords: forest area, forest regeneration, afforestation, thinning, voivodship

1. Introduction

The forest area in Poland in 2019 was 9,258.8 th ha (Rocznik… 2020). Increasing forest cover is a permanent element of spatial, ecological and economic policy of the country. The forested area in Poland has constantly been growing since World War II (Sobczak 1996). Forest cover increased from 20.6% in 1946 to 29.6% in 2019 (Broda 2000, Polna 2017, Leśnictwo… 2017, Rocznik… 2020). The State Forests National Forest Holding manages 76.9% total forest area, privately-owned forests cover 19.3% and the remaining 3.8% is made up of e.g.: forests in National Parks and community-owned forests. In the European Union, Poland is at+ the forefront of countries with the greatest forest area. Of all the forests in Poland, lowland forests cover 7.8 million ha (85% forest area), highland forests – 600 thousand ha, and mountain forests – 795 thousand ha (Jagodziński 2019).

Despite the leading position of Poland in Europe, all the neighbouring countries (excluding Ukraine – 16.7%) have a higher percentage of forests in the land area (Poland – 30.8%) which is 32.8% in Germany, 34.5% in the Czech Republic, 36.4% in Lithuania, 40.4% in Slovakia, and 44.5% in Belarus (Leśnictwo… 2017).

Afforestation is defined as an initiation of the forest establishment process and regeneration (restoration of community structure and function due to internal forces) of the forest ecosystem in the place where, for a variety of reasons and at a different time, the forest was replaced with other land use forms. Both forests and forested areas should be attended to, that is subjected to various practices and actions to control tree stand development. Thinning, being one of such practices, conditions structural diversity, dynamics of development and productivity of tree stands (Brzeziecki 2005, Lockow 2003). In forestry, thinning is defined as the selective removal of trees which is mainly conducted in order to improve the growth rate or take care of the health of the remaining trees. Forest areas developing in this way play many important environmental and economic roles which include: nature and landscape protection, strengthening and expanding the forest functions contributing to water and air protection, reduction of the 'greenhouse effect' and counteracting global climate change, enhancing the aesthetic and recreational advantages of the environment, rehabilitation of contaminated and degraded land, implementation of spatial management policy, land use rationalisation, management of regional development and rural area development in an economic sphere (Gorzelak 1999, Falencka-Jabłońska 2012, Wysocka-Fijorek 2020).

Research indicates that from the point of view of land use structure and environment management in Poland and the present stage of civilisation development, rational forest cover should be 33-34% (Kwiecień et al. 2002). Afforestations are conducted based on the 'The National Programme of Increasing

Forest Cover' (1995). It assumes the proper conditions will be created to increase Poland's forest cover to 30% in 2020 and to 33% in 2050. The programme outlines an optimum distribution of afforestation, establishes ecological and economic priorities and instruments necessary to achieve them. Particular stress is placed on strengthening environmental functions (water and soil conservation, nature protection). Based on the established criteria, afforestations carried out in Wielkopolskie and Kujawsko-pomorskie Voivodships are most preferred, and those in Opolskie, Dolnośląskie and Śląskie Voivodships – the least preferred (Krajowy… 2003, Kaliszewski et al. 2016).

Forests, like other ecosystems, are largely shaped by human activity (Vitousek et al. 1997, Bomanowska, Kiedrzyński 2011). The worldwide concern for the state of forests, the need for their protection and sustainable management of forest resources manifest themselves in international conventions pertaining to forests and environmental protection (Paschalis 1992, Paschalis-Jakubowicz 2011). Sustainable management of forests requires suitable tools which make it possible to implement the overall rules adopted in strategic documents (Rykowski 2006, Wijewardana 2008). It is necessary to adjust forest management and use concepts to new conditions (Gil et al. 2002, Golos 2008).

One of basic tasks of modern forestry is to sustainably meet the needs of the society by permanent maintaining and rational utilisation of forest resources. In order to achieve these tasks, constant control of the effects of human interference with forests ecosystems (Stępień 1995), particularly when there is growing demand for information about forests (Vidal et al. 2008, Talarczyk 2015) and changing expectations of the society as to the functions forests fulfil (Paschalis-Jakubowicz 2011). A proper assessment of the forest's condition requires a clearly defined system of indicators matching the spatial scale of undertaken activities (McElhinny et al. 2005, Motz et al. 2010, Jabłoński et al. 2017).

The Ministerial Conference on the Protection of Forests in Europe (MCPFE), at present referred to as Forest Europe, is indicated as the major initiative of European countries in terms of improving and assessing the permanently sustainable forest management (Paschalis-Jakubowicz 2010). Thus, there is a need for an assessment of forests and forest management. Forest area and its temporal changes are one of basic indicators referred to by authors (State… 2011, Baycheva et al. 2013, Jabłoński 2015). The forest area in Poland undergoes an annual assessment within the programmes of examining public statistics (Rozporządzenie … 2014, Jabłoński 2015), and the results are presented in Statistics Poland (SPL) Yearbooks (Leśnictwo… 2017; Ochrona… 2013).

2. Materials and methods

Data for the years 2015-2019 published in SPL Yearbooks was analysed (GUS 2016, 2017, 2018, 2019).

The first step of the analysis involved calculation of arithmetic means and indicators of structure for all the examined characteristics. In order to study temporal changes in phenomena, an average rate of change (tz) was calculated according to the formula (Sobczyk 2007):

$$tz = \left(\bar{y}_g - 1\right) \tag{1}$$

where: tz – average rate of change; $\bar{y}_g$ – geometrical mean of chain indices for 2015-2019 calculated as follows:

$$I = \frac{y_n}{y_{n-1}} \tag{2}$$

where: I –index of dynamics, y_1 – value of the phenomenon in the study period, y_0 – value of the phenomenon in the base period.

In order to determine the multivariate variation of objects (voivodships) in terms of 11 characteristics, principal component analysis (PCA) was employed. The following variables were selected: X_1 – total forest area, X_2 – state-owned forest area, X_3 – privately-owned forest area; X_4 – total forest regeneration; X_5 – forest regeneration in state-owned forests; X_6 – forest regeneration in privately-owned forests; X_7 – total afforestation; X_8 – afforestation in state-owned forests; X_9 – afforestation in privately-owned forests; X_{10} – natural forest regeneration in state-owned forests; X_{11} – thinning in state-owned forests.

The principal components whose eigenvalues were greater than 1 (according to Kaiser criterion (1958) were interpreted. Next, in order to divide voivodships into groups with similar parameters reflecting silvicultural activities undertaken in forests, cluster analysis was carried out by means of Ward's method, the Euclidean distance being chosen as a measure of multivariate dissimilarity of objects.

To obtain clusters, the dendrogram was divided following Mojena rule according to which the cut-off level is the length of the bond for which the following is true (Milligan and Cooper 1985):

$$\mathrm{d}_{\mathrm{i}+1} > \bar{\mathrm{d}} + \mathrm{ks}_{\mathrm{d}}; \tag{3}$$

where: $\bar{\mathrm{d}}$ and s_{d} are, respectively, mean and standard deviation of d_i and k is a constant ranging from 2.75 to 3.50 (Mojena 1977). Following Milligan and Cooper (1985), the value k = 1.25.

3. Results and discussion

Analysis of values presented in Table 1 revealed that the highest total forest area was in Zachodniopomorskie Voivodship (indicator of structure – almost 9%), followed by Mazowieckie (almost 9%), Warmińsko-mazurskie and Wielkopolskie Voivodships (8.4% for both).

By contrast, the lowest area was found for Opolskie Voivodship (indicator of structure – less than 3%). The total forest area remained unchanged throughout the study period as reflected in the value of average rate of change (0.0%). The same situation was found for state-owned forests. The greatest total forest area was in Zachodniopomorskie Voivodship (indicator of structure – almost 11%) followed by Lubuskie (9.4%) and Pomorskie Voivodship (more than 8%). The smallest area of state forests was found in the Małopolskie Voivodship (indicator of structure – below 3%. The average rate of change in voivodships was 0.0%, too. For privately-owned forests, they covered largest area was in Mazowieckie followed by Lubelskie and Podlaskie Voivodship (21%, more than 13%, and more than 11%, respectively). The lowest value was for Lubuskie and Opolskie Voivodships (less than 1%). The average rate of change in the area of privately-owned forests was the greatest (1.2%) in Zachodniopomorskie and Warmińsko-mazurskie Voivodship. The rate indicates that the average yearly increase in the area of privately-owned forests was 1.2%. Moreover, in 10 voivodships, the average increase was 1%.

Table 1. Arithmetic mean (thousand ha), index of structure (Ws %) and average rate of change (tz %) for total forest area, privately-owned forest area and state-owned forest area in individual voivodships in 2015-2019

Voivodship	Total			State-owned			Privately-owned		
	$\bar{x}$	Ws	tz	$\bar{x}$	Ws	tz	$\bar{x}$	Ws	tz
Dolnośląskie	580.3	6.5	0.0	552.2	7.8	0.0	21.0	1.2	1.1
Kujawsko-Pomorskie	420.5	4.7	0.0	367.5	5.2	0.0	49.4	2.8	1.0
Lubelskie	570.4	6.4	0.0	328.8	4.6	0.0	240.3	13.5	1.0
Lubuskie	682.6	7.6	0.0	667.7	9.4	0.0	12.8	0.7	1.1
Łódzkie	384.8	4.3	0.0	246.7	3.5	0.0	134.8	7.6	1.1
Małopolskie	400.5	4.5	0.0	199.0	2.8	0.0	189.8	10.7	1.0
Mazowieckie	795.3	8.9	0.0	419.6	5.9	0.0	373.3	21.0	1.0
Opolskie	247.0	2.8	0.0	232.7	3.3	0.0	12.8	0.7	1.1
Podkarpackie	638.3	7.1	0.0	488.6	6.9	0.0	121.4	6.8	1.0
Podlaskie	586.7	6.5	0.0	380.9	5.4	0.0	204.3	11.5	1.0
Pomorskie	653.2	7.3	0.0	572.7	8.1	0.0	77.2	4.3	1.0

Table 1. cont.

Voivodship	Total			State-owned			Privately-		
	$\bar{x}$	Ws	tz	$\bar{x}$	Ws	tz	$\bar{x}$	Ws	tz
Śląskie	388.0	4.3	0.0	305.3	4.3	0.0	79.0	4.4	1.0
Świętokrzyskie	321.6	3.6	0.0	225.0	3.2	0.0	95.5	5.4	1.0
Warmińsko-Mazurskie	753.9	8.4	0.0	688.8	9.7	0.0	61.8	3.5	1.2
Wielkopolskie	752.5	8.4	0.0	662.3	9.3	0.0	84.5	4.8	1.0
Zachodniopomorskie	797.5	8.9	0.0	771.7	10.9	0.0	21.3	1.2	1.2

Source: Own compilation based on SPL data.

The largest area of total forest regeneration (Table 2) was observed in Wielkopolskie Voivodship (share in the structure – more than 10%), it being slightly lower in Zachodniopomorskie and Lubuskie Voivodships (respectively, almost 10% and more than 9%). The lowest area of forest regeneration was found in Małopolskie Voivodship (share in the structure – 2.1%).

Table 2. Arithmetic mean (ha), indicator of structure (Ws %) and the average rate of change (tz %) for total forest regeneration in state- and privately-owned forests by voivodships, in 2015-2019

Voivodship	Total			State-owned			Privately-owned		
	$\bar{x}$	Ws	tz	$\bar{x}$	Ws	tz	$\bar{x}$	Ws	tz
Dolnośląskie	4401	7.7	-1.0	4349.6	8.0	-1.0	13.4	0.7	-45.9
Kujawsko-Pomorskie	3337	5.8	16.4	3233.2	5.9	16.0	93.5	5.0	31.1
Lubelskie	2554	4.5	1.1	2462.2	4.5	1.6	89.7	4.8	-11.9
Lubuskie	5258	9.2	4.0	5244.8	9.6	4.0	10.0	0.5	4.1
Łódzkie	2166	3.8	4.5	2070.6	3.8	4.1	69.0	3.7	11.4
Małopolskie	1541	2.7	-10.2	1120.4	2.1	-12.2	245.3	13.1	-9.9
Mazowieckie	3738	6.5	1.3	3492.6	6.4	1.7	237.1	12.6	-4.2
Opolskie	2182	3.8	-3.0	1770.4	3.2	-2.9	18.6	1.0	-15.1
Podkarpackie	3275	5.7	-7.4	2988.8	5.5	-7.9	183.2	9.8	-5.1
Podlaskie	2441	4.3	1.9	2284.4	4.2	1.3	149.7	8.0	11.3
Pomorskie	5103	8.9	16.9	4835.4	8.9	14.9	264.2	14.1	59.1
Śląskie	2947	5.1	-0.2	2793.2	5.1	0.3	144.8	7.7	-10.5
Świętokrzyskie	1778	3.1	-2.6	1615.4	3.0	-3.2	162.2	8.6	3.9
Warmińsko-	5016	8.7	1.5	4947.8	9.1	1.7	51.6	2.8	-15.2
Wielkopolskie	5925	10.3	2.0	5749.1	10.5	1.9	92.8	4.9	-7.9
Zachodniopomorskie	5673	9.9	1.6	5616.2	10.3	1.7	52.1	2.8	-17.3

Source: Own compilation based on SPL data.

The highest rate of change in the value of this characteristic was obtained for Pomorskie and Kujawsko-pomorskie Voivodships (respectively, almost 17% and over 16% per year, on average, the highest drop in the value of this characteristic (-10.2%) being observed for Małopolskie Voivodship. In state-owned forests, the greatest area of forest regeneration was confirmed in Wielkopolskie and Zachodniopomorskie Voivodships (respectively, 10.5 and 10.3%). The lowest area planted to forest regeneration was found in Małopolskie Voivodship (share in the structure – 2.1%). The greatest rate of change was associated with Kujawsko-pomorskie Voivodship (16% increase per year, on average) and Pomorskie Voivodship (almost 15%). The greatest drops in the area of forest regeneration were determined in Małopolskie Voivodship (more than -12% per year, on average).

Table 3. Arithmetic mean (ha), indicator of structure (Ws %) and the average rate of change (tz %) for total afforestations in state- and privately-owned forests by voivodships, in 2015-2019

Voivodship	Total			State-owned			Privately-owned		
	$\bar{x}$	Ws	tz(%)	$\bar{x}$	Ws	tz(%)	$\bar{x}$	Ws	tz(%)
Dolnośląskie	4401	7.7	-1.0	77.7	4.6	-13.2	13.4	0.7	-45.9
Kujawsko-Pomorskie	3337	5.8	16.4	83.8	5.0	-20.4	93.5	5.0	31.1
Lubelskie	2554	4.5	1.1	154.9	9.2	-9.5	89.7	4.8	-11.9
Lubuskie	5258	9.2	4.0	75.8	4.5	40.0	10.0	0.5	4.1
Łódzkie	2166	3.8	4.5	105.6	6.3	-9.3	69.0	3.7	11.4
Małopolskie	1541	2.7	-10.2	31.1	1.8	27.7	245.3	13.1	-9.9
Mazowieckie	3738	6.5	1.3	161.0	9.6	-22.8	237.1	12.6	-4.2
Opolskie	2182	3.8	-3.0	23.5	1.4	-16.4	18.6	1.0	-15.1
Podkarpackie	3275	5.7	-7.4	127.8	7.6	-40.6	183.2	9.8	-5.1
Podlaskie	2441	4.3	1.9	125.8	7.5	-20.8	149.7	8.0	11.3
Pomorskie	5103	8.9	16.9	121.5	7.2	2.7	264.2	14.1	59.1
Śląskie	2947	5.1	-0.2	11.6	0.7	12.8	144.8	7.7	-10.5
Świętokrzyskie	1778	3.1	-2.6	93.6	5.6	-5.2	162.2	8.6	3.9
Warmińsko-Mazurskie	5016	8.7	1.5	197.3	11.8	-17.0	51.6	2.8	-15.2
Wielkopolskie	5925	10.3	2.0	71.3	4.2	-14.0	92.8	4.9	-7.9
Zachodniopomorskie	5673	9.9	1.6	216.5	12.9	-33.5	52.1	2.8	-17.3

Source: Own compilation based on SPL data.

Values for afforestation presented in Table 3 are concurrent with data for forest regeneration. As far as total afforestations are concerned, the superior region was Wielkopolskie Voivodship whose share in the structure exceeded 10%. Slightly lower values for afforestation were obtained for Zachodniopomorskie and Lubuskie Voivodships (respectively, almost 10% and more than 9%), them being the lowest in Małopolskie and Świętokrzyskie Voivodships (almost 3% for both). The rate of change in afforestation was the greatest in Pomorskie and Kujawsko-pomorskie Voivodships whose respective shares in the structure were 17 and more than 16%. The greatest decline in the value of this characteristic was observed for Małopolskie Voivodship (less than -10%). In state-owned forests, the afforested area was the greatest in Zachodniopomorskie and Warmińsko-mazurskie Voivodships (almost 12 and 13%, respectively. By contrast, the lowest value of this characteristic was determined in Śląskie Voivodship (0.7% share in the structure). The highest rate of change in afforestation was found in Lubuskie Voivodship (40%), it being the lowest (-40%) in Podkarpackie Voivodship. In privately-owned forests, afforestations were the greatest in Pomorskie Voivodship (over 14% share in the structure), and Małopolskie and Mazowieckie Voivodships (almost 13%). The lowest value of this characteristic were found for forests in Lubuskie and Dolnośląskie Voivodships (0.5 and 0.7%, respectively). In Pomorskie Voivodship, the afforested area increased at the greatest pace (59% per year, on average) whereas the decline in the value of this characteristic was the highest in Dolnośląskie Voivodship (46% per year, on average).

The final analysis pertained to natural forest regeneration and thinning in state-owned forests.

The greatest area of natural forest regeneration was found in Dolnośląskie, Warmińsko-mazurskie and Podkarpackie Voivodships (the respective shares in the structure: more than 15%, almost 12% and 10%). The lowest value of this characteristic was obtained for Kujawsko-pomorskie Voivodship (0.2%). In Podlaskie Voivodship, the rate of change in the values of this characteristic was the greatest (more than 16% per year, on average) whereas the greatest decline in natural forest regeneration was found in Kujawsko-pomorskie (-26% per year, on average). The greatest thinning area was in Zachodniopomorskie, Warmińsko-mazurskie and Lubuskie Voivodships (respectively, 10, 9 and 9% share in the structure). By contrast, the lowest value of this characteristic was found for Opolskie Voivodship (more than 2%). The greatest annual rate of change in thinning area, 4%, on average, was in Łódzkie Voivodship, the greatest drop in the thinning area being observed in Kujawsko-pomorskie Voivodship (almost -9% per year, on average).

Principal component analysis revealed that the examined characteristics in voivodships were affected by traits connected with the first three principal components (as indicated by eigenvalues of these components which were greater than 1). The components accounted for 84.55% of overall variance, that is total multivariate variation of the characteristics describing forests (Table 5).

The first principal component was strongly positively correlated with the area of state-owned forests (r = -0.978), forest regeneration in state-owned forests (r = -0,937), total forest regeneration (r = -0.936) and thinning in state-owned forests (r = -0.889). These variables had the greatest share in multivariate variation of voivodships in terms of the analysed characteristics.

Afforestation in privately-owned forests, area of privately-owned forests and total afforestation were the most strongly associated with the second principal component (PC2) (respectively, r = -0.902, r = 0.869 and r = 0.698), and caused less variation between voivodships in terms of the examined characteristics (PC2 accounted for 24.26% variation). The third principal components explained about 10% variation between voivodships and was associated with forest regeneration in privately-owned forests (r = 0.638) and natural forest regeneration in state-owned forests (r = 0.485).

Table 4. Arithmetic mean (ha), indicator of structure (Ws %) and the average rate of change (tz %) for natural forest regeneration and thinning in state-owned forests by voivodships, in 2015-2019

Voivodship	Natural forest regeneration			Thinning		
	$\bar{x}$	Ws	tz	$\bar{x}$	Ws	tz
Dolnośląskie	1260	15.4	-0.8	24525.0	4.9	-6.3
Kujawsko-Pomorskie	16	0.2	-26.2	25719.0	5.2	-8.6
Lubelskie	411	5.0	1.2	42694.8	8.6	-2.9
Lubuskie	431	5.3	12.4	44055.2	8.9	-3.1
Łódzkie	226	2.8	4.3	20478.8	4.1	4.1
Małopolskie	667	8.2	-16.6	17218.6	3.5	0.7
Mazowieckie	645	7.9	-1.1	36739.4	7.4	-2.4
Opolskie	193	2.4	-4.0	11677.6	2.4	-8.4
Podkarpackie	822	10.1	-22.1	35338.6	7.1	-5.7
Podlaskie	147	1.8	16.3	25889.4	5.2	1.2
Pomorskie	498	6.1	13.4	37472.6	7.5	-6.1
Śląskie	606	7.4	4.6	16151.2	3.3	-4.1
Świętokrzyskie	269	3.3	1.7	20246.8	4.1	-1.1
Warmińsko-Mazurskie	965	11.8	9.2	45046.8	9.1	-2.6
Wielkopolskie	573	7.0	-5.4	43582.0	8.8	-1.8
Zachodniopomorskie	429	5.3	-4.6	50075.4	10.1	-0.2

Source: Own compilation based on SPL data.

The distribution of voivodships in the system of the first two principal components is presented in Figure 1. The distance between voivodships approximately reflects the multivariate similarity between them in terms of the examined characteristics. Objects (voivodships) which are widely distanced differ in terms of many characteristics. Voivodships whose values of the first principal component were close to zero (Podkarpackie and Lubelskie) had average values of characteristics which were strongly correlated with this components (state-owned forests, total forest regeneration, forest regeneration in state-owned forests and thinning in state-owned forests). The largest negative values of the first principal component were obtained for Zachodniopomorskie Voivodship, which indicates that this region had the highest values of characteristics associated with PC1. The greatest PC1 values were obtained for Małopolskie and Opolskie Voivodships, which is indicative of the fact that in those voivodships values of traits associated with PC1 were the lowest. The relationships result from a negative correlation of these traits with PC1. Zachodniopomorskie and Świętokrzyskie Voivodships varied the most in terms of the examined characteristics whereas Pomorskie and Małopolskie Voivodships had average values of characteristic associated with the second principal component, that is privately-owned forests, total afforestation and afforestation in privately-owned forests.

Table 5. Eigenvalues, share of principal components in the overall variation and correlation coefficients between these components and the examined characteristics

Item	Principal components		
	PC1	PC2	PC3
X_1 – Total forest area	-0.866	-0.359	0.244
X_2 – Area of state-owned forests	-0.978	0.138	0.054
X_3 – Area of privately-owned forests	0.245	-0.869	0.261
X_4 – Total forest regeneration	-0.936	0.207	0.130
X_5 – Forest regeneration in state-owned forests	-0.937	0.226	0.080
X_6 – Forest regeneration in privately-owned forests	0.178	-0.456	0.638
X_7 – Total afforestations	-0.549	-0.698	-0.393
X_8 – Afforestations in state-owned forests	-0.813	0.200	-0.207
X_9 – Afforestations in privately-owned forests	0.018	-0.902	-0.308
X_{10} – Natural afforestations in state-owned forests	-0.465	-0.018	0.485
X_{11} – Thinning in state-owned forests	-0.889	-0.350	-0.147
Eigenvalue	5.52	2.67	1.11
Cumulative variance (%)	50.20	74.46	84.45

Source: Own compilation based on SPL data.

Variation between voivodships in terms of the examined characteristics was confirmed by cluster analysis which produced two groups. One group was formed by the following voivodships: Zachodniopomorskie, Warmińsko-mazurskie, Pomorskie, Wielkopolskie, Lubuskie and Dolnośląskie. The other cluster consisted of Mazowieckie, Lubelskie, Śląskie, Opolskie, Małopolskie, Podlaskie, Podkarpackie, Świętokrzyskie, Łódzkie and Kujawsko-pomorskie Voivodships. The following voivodships were the most similar in terms of the analysed characteristics: Lubuskie and Wielkopolskie, and Łódzkie and Świętokrzyskie; they formed a cluster at the first and second step of agglomeration (Table 6, Figure 2). The voivodships in the first group had a higher average total forest area, area of state-owned forests, total area of forest regeneration and forest regeneration in state-owned forests, area of natural forest regeneration and thinning in state-owned forests.

On average, forests of voivodships which formed group 2 included less privately-owned forests where less forest regeneration and afforestation had been conducted (Table 7).

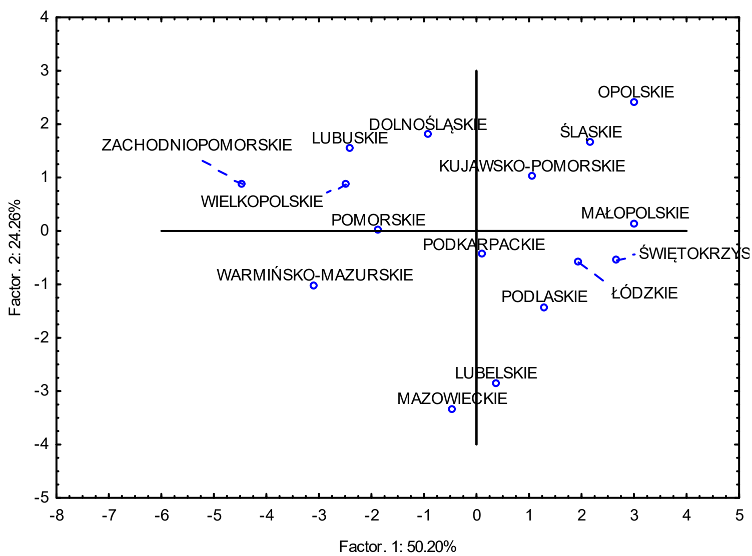

Fig. 1. Division of voivodships, in terms of the examined characteristics, in the system of the first two principal components

Source: Own compilation based on SPL data.

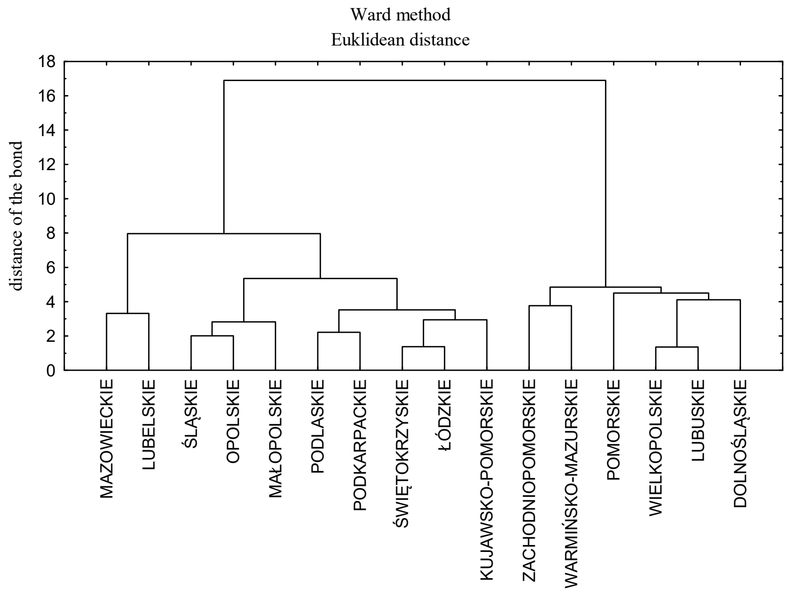

Fig. 2. Clusters of voivodships formed using cluster analysis
Source: Own compilation based on SPL data.

Table 6. Agglomeration course

Step	clusters															
1	LB	WP														
2	Ł	Ś														
3	O	ŚL														
4	PD	PDL														
5	MP	O	ŚL													
6	KP	Ł	Ś													
7	LL	M														
8	KP	Ł	Ś	PD	PDL											
9	WM	ZP														
10	DS	LB	WP													
11	DS	LB	WP	PM												
12	DS	LB	WP	PM	WM	ZP										
13	KP	Ł	Ś	PD	PDL	MP	O	ŚL								
14	KP	Ł	Ś	PD	PDL	MP	O	ŚL	LL	M						
15	KP	Ł	Ś	PD	PDL	MP	O	ŚL	LL	M	KP	Ł	Ś	PD	PDL	MP

LB – lubuskie, WP – wielkopolskie, Ł – łódzkie, Ś – świętokrzyskie, ŚL – Śląskie, PD – podkarpackie, PDL – podlaskie, MP – małopolskie, O – opolskie, KP – kujawsko-pomorskie, LL – lubelskie, M – mazowieckie, WM – warmińsko-mazurskie, ZP – zachodniopomorskie, DS – dolnośląskie, PM – pomorskie

Source: Own compilation based on SPL data.

Table 7. Average values of characteristics describing forests in groups formed using cluster analysis

Characteristics	group 1	group 2
X_1 – Total forest area	716726	495171
X_2 – Area of state-owned forests	653063	319593
X_3 – Area of privately-owned forests	46850	150475
X_4 – Total forest regeneration	5354	259
X_5 – Forest regeneration in state-owned forests	5239	2420
X_6 – Forest regeneration in privately-owned forests	88.4	134.8
X_7 – Total afforestation	99.3	77.5
X_8 – Afforestation in state-owned forests	54.3	8.10
X_9 – Afforestation in privately-owned forests	42.4	67.1
X_{10} – Natural forest regeneration in state-owned forests	702.1	368.8
X_{11} – Thinning in state-owned forests	39150	24540

Source: Own compilation based on SPL data

References

Baycheva, T., Inhaizer, H., Lier, M., Prins, K., Wolfslehner, B. (2013). *Implementing Criteria and Indicators for Sustainable Forest Management in Europe*. EFI.

Bomanowska, A., Kiedrzyński, M. (2011). Changing land use in recent decades and its impact on plant cover in agricultural and forest landscapes in Poland. *Folia Biologica et Oecologica, 7,* 5-26.

Broda, J. (2000). Historia leśnictwa w Polsce. Publishing House of the Agricultural University in Poznań (in Polish).

Brzeziecki, B. (2005). Wpływ trzebieży na zróżnicowanie strukturalne drzewostanów sosnowych. *Sylwan, 149*(10), 11-19 (in Polish).

Falencka-Jabłońska, M. (2012). Walory przyrodnicze polskich lasów i ich uzdrowiskowo-turystyczne wykorzystanie. *Inżynieria Ekologiczna, 30*, 60-69 (in Polish).

Gil, W., Głaz, J., Michalak, R. (2002). *The Place of Continuous Cover Forestry among the Silvicultural Systems in Poland*. In: Gadow, K., Nagel, J., Saborowski, J. [red.]. (2002). Continuous Cover Forestry. Book Series Managing Forest Ecosystems 4, 335-348.

Golos, P. (2008). Stan lasów prywatnych w Polsce. *Leśne Prace Badawcze 69*(4), 321-335 (in Polish).

Gorzelak, A. [red.]. (1999). Zalesianie terenów porolnych. IBL, Warszawa (in Polish).

Jabłoński, M. (2015). Definicja lasu w ujęciu krajowym i międzynarodowym oraz jej znaczenie dla wielkości i zmian powierzchni lasów w Polsce. *Sylwan 159*(6), 469-482 (in Polish).

Jabłoński, M., Wysocka-Fijorek, E., Budniak, P. (2017). Struktura lasów w Polsce na podstawie danych wielkoobszarowej inwentaryzacji stanu lasu. *Sylwan 161*(4), 267-276 (in Polish).

Jagodziński, A.M. (2019). Zasoby leśne Polski. Panorama Akademia Leśnictwo, Magazyn Polskiej Akademii Nauk 3-4/59-60, 4-5 (in Polish).

Kaiser, H.F. (1958). The varimax criterion for analytic rotation in factor analysis. *Psychometrica, 23*, 187-200.

Kaliszewski, A., Młynarski, W., Gołos, P. (2016). Czynniki ograniczające zalesianie gruntów porolnych w Polsce w świetle badań ankietowych. *Sylwan 160*(10), 846-854 (in Polish).

Krajowy program zwiększania lesistości (1995). MOŚZNiL, Warszawa (in Polish).

Krajowy program zwiększania lesistości. Aktualizacja 2003 r. (2003). MŚ, Warszawa (in Polish).

Kwiecień, R., Zając, S., Kaliszewski, A., Świętojański, A., Piotrowska, M., Ślązek, M. (2002). *Modyfikacja krajowego programu zwiększania lesistości – etap III (B3)*. Dokumentacja IBL, Warszawa (in Polish).

Leśnictwo (2015-2020). GUS, Warszawa (in Polish).

Lockow, K.W. (2003). Wpływ trzebieży na dynamikę rozwoju drzewostanów sosnowych. *Sylwan, 147*(9), 3-9 (in Polish).

Marek, T. (1989). Analiza skupień w badaniach empirycznych. Metody SAHN. PWN, Warszawa (in Polish).

McElhinny, C., Gibbons, P., Brack, C., Bauhus, J. (2005). Forest and woodland stand structural complexity: Its definition and measurement. *For. Ecol. Manage. 218*, 1-24. DOI: 10.1016/j.foreco.2005.08.034.

Milligan, G.W., Cooper, M. (1985). An examination of procedures for determining the number of clusters in a data set. *Psychometrica, 50*(2), 159-179.

Mojena, R. (1977). Hierarchical grouping methods and stopping rule: an evaluation. *The Computer J., 20*, 359-363.

Motz, K., Sterba, H., Pommerening, A. (2010). Sampling measures of tree diversity. *For.Ecol.Manage. 260*, 1985-1996. DOI: 10.1016/j.foreco.2010.08.046

Ochrona środowiska (2013). Informacje i opracowania statystyczne. GUS, Warszawa (in Polish).

Paschalis, P. (1992). Zasady światowego ekorozwoju. *Sylwan, 136*(11), 5-9 (in Polish).

Paschalis-Jakubowicz, P. (2010). Analiza wybranych czynników w procesach globalizacyjnych i ich wpływ na kierunki zmian w światowym leśnictwie. I. Założenia metodyczne. *Sylwan, 154*(1), 3-14 (in Polish).

Paschalis-Jakubowicz, P. (2011). Teoretyczne podstawy i realizacja idei zrównoważonego rozwoju w leśnictwie. *Problemy ekorozwoju – Problems of Sustainable Development. 6*(2). 101-106.

Polna, M. (2017). Zmiany lesistości obszarów wiejskich w Polsce w latach 1995-2016. Roczniki Naukowe Stowarzyszenia Ekonomistów Rolnictwa i Agrobiznesu 19(2), 194-199. DOI: 10.5604/01.3001.0010.1188 (in Polish).

Rocznik statystyczny leśnictwa (2017-2020) GUS, Warszawa (in Polish).

Rozporządzenie Rady Ministrów z sierpnia 2014 r. w sprawie programu badań statystycznych statystyki publicznej na rok 2015. 2014. Dz. U. poz. 1330 (in Polish).

Rykowski, K. (2006). O leśnictwie trwałym i zrównoważonym. W poszukiwaniu definicji i miar. CILP, Warszawa (in Polish).

Sobczak, R. (1996). O przywracaniu lasów na grunty porolne w Polsce. *Sylwan, 140*(5), 35-41 (in Polish).

Sobczyk, M. (2007). Statystyka. PWN Warszawa (in Polish).

State of Europe's Forests 2011. Status and Trends in Sustainable Forest Management in Europe. (2011). FOREST EUROPE, UNECE and FAO. Liaison Unit, Oslo.

Stępień, E. (1995). Idea trwałości lasu – nowe treści, problem realizacji. *Sylwan, 139*(12), 5-11 (in Polish).

Talarczyk, A. (2015). Bank Danych o Lasach w Polsce na tle baz danych i systemów udostępniania informacji z zakresu leśnictwa w innych krajach. Zeszyty Naukowe Szkoły Głównej Gospodarstwa Wiejskiego w Warszawie. *Problemy Rolnictwa Światowego, 15*(30), 2, 150-158 (in Polish).

Vidal, C., Lanz, A., Tomppo, E., Schadauer, K., Gschwantner, T., di Cosmo, L., Robert, N. (2008). Establishing Forest Inventory Reference Definitions for Forest and Growing Stock: a Study towards Common Reporting. *Silva Fennica, 42*(2), 247-266. DOI: 10.14214/sf.255.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., Melillo, J. M. (1997). Human Domination of Earth's Ecosystems. *Science 277*, 494-499.

Wijewardana, D. (2008). Criteria and indicators for sustainable forest management: The road travelled and the way ahead. *Ecological Indicators, 8*, 115-122.

Wysocka-Fijorek, E., Gil, W., Gołos, P. 2020. Realizacja zalesień w latach 2001−2018 w różnych regionach Polski. *Sylwan, 164*(9), 726-735. DOI: https://doi.org/10.26202/sylwan.2020059 (in Polish).

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Transient Energy Models of Housing Facilities Operation

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Abstract: Buildings are the main consumer of energy resources in the total energy balance of the countries in Central and Eastern Europe, the main energy consumption is allocated for heating. Efficient use of energy resources for heating needs to a large extent depends on the efficiency of regulation of heating systems. In the article, dynamic mathematical models of a two-room typical apartment in Ukraine, built in 2016, were developed in Matlab and EnergyPlus software environment. The simulations were carried out using IWEC hourly climate data for the city of Kyiv. The results of simulations of thermal energy consumption in Matlab are characterized by a larger range of fluctuations of the heating system load, which is typical for the real operating conditions of the system with the controller of ON/OFF type. In EnergyPlus it is assumed that the gas boiler operates continuously in the ON mode. In the research, the change of load on the apartment heating system was studied at different numbers and locations of air temperature control sensors installation, according to which the controller of the autonomous gas boiler operates.

Keywords: dynamic modeling, simulation, temperature, heating system load, controller, Matlab, Simscape, Simulink, EnergyPlus

1. Introduction

Buildings are one of the main consumers of primary energy resources in the world. For countries with continental and sharply continental climates, heating costs account for more than 85% of energy costs.

Poor indoor temperature control is the most common indoor heating issue for centrally heated households in China (Lu et al. 2021). The article (Lu et al. 2021) focuses on the development of dynamic indoor temperature control approaches. The system developed in the article (Lu et al. 2021) allows DHS to provide heat to a group of buildings with the same temperature demand, while assuring control with a single control system. However, for residents of apartment buildings with an autonomous heating system (usually a gas or electric boiler), the adjustment of the heating system automation is carried out without taking into account a number of influential factors. The energy saving potential for elementary schools with resident-centered controls was assessed in a paper (Ye et al. 2021) for 96 schools in different climate zones; finding out that the energy saving potential ranged from 10.2% to 12.41% depending on the climate zone in the U.S. Building Energy Management Systems (BEMS) have consistently received attention as an effective building control system (Perera et al. 2016, Perera et al. 2015) that requires the use of building energy modeling (BEM). These systems currently work with classical control methods such as ON/OFF, PID control (proportional-integral-derivative controller), and optimal start-stop procedures. The thermal interaction between the different areas of the building and HVAC (Heating, Ventilation and Air-Conditioning) leads to different behaviors that cannot be accurately controlled by classical control methods (Perera et al. 2014). Thus, advanced control systems that can handle multiple inputs and multiple outputs are the best approach to control the thermal condition of buildings and thermal comfort (Deshko et al. 2020b). In addition, with the efficient use of energy resources in the direction of achieving NZEBs in HVAC systems, the study of ventilation systems requires special attention (Bilous et al. 2020, Deshko et al. 2020a).

In the article (Saleh et al. 2016) a comparative analysis of ON/OFF type controllers and PID controllers used to control heating systems in terms of comfort conditions and energy efficiency of buildings. The study (Saleh et al. 2016) showed that the use of Simulink / Matlab has a very high potential for the analysis of control strategies and for taking into account the thermal and other characteristics of the building. ON/OFF controllers are most commonly used because of their constructive simplicity, although great savings in energy-saving modes of operation and providing comfort conditions are better realized by PID controllers. Simulation results (Saleh et al. 2016) showed that buildings with high thermal mass can significantly reduce the air temperature fluctuations in the rooms, which leads to a decrease in energy consumption. Buildings of Ukraine belong to buildings with high thermal mass.

A paper (Kull et al. 2020) analyzed energy consumption for a room with underfloor heating, where local ON/OFF controllers typically regulate the air temperature with poor accuracy. Proportional-integral (PI) controllers are known to be able to accurately regulate most processes (Kull et al. 2020). For NZEBs homes, water heating systems have greater inertia and thus will require more precise adjustment. When the air temperature deviates ±0.5 K from the setpoint, the energy consumption for heating is reduced by 9...5% when using PI controllers compared to an ON/OFF controller, the analysis was done in the Matlab software environment (Kull et al. 2020). In (Võs et al. 2019), energy use for radiator and underfloor heating systems coupled with ON/OFF and PI controls was investigated using the IDA ICE software package. The results of experimental measurements in early 2018 at the nZEB test facility (representative room) near Tallinn University of Technology are used to calibrate radiator models and controllers. In a paper (Võs et al. 2019), the calibrated models are used to estimate the energy performance of systems in simulations. For older buildings, the PI controller, as opposed to ON/OFF, saves 6% energy for heating, for nZEB it saves 12% (Võs et al. 2019).

It should be noted that the article (Kaymaz 1995) compared the use of PI/PID controllers with the ON/OFF controller in terms of accuracy as well as power consumption for the hospital. It is noted that PI/PID controllers are superior to ON/OFF controllers, but are also less reliable. ON/OFF controllers are much less sensitive to changes in system parameters, resulting in greater reliability (Kaymaz 1995).

Integration of BEM mathematical models that can describe building physics can help in successfully controlling energy-efficient energy consumption in buildings while ensuring comfortable conditions.

The purpose of the work is to analyze the energy consumption of heat energy for heating an ON/OFF controlled two-room apartment using dynamic modeling, taking into account characteristics of thermal interaction between zones (rooms).

Tasks:

1) creation of dynamic models of the apartment with division into zones in Matlab software environment,
2) creation of dynamic models of the apartment with division into zones in EnergyPlus software environment,
3) comparative analysis of energy modeling of energy consumption of apartment heating,
4) analysis of the specific features of the heating system configuration and the source of the autonomous heating system of the apartment.

2. Materials and methods

In order to study the energy performance of the building, energy models of a typical two-room apartment of a modern economy class building were created based on the software product EnergyPlus and Matlab. The dynamic EnergyPlus software product uses the DOE-2 and BLAST functions, which are close to the European standards. 3D model of the building geometry was created in the graphic editor Design Builder; thermal properties of the multi-layer enclosure, window structures with optical features of glazing, engineering systems, operation schedule, and temperature regimes, and so on were specified. The software product takes into account the inertial characteristics of the building envelope and systems, the dynamics of climatic data variability. At the output, the software product allows obtaining air temperature, surface radiation temperature, heating/cooling and ventilation system (HVAC-system) load, and others (Deshko et al. 2020). The dynamic model in the Matlab software environment is created using Simulink tool subsystems, which in turn uses Simscape. With Simscape, which allows you to quickly create models of physical systems in the Simulink environment, a model of physical components based on physical relationships, directly integrated into the simulation flowcharts, is created. Matlab software environment allows designing control systems, taking into account the physical system in Simulink. Fig. 1 shows a schematic of the apartment and the interconnection of the rooms/zones of the apartment in Simulink. The heating system of the apartment is regulated by switching the autonomous gas boiler ON/OFF, maintaining a constant flow rate of coolant, the coolant temperature can reach 90°C in the coldest period of the year. The principle of qualitative regulation of heating by the coolant temperature is realized. The ON/OFF controller has no intermediate states, either fully ON or fully OFF. This control scheme is quite typical for the autonomous heating of apartment buildings in Ukraine. The heat output of the gas boiler is 3.5 kW, the efficiency is 79.

The grid model of the thermal-physical characteristics of the room envelope and the relationship between the rooms of the apartment are shown in Fig. 2 (on the example of bedroom 1 / room4).

The energy model of the apartment created in the EnergyPlus software environment reproduces an idealized version of the heating systems operation, i.e. the heating system is inertia-free, and the air temperature in the apartment rooms is maintained at the set level without fluctuations. The energy model of the apartment created in the EnergyPlus software provides that the gas boiler operates continuously (in ON mode) with a constant coolant flow rate of 0.1 kg/s. The supply temperature is constant at 60°C. Regulation takes place at the heater to maintain the set temperature in the rooms, that is, the principle of quantitative regulation is implemented.

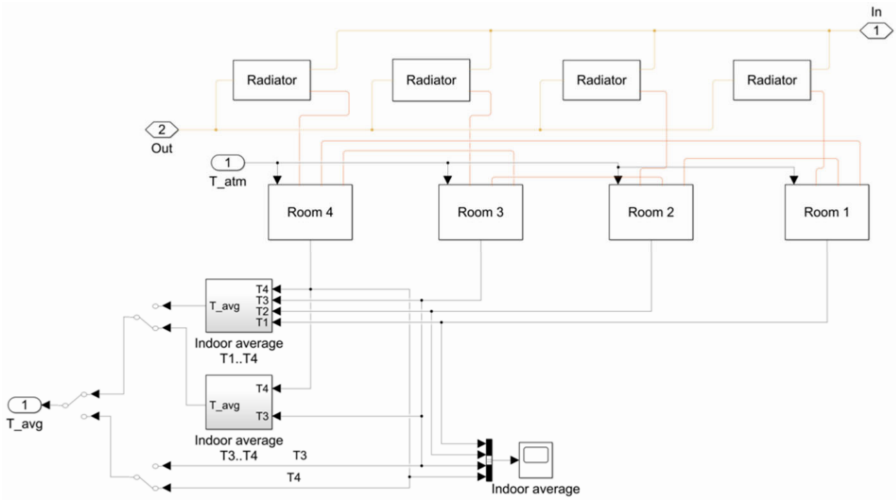


Fig. 1. The thermal energy model of the apartment

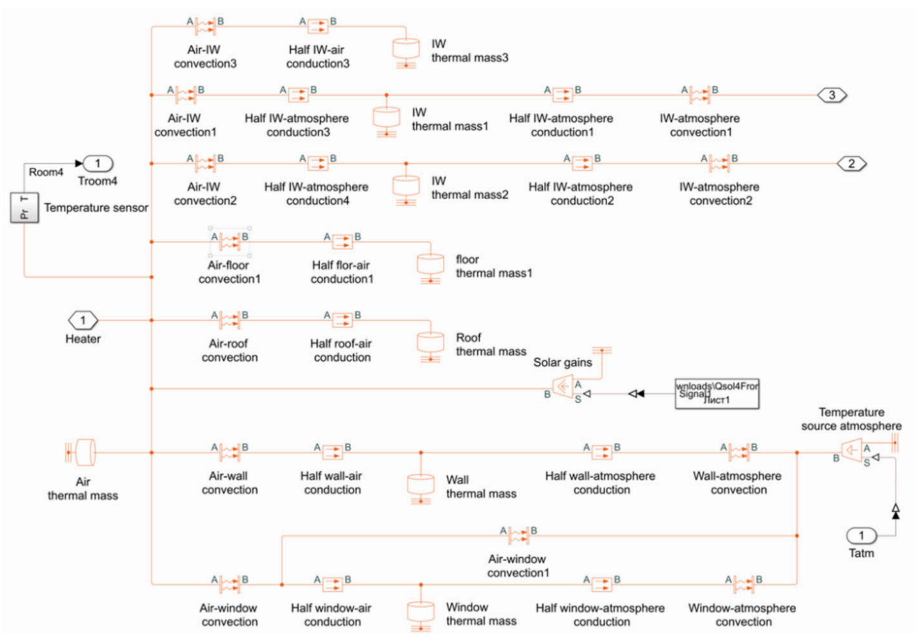


Fig. 2. The thermal grid model of one of the rooms

3. Results and discussion

Initial data

Existing residential housing was chosen for the study. It is a two-room apartment, located on the fourth floor of a five-story apartment building in Kyiv (Ukraine), built in 2016. The total area of the apartment is 49.44 m^2 (Fig. 3, all dimensions are given in meters), the height of the walls is 2.7 m. The apartment has a window orientation to the east (E) and west (W) sides, as well as a blank outer wall oriented to the north (N). Translucent elements of the enclosures are made of metalplastic two-chamber energy-saving double-glazed windows with argon filling of the chambers. The load-bearing part of the external wall is made of 0.4 m red hollow brick, and insulated with 0.05 m layer of mineral wool. Ventilation is natural with a multiplicity of air exchange of 0.6 $hours^{-1}$. The study used hourly climate data of a typical year of the IWEC international weather file for the Kyiv city (Ukraine) conditions. Solar heat inputs in the IWEC weather file are presented as global horizontal, diffuse horizontal, and direct normal. To recalculate the solar heat gains, which come into the area of the room, EnergyPlus software product was used, which allows taking into account the reflections of solar radiation from the surfaces of fences and soil, and take into account the optical transmittance of solar radiation, which is equal to 0.55. Fig. 4 shows hourly climate data.

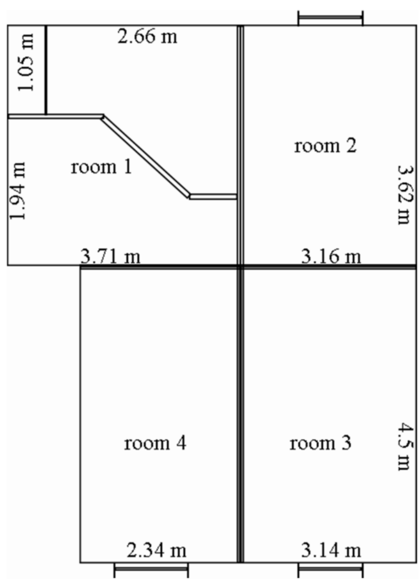
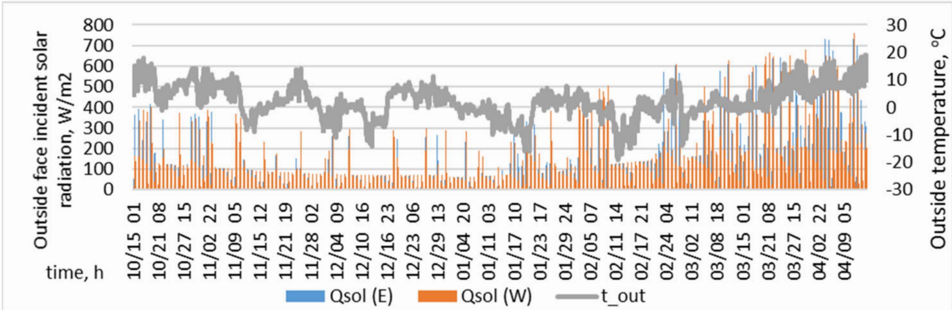


Fig. 3. The studied apartment plan



t_out – outside temperature, ºC; Q_{sol} – heat gain on vertical surfaces of east (E) and west (W) orientation, W/m^2

Fig. 4. Hourly climate data from IWEC file for Kyiv (Ukraine)

Model description

The apartment room was created in Matlab software environment by specifying the enclosure area and thermal resistance, which was introduced through blocks describing the convective and thermal conductivity components, as well as the heat storage properties of the internal and external envelopes, and the air in the room. Rooms are interconnected by thermal interaction. In addition, the hourly amount of heat inputs from the sun to the area of each room and the hourly external air temperature were set. The heat source was a gas boiler in which the mass flow rate was controlled by a valve using ON/OFF controller, which turned on when the air temperature in the rooms fell below the specified limits and turned off when it rose above. The simulation was performed under the condition of maintaining a constant air temperature of 20°C. The step of calculating the energy demand varied automatically depending on the magnitude of changes of external and internal fluctuations of the input parameters and was in the range of 1...200 sec.

Model testing and setup

For the design conditions, the selection of heating devices was carried out based on a mathematical model created in Matlab software environment, where the type of heating devices, area, mass, thermal inertial characteristics of the device were taken into account. Under design conditions, following the DSTU-N B V.1.1-27:2010 standard, for the city of Kyiv, the outside air temperature is assumed to be -22°C and with no solar heat gain. The indoor air temperature, following the DSTU B A.2.2-12:2015 standard, is 20°C. It is determined that the capacity of heating appliances in the apartment rooms are the following: bedroom 1 / room4 – 500 W, bedroom 2 / room3 – 1200 W, kitchen / room2 – 880 W, common areas (corridor, bath) / room1 – 320 W.

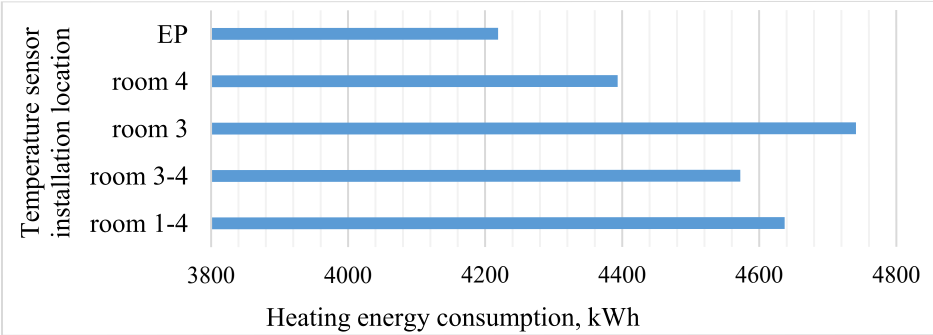
To verify the mathematical model of the apartment created in the Matlab software environment, the results are compared with the data of modeling in the EnergyPlus software environment. Considered grid dynamic models take into account the thermal inertia properties of each fence separately. From the mathematical modeling in Matlab software environment it follows that the total heat consumption of the apartment is distributed: bedroom 1 / room4 – 17%, bedroom 2 / room3 – 40%, kitchen / room2 – 31%, common areas (corridor, bath) / room1 – 12%. In bedroom 1, bedroom 2 steel radiators are installed, in the kitchen – steel radiator and water heated floor, in common areas – water heated floor and a heated towel rail.

It should be noted that the boiler is controlled by the average air temperature in the rooms of the apartment, i.e. the boiler operates at a constant flow rate, and depending on the conditions, it changes the temperature of the water supply, thereby leading to a situation where the hourly air temperature in different rooms under the influence of, primarily, different heat gains varies from 18 to 24°C, while maintaining the average air temperature at 20 ±0.5°C in Matlab software environment.

In real practice, the control of maintaining the specified air temperature in the apartment can be carried out by the values of the air temperature in representative rooms; for a compact typical housing, it is 1-2 points of installation of air temperature control sensors, according to the readings of which the controller sends a signal to the boiler to turn it ON/OFF. Typically, the sensors are installed in the rooms where the residents are spending most of their time, i.e. in the bedrooms or living room. This study looks at four different options for installing temperature sensors, specifically: 1) average reading from two sensors in room4 and room 3, respectively; 2) in room 4; 3) in room 3; 4) average reading from four sensors in each room, respectively. The results of the model calculation are shown in Fig. 5.

From Fig. 5 it follows that with the quantitative regulation of heating and the absence of inertia in the heating devices according to the mathematical model created in EnergyPlus software environment, we have the lowest result of heat consumption for heating needs of the building. For the conditions of Ukraine, it is typical to use ON/OFF controllers for autonomous heating systems, so depending on the number and location of temperature control sensors, the temperature in the premises may vary ±3%. The simulation results in Matlab differ by 4...10% from the simulation results in EnergyPlus.

Under these control conditions, the average load on the gas boiler is: sensors in all rooms – 1073 W; in rooms 3 and 4 – 1058 W; in room 3 – 1100 W; in room 4 – 1010 W; in EnergyPlus – 965 W.



room 1-4 – air temperature control sensor installed in rooms 1-4; room 3-4 – sensor in rooms 3-4; room 3 – sensor in room 3; room 4 – sensor in room 3-4; EP – simulation in EnergyPlus software

Fig. 5. Heat energy consumption for apartment space heating

Fig. 6 shows the hourly simulation results for the heating season in the software environments Matlab and EnergyPlus. The results of modeling the energy consumption of thermal energy in Matlab are characterized by a larger range of fluctuations of the heating system load, which is typical for the real operating conditions of the system. The trend of load variation for the apartment heating system according to the results of modeling in Matlab and EnergyPlus is the same. The maximum deviation of the simulation results of the two dynamic mathematical models is up to 0.5 kW, and the average deviation is 0.1 kW.

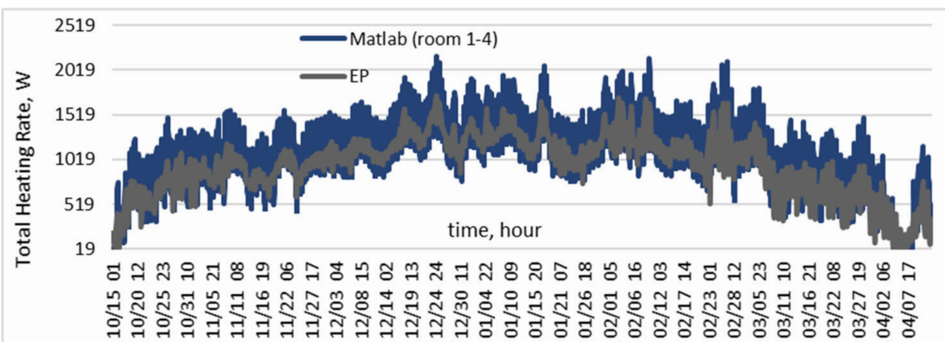


Fig. 6. The load on the heating system of the apartment for the heating season

There is a high solar activity in April, which explains that for this period the average air temperature in the representative rooms/groups of rooms, where sensors are installed, exceeds the value of the internal temperature range set in the controller, that is, at the time of complete short-term heating shutdown (at times of peak solar activity) due to the excess of solar heat gain, the internal air temperature in the apartment rooms increases.

Fig. 7 shows the loads on the autonomous apartment heating system for the period of January 10-14, which is characterized by low solar activity and external temperature in the range of -10...-2°C. A decrease in the graph of daily load variation is characteristic for the periods of solar heat gain. Simulations in EnergyPlus result in a smooth change in the load on the heating system with a decrease in the load during peak load hours, and then with a smooth increase. Four series of simulations were performed in Matlab for different locations of the temperature control sensor installation. For the considered apartment, room 3 is the largest, which in turn, when installing an air temperature sensor only in this room, leads to less load fluctuations compared to the similar situation of installing a control sensor in room 4 (which has dimensions up to 10 m^2, Fig. 3), which is half as large and with a higher glazing factor. For other combinations of installation of air temperature control sensors in the apartment, the load variation graphs will fluctuate within the range of load variation in the case of installation of one sensor in room 4 and 3.

During the period of solar activity, there is a decrease in the load on the heating system for different control options. With quality regulation and operation of the gas boiler with the controller of ON/OFF type, and taking into account the thermal inertia of engineering networks, there are significant fluctuations in the load on the heating system, which lasts from 3 to 10 hours during daylight hours. When installing the temperature control sensor in room 4, which is characterized by having a large area of glazing (which leads to significant solar heat gain in the room during daylight hours), and having most of the perimeter walls being internal, leading to long shutdowns of the autonomous gas boiler, which causes the nature of the load decreasing in Fig. 7. The scenario where the temperature control sensors are installed in large rooms of the apartment with two outer walls/larger area of outer walls leads to significantly shorter boiler shutdown intervals.

Fig. 8 shows the variation of the average air temperature in the apartment for different variants of the location of the temperature control sensors, according to the results of simulation in the Matlab software environment.

The indoor temperature is maintained at 20°C in the deviation range of 0.5...+0.1°C from the reference level. The upper control limit is slightly lower than the lower control limit. This control range is due to the inertia of the heating system; in order to ensure comfortable conditions (avoiding overheating) and energy-efficient use of thermal energy, the above range of maintaining the internal temperature was set. In the EnergyPlus software environment, the heating system is inertia-free and the room temperature is maintained according to a setpoint value of 20°C utilizing a thermostat on the heater.

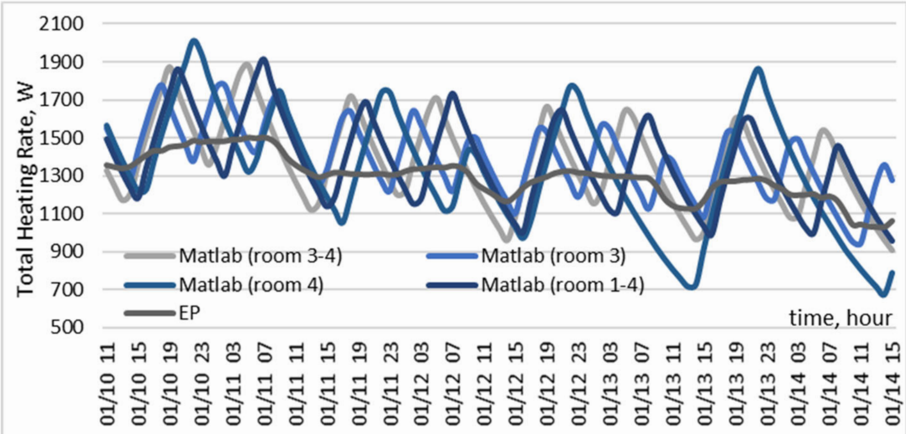


Fig. 7. Heating system load of the apartment for different variants of heating system control

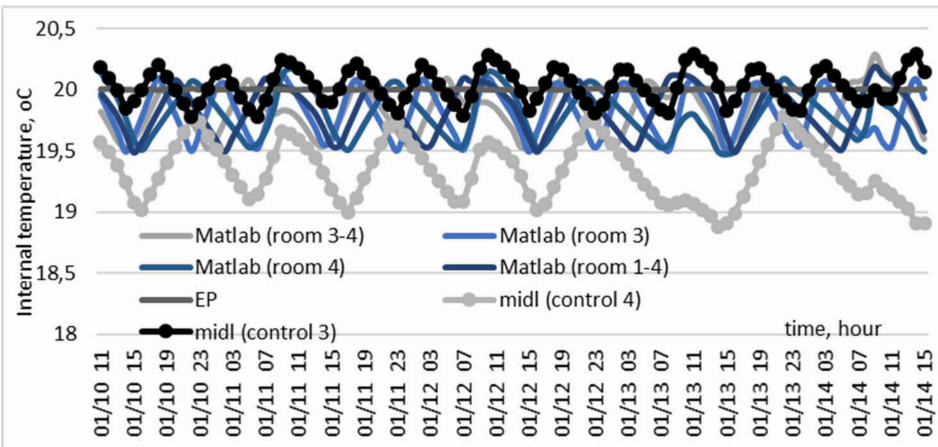


Fig. 8. Average air temperature in the rooms of the apartment, where sensors are installed, and in the apartment as a whole at different variants of heating system regulation

Fig. 8 shows the average air temperature in the apartment according to the results of modeling in the EnergyPlus software environment, which is at 20°C. The average air temperature in the apartment (the average of the four rooms) according to the results of modeling in the Matlab software environment when installing the temperature sensor in room 4 is 19.1°C – the lowest compared to other variants of modelling, when installing the sensor in room 3 (the largest room of the apartment with 2 external walls) – 20.2°C (the highest value).

4. Conclusions

The paper analyzes the transient heating modes when controlling the heating systems of a two-room apartment with an autonomous heating system. In the work, dynamic models of the apartment were created in EnergyPlus and Matlab software environments. The heating system has been configured; the following heating devices have been selected: bedroom 1 / room 4 – 500 W, bedroom 2 / room 3 – 1200 W, kitchen / room 2 – 880 W, common areas (corridor, bath) / room1 – 320 W.

Regulation of the apartment heating system in Matlab is performed by switching ON/OFF the autonomous gas boiler, maintaining a constant flow rate of the medium, the heating medium supply temperature can reach 90°C in the coldest period of the year, i.e. there is a qualitative regulation of the heating medium temperature. In EnergyPlus it is provided that the gas boiler operates continuously in ON mode with a constant supply temperature of 60°C, which is an idealized version of the heating system operation with quantitative regulation of the flow rate of the heating medium at the heaters.

The results of the simulation of the energy consumption of thermal energy in Matlab are characterized by a larger range of fluctuations of the heating system load, which is typical for real system operating conditions. The trend of the load variation of the apartment heating system according to the simulation results in Matlab and EnergyPlus is the same. A decrease in the graph of daily load variation is characteristic for the periods of solar heat gain in the apartment area. The simulation in EnergyPlus results in a smooth change in the load on the heating system with a decrease in the load during the peak hours of the load, and then with a smooth increase in the load. Four series of simulations were performed in Matlab for different numbers of temperature control sensors and their installation locations.

The different period of variation of the load on the heating system depends on the interconnection between the place of installation of the sensor in the apartment rooms and their heat load relative to the total load of the apartment. For the considered apartment, room 3 is the largest, which leads to less load fluctuations when installing the air temperature sensor only in this room compared to the similar situation of installing the control sensor in room 4, which is half the area and with a large glazing factor. The average temperature in the apartment, when the temperature sensor is installed in room 4, is 19.1°C, in room 3 – 20.2°C. Regardless of the controller type, the number and place of installation of temperature control sensors is important, which not only determine the operation of the apartment heating system but also the general assurance of comfort in the entire apartment.

In future research, it is planned to investigate the use of more complex/detailed PI controllers.

References

Bilous, I.Yu., Deshko, V.I., Sukhodub, I.O. (2020). Building energy modeling using hourly infiltration rate. *Magazine of Civil Engineering*, *96*(4), 27-41. DOI: 10.18 720/MCE.96.3

Deshko, V., Bilous, I., Vynogradov-Saltykov, V., Shovkaliuk, M., Hetmanchuk, H. (2020a). Integrated approaches to determination of CO_2 concentration and air rate exchange in educational institution. *Rocznik Ochrona Srodowiska, 22*(1), 82-104.

Deshko, V., Buyak, N., Bilous, I., Shevchenko, O. (2020b). *The Impact of Energy-Efficient Heating Modes on Human Body Exergy Consumption in Public Buildings*. *2020 IEEE 7th International Conference On Energy Smart Systems*. Kyiv, Ukraine, May 12-14, 2020. DOI: 10.1109/ESS50319.2020. 9160270

DSTU N B V.1.1-27:2010. Budivelna klimatolohia. [Natsionalnyi standart Ukrainy] – K., 2011. 127 s. (in Ukraine).

DSTU B A.2.2-12:2015. Enerhetychna efectyvnist budivel. Metod rozrahunku enerhospozhyvannia pry opalenni, okholodzhenni, ventyliatsii, osvitlenni ta hariachomu vodopostachanni. [Natsionalnyi standart Ukrainy] – K.: Minrehion Ukrainy, 2015, - 203 s. (in Ukraine).

International Weather for Energy Calculations (IWEC): https://energyplus.net/weather-location/europe_wmo_region_6/UKR.

Kaymaz, Emre. (1995) Adaptive environmental control for optimal energy consumption in hospitals. P*roceedings of the IEEE Symposium on Computer-Based Medical Systems.* Pages 165-172Proceedings of the 8th IEEE Symposium on Computer-Based Medical Systems; Lubbock, TX, USA; 43511.

Kull, T.M.,Thalfeldt, M., Kurnitski, J. (2020). PI parameter influence on underfloor heating energy consumption and setpoint tracking in NZEBs. *Energies*, *13*(8), 2068. DOI: 10.3390/en13082068

Liu, G., Zhou, X., Yan, J., Yan, G. (2021) A temperature and time-sharing dynamic control approach for space heating of buildings in district heating system. *Energy, 221*. DOI: 10.1016/j.energy.2021.119835

Perera, D.W.U., Halstensen, M., Skeie, N.O. (2015) Prediction of space heating energy consumption in cabins based on multivariate regression modelling. International *Journal of Modeling and Optimization, 5*(6), 385-392. DOI: 10.7763/IJMO. 2015.V5.493

Perera, D.W.U., Pfeiffer, C., Skeie, N.O. (2014) Control of temperature and energy consumption in buildings. *International Journal of Energy and Environment, 5*(4). 471-484. In: http://hdl.handle.net/11250/2438435

Perera, D.W.U., Winkler, D., Skeie, N.-O. (2016) Multi-floor building heating in MATLAB and Modelica environments. *Applied Energy, 171*, 4-57. DOI: 10.1016/ j.apenergy.2016.02.143

Saleh, A., Mosa, M. (2016) Analysis of control strategies and simulation of heating systems using Simulink/ Matlab potential. *Journal of Thermal Engineering, 2*(5), 921-927. DOI: 10.18186/jte.97874

Ye, Y., Chen, Y., Zhang, J., Pang, Z., O'Neill, Z., Dong, B., Cheng, H. (2021) Energy-saving potential evaluation for primary schools with occupant-centric controls. *Applied Energy, 293*, 116854. DOI: 10.1016/j.apenergy.2021.116854

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Municipal Heat Energy of Ukraine – Adaptation to Global Warming

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Abstract: Rising global temperatures have exacerbated the problems of adaptation to climate change in various sectors of the economy, including municipal energy. Therefore, the task is to develop measures and mechanisms, the implementation of which will guarantee cost-effective comfortable and reliable heat and cold supply of buildings and structures in climate change. Experimental studies of heat transfer and monitoring of thermal regimes in enclosing structures and building elements were conducted with the development of innovative engineering systems for energy supply of a passive house of the "zero-energy" type. Experimental developments of innovative energy-efficient greenhouse gas-reducing technologies and equipment for energy supply systems of buildings have been performed and their architectural and construction solutions for adaptation to climate change have been optimized. In order to expand and deepen the theory and practice of improving the energy efficiency of buildings in the near future, the scientific priority and subject of basic and applied research have been identified. Developed adaptive to climate change innovative, energy efficient technologies and equipment of engineering systems of energy supply of buildings with the use of renewable energy sources can be used in the practice of energy supply of housing and communal services.

Keywords: global warming, municipal energy, innovations, adaptation, energy efficiency of buildings

1. Introduction

From the second half of the twentieth century, meteorologists began to instrumentally record significant climate change on our planet, including rising global temperatures. At the end of 2020, experts from the UN World Meteorological Organization (WMO) noted that the average temperature increased by 1.2°C compared to the period 1850-1900. Currently, the geophysical phenomenon of global warming is explained by the intensification of the greenhouse effect due to the increase in the concentration of so-called greenhouse gases (GHG) in the Earth's atmosphere. This problem has caused concern and debate in the expert community and among politicians, as global climate change directly affects the living conditions of the world's population. Numerous publications make various predictions and discuss the dramatic consequences of global warming. Different regions of the planet have their own capabilities both to counter the effects of abrupt climate change and to adapt to new conditions.

Today, no one denies the rise in global temperature, but there is no consensus on the nature of such climate change. From time to time, new objects of environmental research appear that affect the climate due to natural GHG emissions.

It is known that GHG emissions due to natural factors significantly exceed greenhouse gas emissions due to anthropogenic activities. As humanity is not yet able to significantly influence GHG emissions of natural origin, the international community is widely discussing and trying to take measures to reduce anthropogenic emissions.

Supporters have both anthropogenic and natural concepts of increasing global temperature. The anthropogenic concept is advocated by the Intergovernmental Panel on Climate Change (IPCC). However, there are reputable experts and leading research teams who believe that the key cause of global warming is natural factors. Yet today, the IPCC approach remains the main scientific basis for studying climate change. According to the IPCC, the determining factor of global warming is the anthropogenic impact, namely: the increase in the GHG concentration in the Earth's atmosphere, primarily the main one – CO_2, due to the combustion of fossil fuels. Indeed, the concentration of carbon dioxide in the atmosphere increased from 278 ppm in 1750 (pre-industrial period) to 414 ppm in 2020, methane, respectively, – from 722 to 1869 bpm, and nitric oxide – from 270 to 331 bpm. In the period from 1990 to 2018, the concentration of long-lived GHGs in the atmosphere increased by 43%, with CO_2 accounting for 81% of this increase (WMO Greenhouse Gas Bulletin, 2019).

In total, in 2019, the total emissions of all GHGs were 59.1 gigatonnes (Gt) in CO_2 equivalent. CO_2 accounted for 65% of the world's GHG emissions, mainly due to energy production and use, and CH_4 and N_2O emissions were generally due to agriculture and nature. All energy is responsible for 41% of

GHG emissions, industry accounted for 20%, transport – 14%, and agriculture and waste generated 15% of GHG (Emissions Gap Report 2020).

In 2019, CO_2 emissions from the use of fossil fuels reached a record level, amounting to 38.0 Gt CO_2 (range: ± 1.9 Gt CO_2). Due to the COVID-19 pandemic, total CO_2 emissions in 2020 could be reduced by approximately 7 percent (range: 2-12%) compared to emission levels in 2019, but the expected reduction in GHG emissions will be not so significant, as GHG emissions (other than CO_2) are likely to be altered to a lesser extent.

According to (IEA, Global Energy Outlook 2021) in 2020 the demand for primary energy decreased by almost 4%, global CO_2 emissions related to energy decreased by 5.8% according to the latest statistics from 33.4 Gt CO_2 (in 2019.) to 31.5 Gt CO_2 (in 2020), which is the largest annual decrease since World War II. In absolute terms, emission reductions of almost 2.0 Gt CO_2 are unprecedented in human history – in general, this is equivalent to avoiding all emissions from the European Union. However, the concentration of GHG in the atmosphere continues to rise. For example, the average monthly CO_2 concentrations in Mauna Loa, Hawaii – at the atmospheric monitoring station – in February 2021 were 416.75 ppm, and in February 2020 it was 414.34 ppm, an increase of 0.6%, and the concentration of methane, respectively: 1892.3 bpm (December 2020) compared to 1874.6 bpm in the previous December, an increase of 0.9% (NOAA). In terms of N_2O concentration, the situation is similar: an increase of 0.4% from 332.3 bpm in November 2019 to 333.6 bpm in November 2020. Also at Cape Grimm in Tasmania, another key air pollution measurement station, in September 2020 the CO_2 concentration reached 410.8 ppm compared to 408.58 ppm in September 2019, an increase of 0.55% (Climate change…).

2. Results

2.1. Climate change in Ukraine

The trend of climate change fully applies to Ukraine. Over the last century, the average annual air temperature in Ukraine has risen by more than 1.9°C. In the cold period, the increase in air temperature averages 1.35°C, in the warm – 1.0°C. Since 1989, the average annual temperature in Ukraine has increased by almost 1.0°C. There is an almost continuous period of warming, during which the average air temperature in 70% of cases was higher than normal. The positive fluctuation of air temperature in the period 1989-2013 is the most powerful in the history of instrumental observations of the weather (Lyalko et al. 2016).

The rate of air temperature rise in Ukraine is ahead of global trends. If the world does not abandon the use of fossil fuels in the second half of the century, then in 30 years the average annual temperature in Ukraine may rise by another 1-1.5°C, and by the end of the century by 3.4-4.0°C. There is a steady rise in air temperature in all seasons:

- The world's average annual temperature has risen by 1.2°C over the past one hundred and fifty years.
- In Ukraine the average monthly air temperature in February, March, June, October, November and December 2019 was the highest or one of the highest for these months for the entire period of instrumental weather observations (since the end of the 19th century).
- In Ukraine, since 1991, each subsequent decade has been warmer than the previous one: 1991-2000 – by 0.5°C, 2001-2010 – by 1.2°C, 2011-2019 – by 1.7°C from the level temperature in 1991 (Fig. 1), which exceeds the global temperature growth rate (Ministry 2020).

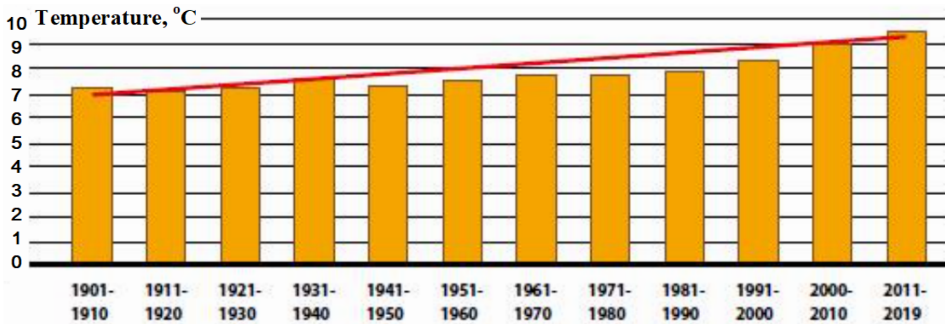

Fig. 1. Average ten-year climate temperatures of all Ukraine in the period 1900-2019

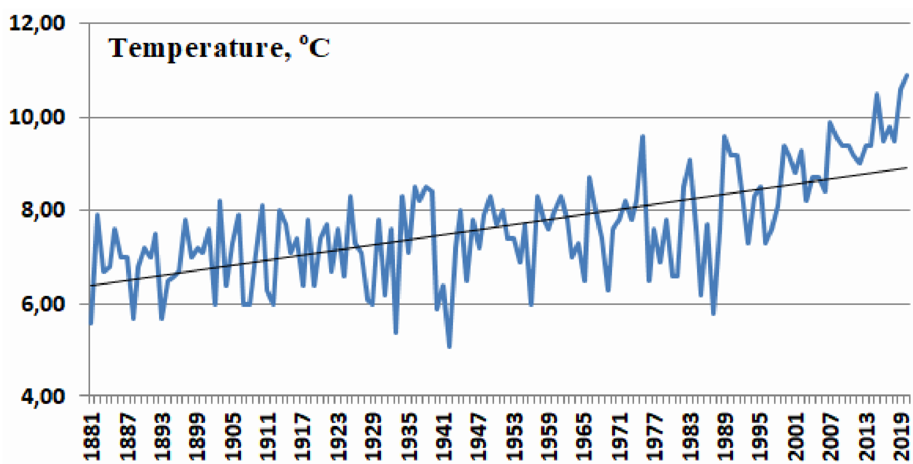

Fig. 2. Average annual air temperatures in Kyiv in the period from 1881 to 2020

The growth rate of temperature in large cities of the country exceeds the all-Ukrainian indicators. For example, the average monthly and annual temperatures in Kyiv (3750 degrees-days of the heated period) in the period from 1881 to 2020 are shown in Fig. 2, (Climatic data…).

The graph shows that for almost 140 years the average annual temperature in Kyiv has increased from about 6.3°C to 8.5°C, ie by 2.2°C. Moreover, temperature fluctuations in the period from 1881 to 1965 remained in the range of 5.4-8.3°C, the temperature began to rise rapidly from the 1990s and no longer became lower than 7ºC. 1942 is the coldest year in the last 140 years (5.1°C), and 2020 is the warmest year (10.9°C).

Scenarios of anthropogenic strengthening of the global greenhouse effect, thermal, hydrological regimes and the main conclusions for possible temperature changes of climate in Ukraine were considered in the early 90s of the twentieth century and presented in (WMO 2019):

1. with global anthropogenic warming of about 1°C (in the first quarter of the XXI century) in the southern regions of Ukraine the level of warming will almost coincide with the global, and in the north may increase to 40%;
2. the latitudinal temperature gradient on the territory of Ukraine will decrease in absolute value to 10% (in the modern era the latitudinal gradient of surface annual temperature is about 0.8°C per 1° latitude);
3. if the annual global temperature rises by 3°C (around the middle of the XXI century), the temperature regime of the northern regions of Ukraine may become similar to the temperature regime of its southern regions.

It is noted that the results obtained by a number of researchers of mathematical modeling of the dynamics of the terrestrial climate system to create RCP scenarios of regional climate change with anthropogenic strengthening of the greenhouse effect are still unreliable. The difficulties here are in the insufficiently deep study of the whole set of physical processes that form the latitudinal-longitudinal distribution of temperature fields and other climatic parameters (precipitation amounts, weather variability, etc.).

The publication of forecasts ten years later showed that in Ukraine the increase in the average surface temperature in the period 1900-2000 was 0.4-0.6°C, and in the regions: northeast about – 1°C, woodland and forest-steppe – 0.7-0.9°C, steppe – 0.2-0.3°C. By seasons: 1.2°C in winter, 0.8°C in spring, 0.2-0.3°C in summer. A negative trend in the number of frosty days and decontinentalization of the climate. Forecast estimates of changes in the average surface temperature in Ukraine by 2050 are reduced to the fact that the increase will be 1.5-2.0°C, and in January for the south – 2.0°C, for the north – 2.8°C and in July for Ukraine – 0.5-1.0°C (Lyalko et al. 2016).

The recent forecast for warming in Ukraine for a number of periods up to 2100 is shown in Fig. 3. It is clear that the results of instrumental measurements of temperature rise and warming forecasts in Ukraine generally correspond to trends in global temperature, and Ukraine faces the same challenges and risks that the world is concerned about (Increasing… 2015). In the near future (by 2030), the average monthly temperatures are projected to increase by 0.44°C; for the medium term (until 2050) – by 1.57°C, for the long term (until 2100) – by 3,15°C. The expected temperature changes will be heterogeneous for different regions of Ukraine.

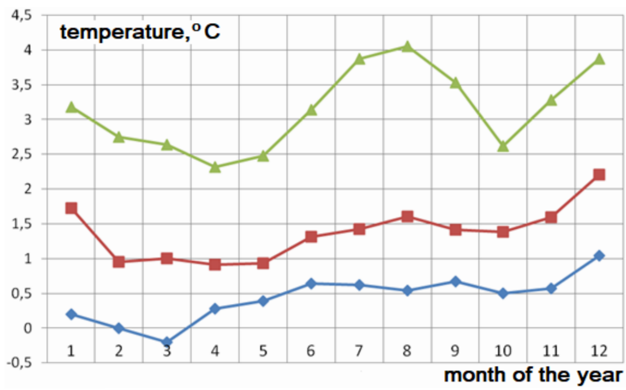

Fig. 3. Projections of changes in average monthly air temperatures in Ukraine with confidence intervals for an ensemble of 10 RCM (regional numerical climate models) compared to 1991-2010. Designations: ◆ – 2011-2030 (average value – 0.44°C), ■ – 2031-2050 (average – 1.57°C), ▲ – 2051-2100 (average – 3.15°C)

2.2. Adaptation to global warming

Measures and mechanisms to mitigate the possible negative effects of climate change and implement the inevitable adaptation to such changes in the lives and economies of countries and regions are actively discussed at international summits. Ukraine has also taken a number of initiatives on climate change. At the disposal of the Cabinet of Ministers of Ukraine dated December 7, 2016, #932-r. "On approval of the Concept for the implementation of state policy in the field of climate change until 2030" (On… 2016) it was emphasized that one of the main directions of "implementation of the Concept is adaptation to climate change, increasing resilience and reducing risks associated with climate change." Such adaptation is carried out through the development and implementation of a medium-term strategy for adaptation to climate change in Ukraine for the period up to 2030, coordinated with strategies and plans for the development of economic sectors and regional development strategies. Currently (in 2021) the draft "Strategies for Environmental Safety and Adaptation to Climate Change until 2030", which is sponsored by the Ministry of Environment of Ukraine, is being actively discussed in society. The importance of adaptation to climate change in Ukraine is of particular importance in the context of the Association Agreement between Ukraine and the European Union, as in Art. 365 states that the cooperation of the parties covers the development and implementation of climate change policy.

Adaptation is the process of adapting to an existing or expected climate and its impacts. In anthropogenic systems, the purpose of adaptation is to reduce harm, prevent it, or take advantage of opportunities. Adaptation to global climate change and global warming is the adaptability of natural or man-made systems in response to actual or expected climate change, which allows you to reduce your own vulnerability and take advantage of favorable conditions. Another definition can be proposed: the strategy of adaptation to climate change is the development of such measures and mechanisms for their implementation, which allow in a technically and economically sound way, taking into account the current and projected state of the economy to eliminate or mitigate the negative effects of climate change of Ukraine. The policy of adaptation to climate change involves conducting comprehensive interdisciplinary research with the development of the necessary technological (at the level of the 5th and 6th technological modes of development) innovations: from identifying and clarifying the causes of climate change, possible threats and consequences of these changes to develop measures, aimed at preventing or reducing the negative impact of changes or adaptation to them sectors of the economy and life of the population.

The purpose of the strategy of adaptation to climate change for municipal energy is to ensure a state of municipal energy supply (heating and air conditioning), which guarantees a comfortable and reliable current and future heat and cold supply in a technically and economically sound way while complying with environmental requirements.

It is important for housing and communal services and heat utilities to know how the demand for heat supply may change in the coming years due to global warming. According to observations, the parameters of low-frequency variability of the average heating temperature in the south of Ukraine and the corresponding change in energy consumption for heat supply for the population were analyzed, changes in average monthly temperatures in the regions of Ukraine from 1961 to 1991 were analyzed, their trends from October to April energy consumption for heating buildings (Anisimov 1999, Degterev et al. 2002, Degterev et al. 2008).

Further work on the assessment, determination of the effects of global warming and its impact on the characteristics of the heating season was expanded and deepened. Studies (Lyalko et al. 2015, Lyalko et al. 2016, Khodakov et al. 2016, Stepanenko et al. 2015, Degterev 2020) determine the temperature characteristics and dynamics of changes in the heating period for 1900-2013 and in some periods of this range and show a significant reduction in the duration of the heating period. There is also a brief analysis of previous publications on changes in climatic characteristics of the heating period using data that are important for a methodological approach to the study of patterns of changes in the parameters of the heating period (Lyalko et al. 2016). The impact of climate on humans and socio-economic systems is traced, in particular, climate change in connection with global warming and their impact on the efficiency of activities in various sectors of the economy of Ukraine until 2050 (Boychenko 2008). An assessment of the change in the duration of the heating period, the possibilities of development of solar and wind energy. The results of these studies can serve as a basis for further development of work on the adaptation of municipal energy supply to climate change.

It is advisable to adopt medium- and long-term roadmaps that provide for the development of programs (https://niss.gov.ua/doslidzhennya/nacionalna-bezpeka/prioriteti-politiki-ukraini-schodo-poperedzhennya-globalnogo), the implementation of which in relation to heat should be aimed at:

1) reduction of anthropogenic GHG emissions,
2) preservation and improvement of the quality of natural ecosystems,
3) adaptation of life of the population and sectors of economy.

The main volume (about 70-80%) of anthropogenic GHG emissions in Ukraine (Ukraine and the policy of combating climate change, 2016) falls on the fuel and energy complex. It is generated mainly during the combustion of hydrocarbon fuels in "large" energy (thermal power plants) and in municipal heat (thermal power plants, district and autonomous boilers). Regarding this energy sector of the economy, the directions of reducing greenhouse gas emissions are as follows:

1) increase energy efficiency of energy resources by:
   - improvement of organizational and economic mechanisms of management of objects of fuel and energy complex;
   - introduction of energy-efficient innovation-oriented technologies in the entire technological chain – from production to end use of energy resources;
2) optimization of hydrocarbon fuel combustion processes with improved environmental performance (low-emission environmentally friendly combustion);
3) the use of economically and environmentally justified way of renewable energy sources – the so-called low-carbon energy.

The main measures and mechanisms of adaptation to climate change for communal energy should be developed for the final consumer – energy supply of buildings of the housing and communal sector. Observations of changes in climatic characteristics – duration and average temperature of the heating period, amplitude of outdoor temperature fluctuations, number of the coldest days, etc. determine plans and forecasts of energy consumption, changes in capacity of heat generating plants, the degree of involvement in the fuel cycle of renewable energy sources. At the same time, the role of adaptation measures related to the introduction of architectural and construction innovations of buildings – thermal modernization of enclosing structures; the choice of materials that reflect or, conversely, absorb solar radiation; "Green" shielding of building facades, etc. There is a growing interest in bionics – the development of mechanisms for adaptation to climate change, created by analogy with their action in wildlife. The world now has high hopes for such global technologies to solve the global environmental crisis. These technologies involve the creation of innovations based on duplication in the technosphere of efficient processes observed in wildlife (reproducible technologies); development of technological systems using the transfer to the technosphere of an effective functional structure of the behavior of matter and energy in biological systems (convergent technologies) (Trubetskoi et al. 2020). One of the urgent tasks of architectural bionics (architectural style based on the use of bionics principles in architecture) is to find such architectural and technical solutions that would allow the use of environmentally friendly types of energy – solar, wind, soil, water, etc. (Lebedev et al. 1990, Hugh Aldersey-Willams 2003).

2.3. Experimental house

In this direction, in order to thoroughly study innovative scientific and technical measures to improve the energy efficiency of existing housing and modern buildings, a project was developed and built on the territory of the Institute of Technical Thermophysics of NAS of Ukraine a unique experimental passive house type "zero energy".

The building has three full floors (main building), the fourth floor with an area of 70% of the main building and the fifth – with an area of 30% of the main building, which houses a research climate chamber of the real climate of the environment. The first ground floor at 2/3 of the height (about 2.0 m) is sunk into the ground. The total heated area is 306 m^2, ie it is analogous to a cottage for the middle class. The house is clearly oriented around the world, has a flat pitched roof to the south. Facade walls on all floors are made of various combinations of socially available building materials (mostly environmentally friendly and chemically non-aggressive), they have a thickness of 38-40 cm (analog of the wall thickness of one and a half ordinary bricks).

Additionally, the facade is glued with a multilayer thermal insulation of light thermal insulation materials with a total thickness of 33-34 cm. The roof of the house is insulated with a layer of light basalt wool with a total thickness of 50 cm. The southern and northern facades are deaf, without windows. Windows of the eastern and western facades are double, double-chamber, with the formula 4M1i-8-4M1i-8-4M1 and 4M1i-10-4M1i-10-4M1, respectively. Window profiles of frames – five-chamber.

This design of wall facades allowed to obtain heat transfer resistance from 10.5 to 11.4 $m^2 \cdot K/W$, which is 3.3 times higher than the requirements of the current standard DBN B.2.6-33:2018. The heat transfer resistance of translucent structures has increased to 2.0 $m^2 \cdot K/W$, which is 2.7 times higher than the standard. The estimated specific annual (monthly) heat consumption of such a passive house is 14.8 kW·hour/(m^2·year) at -1.1°C (standard average temperature of the heated period for the climate of Kyiv) and 21.8 kW·hour/(m^2·year) at -10.0°C (standard average temperature of the coldest month of the heated period (January) for the climate of Kyiv). The average estimated heat consumption of the heating period is 2.6 kW, ie up to 12.0 W per 1 m^2, the actual heat consumption of the house is even less. Note that in the EU, despite a much more favorable climate, a passive house consumes 15.0 kWh(m^2·year). Experimental specific heat losses through the facades of the house at an ambient temperature of -10°C are only 1.2-1.8 W/m^2.

2.4. Innovative engineering systems of power supply of an experimental house

Heat supply. A basic low-temperature storage heat pump system (capacity 6 kW) was used for heating and hot water supply. Natural and/or accumulated heat of soil or water (in a water intake well) is used as a source of low-potential energy. For this purpose, a landfill of soil heat exchangers of different geometries was built on the territory around the house (horizontal shallow, vertical; multi-loop pipes, multi-pass, borehole; soil-water (liquid), soil-water-water, soil-air type). Solar heat collectors (flat, tube-vacuum) were used as an additional heat source. Heating devices are warm water floors of various laying geometries, including capillary floor, warm wall, warm partition, floor and wall fan coils. As a backup or peak heating system, the classic radiator-convector heating system based on the Viadrus solid fuel boiler, equipped with an original automated pellet burner, and/or partially floor and wall electric heating is used. According to the obtained experimental data, the use of energy-active windows for heat supply is promising. For emergencies (in the complete absence of electricity) an upgraded wood-burning furnace with a passive free-convection air heating system of the first two floors is used.

Power supply. The basic power supply is realized by solar BAPV-panels (Building Applied Photovoltaics) with a total area of 80 m^2 and a nominal power of 10 kW (photomodules on polycrystalline silicon and on thin films of cadmium telluride). Photovoltaics are supplemented by a Fortis Montana wind turbine with a nominal power of 5.0 kW and a block of lead-acid batteries. A 2.6 kW Honda portable gasoline power plant is used as a reserve. As an additional power source it is planned to use BIPV-windows (Building Integrated Photovoltaics), organically and structurally built into the structure.

Thus, in the building consistently during construction and operation implemented a chain: basic building – energy efficient building (facade walls of thermal insulation materials) – passive building (originally thermo-modernized facades) – zero-energy building (energy-independent) – "smart" building (diagnostics systems and operational monitoring, extensive use of process automation in engineering systems) – energy-efficient building (this is still in our plans – the excess electricity in the summer will be given to the needs of the Institute).

2.5. Auxiliary engineering systems

Ventilation. The basic ventilation system is recuperative with additional heating of the air leaving the heat exchanger and pre-passage of the supply air through the bulk ground accumulator. In another embodiment, the supply air forcibly passes through a tubular ground heat exchanger and enters the room directly. Experiments have shown that in winter the temperature of such air does not fall below 2°C, and in summer it does not rise above 18°C, the ventilation system partially performs the function of air conditioning. Basic recuperative ventilation in winter contributes to the heating system of a passive house, providing up to 30-35% of heat. For ordinary houses, this share averages about 10-15%.

Air conditioning. The basic cooling system uses a cold circuit of a passive heat pump, a system of heated floors and fan coils, as well as a separate mini-sewer system for condensate drainage. Additionally, a system of ground (geothermal) ventilation is used.

Air and heat protection. A system of passive thermal protection of all facades and the roof of the house has been developed due to the organization of a free layer in the system of facade and roof insulation, in which air flows freely from outside through bulk soil accumulators (northern and southern), heating in winter (maximum 8°C) and cooling in summer (12°C) when interacting with the soil. In the environment, the flow goes to the top of the house. In fact, it is a system of washing almost the entire house with air with more favorable temperature than the environmental parameters, ie the creation of a special external-local microclimate.

The use of autonomous heat and power supply systems during the year allows us to classify our experimental passive house as a "zero-energy" type of building, ie energy-autonomous (and non-energy-efficient) building that does not attract energy from centralized networks, but produces it in the building or on the adjacent area from renewable energy sources. In general, this house is a typical example of successful implementation of energy-efficient solutions for autonomous energy supply of passive buildings using only environmental energy, which meets current trends in low-carbon energy and helps reduce greenhouse gas emissions.

In the upper part of the house there is a climatic chamber of real climate, which allows year-round monitoring of building structures and building insulation materials up to 20 cm thick.

In general, the building is a full-scale research and diagnostic demonstration stand for the study of thermophysical properties of promising thermal insulation building materials in real conditions of their operation; to create reliable building facade thermal insulation structures from them and innovative energy (resource) -supply systems. In fact, the house is an example of the latest trend in efficient construction – the creation of Triple Zero buildings – the concept of "three zeros" by architect Werner Zobek: 0-energy, 0-CO_2 emissions, 0-waste, because after the end of life all structures are recycled and used and do not harm the environment.

2.6. Areas of research

In a more general aspect (Paton et al. 2014, Basok et al. 2018), conducted detailed studies on energy efficiency of the entire heat supply sector. Proposals for technological, organizational and socio-economic innovations aimed at improving the energy efficiency of buildings, as well as equipment and engineering systems for their energy supply, in particular in the construction of passive buildings such as "zero energy". The results of these studies, important for the development of energy efficiency and innovation strategy for energy supply of buildings and, as a consequence, reducing the use of primary energy resources and energy intensity of the economy of Ukraine, are given in (Basok et al. 2017), in particular:

- substantiated new original approaches, principles and methods of solving strategic management of technological modernization of energy supply and energy efficiency of buildings and structures with the use of technological and organizational and economic innovations, taking into account the trend of renewable energy sources and intelligent systems;
- a system of indicators and guarantees of technological modernization of heat supply of buildings and structures aimed at safety, preservation and improvement of the quality of human life in the implementation of technological solutions has been developed;
- formulated a new scientific direction – methodology of organizational, economic and innovative support for modernization of energy supply systems and energy efficiency of buildings and structures, taking into account their thermal modernization and the trend of low-carbon technologies in the energy-economy-ecology triad.

The social significance of the work was the scientific substantiation of innovative development of energy supply of settlements of Ukraine in the context of climate change (taking into account the trend of renewable energy sources and the relationship of requirements for energy efficiency, economy, environmental friendliness), competitiveness and competitiveness energy supply of buildings and structures of housing and communal and public spheres.

Taking into account the results of research on the energy supply infrastructure of the demonstration passive house and in order to deepen and expand the theory and practice of energy efficiency of buildings, in the near future the main objectives of research, basic and applied research, topics, methods and tools of such research.

Basic research. The subject of research is the development of scientific and technical bases for the development of energy-efficient technologies for energy supply of buildings in the housing and communal sphere. Research topics:

1) deepening and expanding the theory of heat transfer in the construction of buildings, in particular, taking into account the thermal balance of buildings passive contribution of solar energy;
2) deepening and expansion of the theory of heat transfer in soil massifs when using geothermal energy of upper layers of soil for energy supply of buildings;
3) systematic and continuous accounting during the year of all manifestations of climatic factors (solar radiation, wind speed and direction, outdoor air temperature), analysis of their impact on heat transfer through the external elements of buildings.

Applied research. The subject of research is the development of technologies for energy efficient energy supply systems of buildings, taking into account the optimization of architectural and planning solutions of buildings. Research topics:

1) assessment of the potential and state of the market of fuel and resource base of energy supply, including taking into account non-traditional and renewable energy sources;
2) experimental researches on development of scientific and constructive decisions at creation of energy-efficient technologies and the equipment of power supply of buildings with definition of initial data and dependences for engineering calculations of the equipment and constructive elements of buildings;
3) development of methods of in-depth technical and economic analysis of energy efficiency of energy supply of the building;
4) development of organizational, economic and managerial measures and mechanisms to increase the efficiency of energy supply of buildings.

In 2016, the European Parliament adopted the EU Strategy on Heating and Cooling (COM 2016), the main priorities of which are to increase energy efficiency and decarbonization of existing and newly constructed buildings in all sectors of the economy. Therefore, one of the main activities of the Energy Union is the development and implementation of medium- and long-term programs to reform inefficient heating (cooling) systems, which will reduce the use of fossil fuels and reduce import dependence of EU countries.

At the international level, it is proposed to discuss and approve a Climate Strategy, which would identify the main areas of work on GHG emissions management and activities in the field of adaptation to climate change. Ukraine also needs a more systematic approach to developing effective policies to combat and adapt to climate change.

3. Conclusions

In view of the above, it is necessary to make adjustments to the management system of many sectors of the economy of Ukraine, including communal energy, primarily heating of buildings and air conditioning of housing and communal services (Basok et al. 2021). Therefore, it is extremely important to develop measures to shape the policy of adaptation of municipal energy, ie to identify and justify the main directions of solving key problems of adaptation of municipal energy supply (heat and cold supply) to global warming, taking into account norms and standards in energy efficiency, public construction and reconstruction. It is necessary to harmonize the normative documents of municipal energy supply with the directives of the European Union on the field of municipal energy supply and energy efficiency of buildings. It is also necessary to change the applied temperature characteristics, especially the number of degrees-days of warm and cold periods, to improve engineering systems and equipment for energy supply of buildings, to optimize thermal characteristics of enclosing building structures, in particular in the construction of passive houses, zero-energy houses, "green" houses, improve the architecture of buildings, etc.

It is necessary to form a policy of adaptation to climate change to the conditions of Ukraine, to develop an appropriate regulatory document – a strategy for adaptation of municipal energy supply to climate change and control over its implementation. The main provisions of the strategy of adaptation to climate change of municipal energy supply should include:

- goals of the strategy of adaptation to global warming;
- characteristics of conditions and identification of global warming threat factors for municipal energy supply (heat supply and air conditioning);
- definition of indicators, indicators, their threshold values, exceeding which poses a threat to municipal energy supply;
- principles of ensuring adaptation to global warming;
- development of measures and mechanisms that eliminate or reduce the impact of negative conditions and factors due to global warming;
- creation of monitoring as an operational and analytical system for managing adaptation measures and mechanisms to eliminate emerging deviations from the threshold values of indicators that pose a threat to municipal energy supply.

Implementation of the strategy of adaptation of communal energy to climate change will contribute to the economy and rational use of fuel, energy and material resources; reduction of energy costs for the housing and communal sector; introduction of new architectural, innovative engineering and construction solutions; improving the comfort and standard of living of the population; reducing the country's dependence on imports of fuel and energy resources, and therefore will increase the country's energy security.

The first steps towards creating a framework strategy for the adaptation of the whole country to global warming are already planned. In particular, on January 24, 2020, the Cabinet of Ministers of Ukraine established an interagency group to overcome the effects of climate change. The purpose of its activities is to protect the health and well-being of citizens from the risks and consequences of climate change. A recent event is the adoption in Ukraine of the Energy Security Strategy for the period up to 2025 (Energy… 2021).

In the framework of the Paris Agreement, the EU policy "European Green Course" (COM 2019), the EU concept of "Carbon footprint" (Europarl. 2020) Ukraine, as a European country, together with the world will develop measures and mechanisms aimed at reducing emissions, including related to the operation of buildings, as provided for in (IEA, July 2021), scenario NZE2050. This is especially true on the eve of the next world climate summit in Glasgow this fall. Therefore, the physics and geopolitics of global warming have become one of the most pressing transdisciplinary problems of the modern world. It is necessary to develop and deepen the scientific, technological and organizational (for example, strategic energy management) bases of adaptation of life to current and expected climate changes.

References

Anisimov, O.A. (1999). Impact of anthropogenic climate change on heating and air conditioning of buildings. *Meteorologiya i Gidrologiya, 6*, 10-17 (in Russian).

Basok, B.I., Baseyev, Ye.T., & Kurayeva, I.V. (2021). Adaptation of municipal heat energy to climate change. *Visn. Nac. Akad. Nauk Ukr. 4*, 60-75 (in Ukrainian).

Basok, B.I., Novoseltsev, O.V., Dubovsky, S.V., Baseyev, E.T. (2018). *Modernization of district heating systems of settlements of Ukraine. Thermal Physics. Energy. Efficiency. Energy Economy. Ecology.* Kyiv: Kalita (in Ukrainian).

Basok, B.I., Bazeyev, E.T. (2017). Priority of Increase of Energy Efficiency in Ukraine. *Thermophysics and Thermal Power Engineering. 39*(4), 61-67. (in Ukrainian). DOI: https://doi.org/10.31472/ihe.4.2017.09

Boychenko, S. (2008). *Semi-empirical models and scenarios of global and regional climate change (Napivempirychni modeli ta stsenarii hlobalnykh i rehionalnykh zmin klimatu).* Kyiv: Naukova Dumka (in Ukrainian).

Climate change: Covid pandemic has little impact on rise in CO_2 – BBC News. https://www.bbc.com/news/science-environment-55018581.

Climatic data on the city of Kyiv. http://cgo-sreznevskyi.kyiv.ua/index.php?fn=k_klimat &f=kyiv

COM (2019). European Green Deal. Communication from the commission to the european parliament, the european council, the council, the european economic and social committee and the committee of the regions.

COM (2016), EU strategy on heating and cooling. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52016DC0051

Degterev, A.Kh. (2020). Climate change in Crimea over the past decades. *Voprosy Bezopasnosti, 2,* 1-6. DOI: https://doi.org/10.25136/2409-7543.2020. 2.32821. (in Russian).

Degterev, A.Kh., Degtereva, L.N. (2008). Assessment of changes in energy consumption for heat supply in connection with interannual temperature variability in the south of Ukraine. *Meteorologiya i Gidrologiya,* 11, 53-56 (in Russian).

Degterev, A.Kh., Degtereva, L.N. (2002). Assessment of the influence of seasonal temperature changes on energy consumption in Ukraine during the heating season. *Meteorologiya i Gidrologiya, 12*, 58-61 (in Russian).

Emissions Gap Report (2020) / UN Environment Programme. 2020. 128.

Energy security strategy for the period up to 2025. Ukraine, August 2021. http://materialy.kmu.gov.ua/5a593067/docs/77be4c6b/Dodatok.pdf (in Ukrainian).

European Parliament, Committees, 2020. Carbon Border Adjustment Mechanism, https://www.europarl.europa.eu/committees/en/carbon-border-adjustment-mechanism/product-details/20201009CDT04181

Hugh, Aldersey-Willams (2003). *Zoomorphic: New Animal Architecture*. Collins Desingn.

IEA, (July 2021), Net Zero by 2050 A Roadmap for the Global Energy Sector https://iea.blob.core.windows.net/assets/beceb956-0dcf-4d73-89fe-1310e3046d68/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

IEA (2021), Global Energy Outlook: CO2 Emissions in 2020, IEA, Paris. https://www.iea.org/articles/global-energy-review-co2-emissions-in-2020.

Increasing the climate resilience of the agricultural sector of the South of Ukraine. Hungary, Szentendre. Regional environmental center, 2015. http://documents.rec.org/publications/ClimateResilienceUkraine.pdf (in Ukrainian).

Isotopes confirm the dominant role of fossil fuel combustion in increasing levels of atmospheric carbon dioxide. *WMO Greenhouse Gas Bulletin.* 2019. Nu. 15, November 25.

Khodakov, V.E., Sokolova, O.N. (2016). *Natural and climatic factors and socio-economic systems*. Kherson, P. 567-601/ (in Russian).

Lebedev, Yu.S., Rabinovich, V.I., Polozhai, E.D. et al. (1990). *Architectural bionics (Arkhitekturnaya bionika)*. Moscow: Stroyizdat. (in Russian).

Lyalko, V.I., Elistratova, L.O., Apostolov O.A. (2016). Changes of parameters of the heating period on the territory of Ukraine as a result of global warming. *Dopov. Nac. Akad. Nauk Ukr., 11,* 61-69. DOI: https://doi.org/10.15407/dopovidi 2016.11.061 (in Ukrainian).

Lyalko, V.I. (ed), (2015). *Greenhouse effect and climate change in Ukraine: assessments and consequences*. Kyiv: Naukova Dumka, 610 (in Ukrainian).

Ministry of energy and environmental protection of Ukraine. How the climate in Ukraine is changing. https://mepr.gov.ua/news/35246.html (in Ukrainian).

NOAA. Trends in Atmospheric Carbon Dioxide / Nitrous Oxide. https://gml.noaa.gov/ccgg/trends/, https://gml.noaa.gov/ccgg/trends_n2o/.

On approval of the Concept for the implementation of state policy in the field of climate change until 2030. https://zakon.rada.gov.ua/laws/show/932-2016-%D1%80#Text. (in Ukrainian).

Paton, B.E., Dolinsky, A.A., Heyets, V.M., Kukhar, V.P., Basok, B.I., Bazyeev, E.T., Podolets, R.Z. (2014). Target reference points of the National Strategy for Heating Supplies of Settlements of Ukraine. *Visn. Nac. Akad. Nauk Ukr. 9,* 29-47. DOI: https://doi.org/10.15407/visn2014.09.029 (in Ukrainian).

Priorities of Ukraine's policy to prevent global warming in the post-Kyoto period. Analytical report. The National Institute for Strategic Studies. 2011. https://niss.gov.ua/doslidzhennya/nacionalna-bezpeka/prioriteti-politiki-ukraini-schodo-poperedzhennya-globalnogo (in Ukrainian).

Stepanenko, S.M., Pol'ovyi, A.M., Loboda, N.S., Khokhlov, V.M., Ermolenko, N.S. (2015). *On climate change and its impact on the economy of Ukraine.* Odesa (in Ukrainian).

Trends in Atmospheric Carbon Dioxide. https://www.esrl.noaa.gov/gmd/ccgg/trends/

Trubetskoi, K.N., Zakharov, V.N., Galchenko, Y.P. (2020). Naturelike and Convergent Technologies for Developing Lithosphere Mineral Resources. *Herald of the Russian Academy of Sciences, 90*(3), 332-337 DOI: https://doi.org/ 10.1134/S101933 1620030065 (in Russian).

Ukraine and the policy of combating climate change: the economic aspect. Analytical report. Kyiv: Zapovit, 2016 (in Ukrainian).

WMO Provisional Statement of the State of the Climate, 2019. https://library.wmo.int/doc_num.php?explnum_id=10108

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The Influence of Modern Refrigerants on Environmental Protection

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Abstract: The aim of reviewing information was characterizing in the labor factor using in refrigeration technology is and their impact on the environment. The development of the refrigeration industry occurred thanks to progress towards coolants. The most important aspect of using of refrigerators is their impact on health and human life, and atmosphere. By caring for health, the European Union achieves legal rights. Research on thermodynamic factors pose a wide field of work for many scientists and are the most popular, new information, that can be used in practice.

Keywords: refrigerant, protection, environment, GWP, ODP

1. Introduction

The beginnings of refrigeration can be seen in ancient Egypt and India, where drinking water was cooled several thousand years ago in porous, clay jugs.

In ancient China, during the summer season, to cool drinks, people used snow and water ice collected in the winter. It was stored in well-protected pits. In the reign of Alexander the Great, the above method was used to cool wine for legionnaires, and at Nero's feasts. Drinks were also served chilled as indicated. Francis Bacon (1561-1621) assessed as first the importance of cooling to maintain perishable products in good condition. In Italy was very popular method of cooling water by dissolving saltpetre in it, and to obtain even lower temperatures – a mixture of saltpetre and snow. The above-described methods of cooling were based on the use of appropriate properties and physical processes carried out in a natural way. The scientific foundations of refrigeration began to emerge at the turn of the 18th and 19th centuries. Josepf Black defined the concept of the heat of vaporization and developed the basics of calorimetry Gay-Lussac and Dolton investigated the phenomena of gas cooling during their expansion. Faraday liquefied some gases (e.g. chlorine). Sadi Carnot studied thermodynamic processes and transformations, developed the science of ideal and irreversible processes, and carried out an analysis of thermodynamic cycles enabling the reception of heat at the expense of providing mechanical work. The discovery and definition of many concepts and physical laws made it possible to make the first technical attempts to describe the issue of cooling processes and the construction of industrial refrigerators – cooling devices. The first attempts to build mechanical air and vapour chillers as well as sorption chillers were made around the mid-19th century. Dr Garricka from Florida, initiated air chillers. The air chillers were developed and produced by Bell-Coleman, Lightfoot, Leicester. Allan, Windhausen produced significant capacities for those times. Vapour coolers were created in parallel with the air ones. In 1830 Jacob Perkins patented a refrigerator with a solution corresponding to the modern one, with a working medium – ethyl ether. The initiative and design work of David Boyle from Chicago and Karol Linde from Munich resulted in the replacement of ether with ammonia. Some, especially positive, thermodynamic properties of ammonia as a refrigerant caused the refrigeration system with this refrigerant to displace others for many years.

In the same period (1859), Ferdynand Carre constructed an absorption refrigerator that was extremely carefully and well thought out, the basic idea of which has survived to this day. The transport of food products (meat, fruit) from overseas countries (South America, Australia, New Zealand) to Europe had a significant impact on the development of refrigeration. A distinguished pioneer in this field is Ch. Tellier, who was the first to implement the idea of transporting perishable food products by ocean vessels, adapting the ship "Le Frigorifique" and then "Le Paraquay". The development of land refrigeration was mainly based on the ammonia (approx 90%), partly on carbon dioxide (carbonic anhydride approx 10%) and to a small extent on sulfur dioxide (sulfur anhydride approx 1%) (Kuprianoff et al. 2014, Niebergall 1959, Stefanowski 1949).

Nowadays, they strive for energy efficiency, miniaturization, and being eco on every level of life also in the field of refrigerants, new solutions are used to allow the most economical steps to improve efficiency (Abas et al. 2018, Antunes et al. 2016).

2. Research

The refrigerants used in a cooling device for heat transport should meet certain specific requirements, the most important of which are:

1. Pressures used in refrigeration should not be too high, not exceeding those used in other fields of technology, but not lower than the atmospheric pressure, so that any leaks result in harmful suction of air and moisture from the outside;

2. The heat of evaporation (evaporation enthalpy) should be as high as possible, and the specific volume of vapors as small as possible, so that the dimensions of the refrigerator are not excessively large;
3. The refrigerants must not react chemically and may not have a harmful effect on the elements of machines and other technical devices or on their surroundings;
4. The production price, cost, and ease of purchasing factors should correspond to economic conditions;
5. Refrigerants and their products resulting from their decomposition (caused by e.g. too high temperature, moisture content) should not affect on the environment.

In the area of large on-ground cooling towers, ammonia is most used due to its ease of production (e.g. in the production of fertilizers for agriculture or by hydrogen and nitrogen synthesis), not very high vapor pressure in the cooling device (maximum approx 13 MPa), the possibility of using iron-based materials, high, practically unlimited solubility in water, easy to identify presence in the air due to the characteristic smell (0.001% by volume can be detected by smell).

The basic disadvantages of ammonia as a refrigerant include its harmful effect on human health when its content in the air exceeds 0.1% by volume.

Carbonic acid anhydride is also used in refrigeration. This fluid when used in refrigeration, makes the devices relatively small, due to high operating pressures and a small volume of vapors. Carbon dioxide is an odorless and does not chemically interact with metals and refrigerants, but for humans, air containing more than 5% by volume becomes suffocating. There are several methods of obtaining carbon dioxide relatively easily, so its availability does not pose any problems. On the other hand, a negative property of carbon dioxide is its very high, maximum pressure of up to about 100 bar and a low critical point (about 3 MPa, at a temperature of +35°C and a pressure lower than 5.28 MPa) it may solidify – freeze. High pressures and low cooling (evaporation) efficiency have limited its use.

Sulfuric anhydride – sulfur dioxide SO_2 has found little use, because of a low content in the air (about 0.01%) it has a choking effect and irritates the respiratory system. The liquefied oil shows oily properties, so the friction elements of the compressors do not require the use of lubricants, which would, however, be aggressive. In the presence of moisture, it becomes aggressive towards metals.

Methyl chloride CH_3Cl, when inhaled in larger amounts, has a stunning effect – similar to the action of alcohol, it is flammable, has a weak chemical effect on metals and breaks down greases and oils.

Sulfur dioxide and methyl chloride have been used sporadically in refrigeration, mostly in small refrigerators, especially household refrigerators, as well as in gastronomic refrigeration.

Extremely intensive development of refrigeration at the beginning of the 20th century in transport, especially sea transport, led to the search for a refrigerant that is safer than ammonia, especially in shipbuilding, the use of which in the face of the threat of a sea disaster or other major failure has become problematic for ship crews. This search was directed to the compounds of carbon, chlorine, fluorine and hydrogen, the so-called freons.

The first, used from around the 1930s, was deufluoride chloromethane (CF_2Cl_2), known as freon 12. It is a colorless gas with no odor heavier than air, non-poisonous, non-flammable, aggressive to metals in the presence of moisture. HCl and HC – extremely dangerous, gases – choking on the body through the respiratory tract.

The introduction of freon 12 as a refrigerant increased the operational safety of ship refrigeration equipment, however, it did not meet the demand for refrigerants in a wide range, especially in terms of efficiency. The search for more universal agents resulted in the development and production of new agents with a wide range of applications including various mixtures, which continues to this day. The new refrigerants, however, are mostly based on components characteristic of freons, but more stable and containing much less chlorine and fluorine.

The gigantic development of refrigeration, including the production of refrigerants, has led to the need to analyze the harmfulness of their impact and introduce mechanisms limiting their use.

As a result of the destructive impact of CFC and HCFC refrigerants on the natural environment, in particular the destruction of the ozone layer and the intensification of the greenhouse effect, radical measures were taken to eliminate halogen derivatives from common use. The first international agreement to protect the ozone layer was the Vienna Convention adopted on March 22, 1985. Next international agreement to protect the environment was the Montreal Protocol, which entered into force on September 16, 1987. Since the entry into force of the Montreal Protocol, the production and consumption of ozone-depleting substances (CFCs, HCFCs, halons) has fallen by more than 97 percent (https://www.schiessl.pl/pl/czynniki-chlodnicze). Its implementation was adopted by the Council of the European Union and ratification by the Sejm of the Republic of Poland of the Act on Substances that Deplete the Ozone Layer of April 20, 2004. These documents define the principles of using substances harmful to the ozone layer in the operation of equipment, and introduced a ban on the widespread use of CFC agents (R11, R12) and from 01.01.2010 R22 freon in newly designed cooling devices.

On the basis of the new Act of May 15, 2015 on substances that deplete the ozone layer and some fluorinated greenhouse gases – Journal of Laws of 2015, item 881 and the Regulation of the Minister of Development of January 11, 2016 on leakages in refrigeration, air conditioning and heat pumps as well as the fire protection system containing controlled substances or harmful fluorinated greenhouse gases (Journal of Laws of 2016, item 89), it is required to check the tightness in accordance with the schedule temporarily.

The above provisions triggered an increased search for substitutes for the above-mentioned prohibited substances, which had to meet a number of chemical, physical, physiological, temperature, ecological, economic and safety criteria.

The necessity to withdraw the refrigerants identified as dangerous resulted in replacement with pro-ecological agents (e.g. R401A, R407C, R410A), including those of natural origin (NH_3, CO_2, propane).

The R134a refrigerant has become the most popular substitute for R12 in recent years, despite its indisputable thermodynamic advantages, but this refrigerant is characterized by a very high greenhouse effect (GWP134a = 1430). This property influenced the decision to withdraw from use and operation with the Directive of the European Parliament and the Council of Europe in 2006 EG in all newly manufactured refrigeration devices and MAC (Mobile Air Conditioning) systems the use of fluorinated greenhouse gases for which the GWP is greater than 150. So it was proposed to withdraw the R134a refrigerant from car air conditioning systems in all new models from January 2011, while from January 2017, the use of R134a was banned in all newly manufactured cars.

This refrigerant has been replaced by a new, environmentally friendly refrigerant from the HFO group currently used.

The use of freons in EU countries is covered by the Regulation of the European Parliament and of the Council of Europe (EC No. 517/2014 of April 16, 2014) on certain so-called fluorinated greenhouse gases. The limitation and elimination of harmful gas emissions to the atmosphere is an important issue in refrigeration technology. Each EU regulation is a stimulus for national law and is the basis for the development of national internal regulations. The European Parliament has created a strict situation defining the methods of dealing with substances that deplete the ozone layer – CFC chlorofluorocarbons, HCFC hydrochlorofluorocarbons as well as substances contributing to the greenhouse effect – the so-called F-gases – HFC hydrofluorocarbons.

A positive results of the application of the above-mentioned measures are signals of a slow recovery of the ozone layer in the atmosphere.

The Prozon Foundation in Poland works to protect the ozone layer, which protects the Earth from harmful UV-B solar radiation. Prozon supports the reduction of the consumption and emissions of ozone-destroying substances, CFCs and HCFCs (https://prozon.org.pl/index.php).

Now the most commonly used synthetic HFC and HFO refrigerants. Many of them are modern. These are factors with the global warming potential of GWP less than 1500, 750 or even 150. From January 2020, it is forbidden to replenish the losses of R404A, R507 or R23 refrigerants. The ban also applies to direct substitutes for R22 – i.e. R419A, R422A, R422D and MO89. The ban has several exceptions, e.g. it does not apply to military equipment and devices for freezing products at -50°C (http://www.rynekinstalacyjny.pl/artykul/id3695, czynniki-chlodnicze-legislacja-dzis-i-jutro?gal=1).

3. Results of research

In addition to the production and appropriate selection of new and new refrigerants, a serious problem is obtaining information about their thermodynamic properties, including heat transfer. An additional difficulty is obtaining this information in multiphase processes: evaporation and condensation. It requires a lot of painstaking work that is carried out by specialized research centers around the world. The great complexity of the heat transfer processes of such substances makes it impossible to conduct effective theoretical research, which forces us to carry out experimental works, and therefore practical ones, requiring the construction of complex, costly research and measurement stands that greatly increase costs and time-consuming. Hence, few scientific centers undertake the above-mentioned research. One of them is the Koszalin University of Technology, where such research is successfully carried out at the Department of Heat and Cooling Technology – currently the Department of Energy. These studies concern obtaining the values of the heat transfer coefficients of new pro-ecological refrigerants entering into service:

1. Heat transfer coefficients during evaporation in tube, mini-channel and plate heat exchangers,
2. Heat transfer coefficients in tubular heat exchangers and long coils during condensation processes,
3. Heat transfer coefficients of refrigerants in the area of superheated of compressed vapors,
4. Research on the flow resistance of refrigerants during evaporation, condensation in tubular exchangers and mini channels,
5. Research on the possibility of extending the use of various refrigerants.

Fig. 1 shows the ecological indicator set for the selected refrigerants.

Fig. 2 shows for new small refrigeration equipment commercial and industrial and air conditioning and safety groups according to EN 378.

Refrigerants		Temperature of boiling [K] (p = 1013 hPa)	Ecological indicators		Vitality in the atmosphere [years]
group	type		ODP	GWP	
CFC	R11	296,9	1,00	4750	45
	R12	243,4	1,00	10900	100
	R113	320,7	1,00	6130	85
	R114	276,7	1,00	10000	300
	R115	233,9	0,44	7370	1700
	R502	227,6	0,25	4657	876
HCFC	R22	232,3	0,05	1810	12
	R401A	240,1	0,03	1182	8,5
	R402A	223,95	0,03	2788	22,2
HFC	R134a	247,1	0,00	1200	15,5
	R23	191,1	0,00	14800	270
	R152a	249,1	0,00	124	1,4
	R404A	226,4	0,00	3922	40,4
	R407A	227,4	0,00	2107	18,2
HC	R50	111,7	0,00	25	12
	R170	184,6	0,00	5,5	12
	RC270	241,7	0,00	1,8	
	R290	231,0	0,00	3	12
	R600	272,7	0,00	4	12
	R600a	261,4	0,00	3	12
	R601	309,2	0,00	4	0,08
	R601b	282,7	0,00	4	12
	R1150	169,4	0,00	3,7	12
	R1270	225,5	0,00	1,8	12
Natural	R717	239,8	0,00	0	0,02
	R718	373,1	0,00	0,2	0,03
	R744	194,8	0,00	1	29 300
	R744A	184,7	0,17	298	114

Fig. 1. Ecological factors of chosen refrigerants-compare (Białko B. 2019)

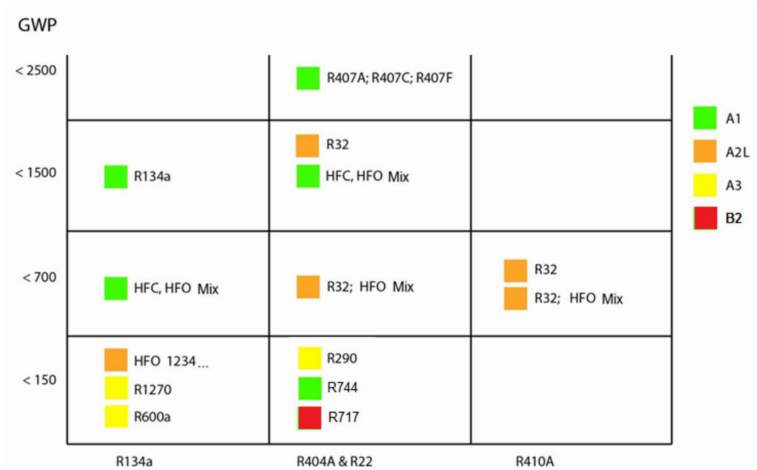

Fig. 2. Replacements for new small refrigeration equipment (for R134a), commercial and industrial (for R404A) and air conditioning (for R410A) – safety groups according to EN 378: A – non-toxic, B – toxic, 1 – non-flammable, 2L-slightly flammable, 2 – medium flammable, 3 – flammable (Danfoss drawing) (Targański W.)

TEWI – Total Equivalent Warming Impact.

$$TEWI = GWP\ L\ n + GWP\ m\ (1\text{-}f) + n\ E\ z$$

Ingredients this impact are (Zakrzewski, B. 2014):
GWP – refrigerant capacity factor to global warming with reference to the CO_2,
L – emission factor to air [kg/year],
n – operation time [years],
m – filling installation of refrigerant [kg],
f – dimensionless number of assessment the degree of recovery [-],
E – energy consumption by the device during the year, ($E = n \cdot tr$),
z – CO_2 emissions per unit of energy conversion [kg CO_2/kWh],
n – power of heat pump [kW],
tr – annual working time [h].

Legislation has been developed on ozone-depleting substances and on certain fluorinated greenhouse gases. EU regulations must also be respected by our country. Legal regulations are the provisions of the European Union treaty on which the regulations in the individual EU member states are based. There have been many directives, regulations and journals of laws which regulate the provisions in this matter (Commission Regulation (EU)… 2015, Journal of Laws… 2018, Commission Regulation (EU)… 2016/2281). Fig. 3 present a process of reducing internal greenhouse gasses in UE.

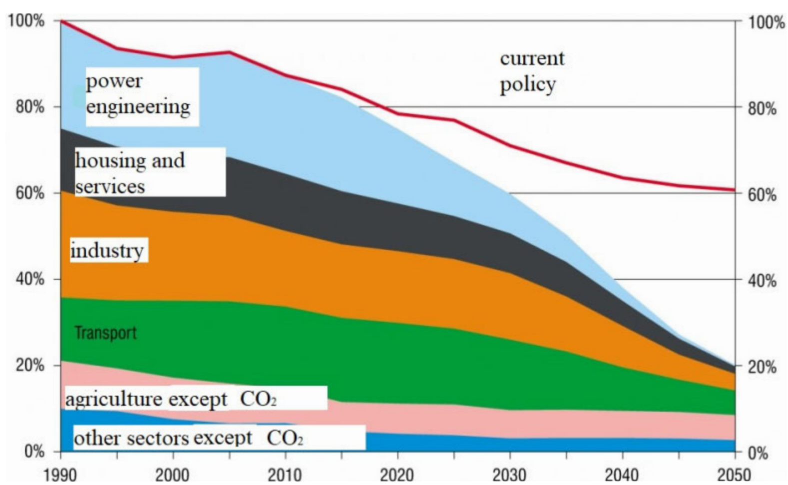

Fig. 3. The process of reducing internal greenhouse gasses in UE (100% = 1990)
Source: http://www.rynekinstalacyjny.pl/artykul/id3695,czynniki-chlodnicze-legislacja-dzis-i-jutro?gal=1

Fig. 4. present a global refrigerant standards and codes.

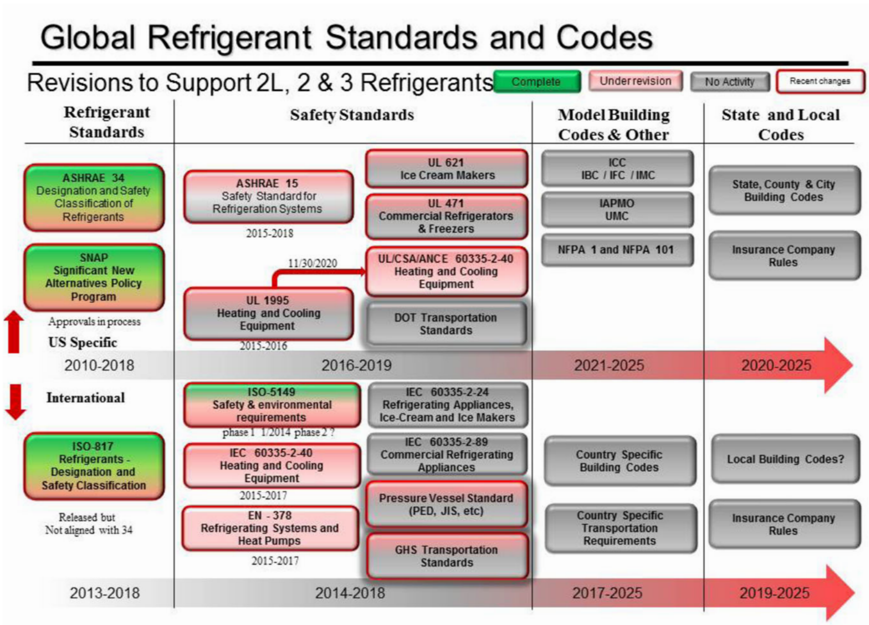

Fig. 4. Global refrigerant standards and codes
Source: Carrier Engineering Newsletter Vol. 3, Issue 2, Carrier Corporation 2015, New Refrigerants Impact Standards and Codes. Available: www.carrier.com/commercial

Compared to the 1990s, industrial countries should reduce greenhouse gas emissions by as much as 95% by 2050. There are 6 sectors spread over the years and with an increasing percentage of HFC reduction. The European Commission implements the Low Carbon Economy Roadmap, a low-carbon economy. They are withdrawn from the use of substances that destroy the ozone layer (i.e. CFC and HCFC freons). All this to protect our life and planet (http://www.rynekinstalacyjny.pl/artykul/id3695,czynniki-chlodnicze-legislacja-dzis-i-jutro?gal=1).

4. Conclusion

When using refrigerants, safety is the first priority! Of course, it is best if the GWP potential indicator is as low as possible and the ODP potential indicator is zero. However, factors with low GWP are usually highly flammable, while factors with a high energy content can be toxic (https://prozon.org.pl/index.php). It is a matter of the appropriate selection of priorities and a compromise between thermodynamic indicators and ecology.

From the beginning of its existence, refrigeration technology has set specific and very complex and excessive requirements regarding the construction, material engineering, durability of both individual elements (compressors, heat exchangers, evaporators, coolers, condensers, subcoolers, safety and automation elements and systems) as well as appropriate, certain permanent entire systems, sometimes operating in variable, often extreme environmental conditions, especially in relation to the function of the need to secure food storage, including all types of transport (land, sea and air), as well as ensuring appropriate climatic conditions, both in general and specialized systems, (medical facilities, in recent years even in space).

References

Abas, N., Kalair, A.R., Khan, N., Haider, A., Saleem, Z., Saleem, M.S. (2018). Natural and synthetic refrigerants, global warming: A review. *Renewable and Sustainable Energy Reviews, 90*, 557-569.

Antunes, A.H.P., Filho, E.P.B. (2016). Experimental investigation on the performance and global environment talimpact of a refrigeration system retrofitted with alternative refrigerants. *International Journal of Refrigeration, 70*, 119-127.

Białko, B. (2019). *Termodynamiczne aspekty stosowalności mieszaniny węglowodorów nasyconych do realizacji obiegów lewo bieżnych*. Publishing House of the Wrocław University of Technology, Wrocław, Poland, 11 (in Polish).

Carrier Engineering Newsletter 3(2), Carrier Corporation (2015). New Refrigerants Impact Standards and Codes. Available: www.carrier.com/commercial

Commission Regulation (EU) 2015/1095 of 5 May 2015 implementing Directive 2009/125 / EC of the European Parliament and of the Council with regard to ecodesign requirements for refrigerated and freezing cabinets, blast chillers or freezers, condensing units and chillers for cooling liquids. Official Journal of the European Union L 177/19 of 8.7.2015 (in Polish).

Commission Regulation (EU) 2016/2281 of 30 November 2016 on the implementation of Directive 2009/125 /WE of the European Parliament and of Council Directive 2009/125 / WE establishing general principles for setting ecodesign requirements for energy-related products with regard to ecodesign requirements for air heating products, cooling products, high temperature chillers and fan coil-fan tracks. Official Journal of the European Union L 346/1 of 20.12.2016 (in Polish).

Journal of Laws, 2018, item 669, Act of February 8, 2018 on the ratification of the Doha Amendment to the Kyoto Protocol to the United Nations Framework Convention on Climate Change, done in Kyoto on December 11, 1997, done in Doha on December 8 2012 (in Polish).

Kuprianoff, J., Plank, R., Steinle, H. (2014). Die Kąltemittel Band 4, Handbuch der Kąltetechnik, Amazon.

Niebergall, W. (1959). *Handbuch der Kąltetechnik siebenter Band Springer Verlag.* Berlin, Góttingen, Heidelberg, (Herausgegeber) Rudolf Plank,

Stefanowski, B. (1949). *Chłodnictwo*, Sweden, Stockholms Bokindustri Aktiebolag (in Polish).

Targański, W. *Wymagania prawne i wytyczne UE w sprawie wycofywania czynników chłodniczych z grupy HFC*. Available: https://mech.pg.edu.pl (in Polish).

Zakrzewski, B. (2014) Available: https://docplayer.pl/37732674-Wyklad-5-czynniki-chlodnicze-klasyfikacja-wskazniki-oceny-ekologicznej-gwp-tewi-wykrywanie-nieszczelnosci.html

https://www.schiessl.pl/pl/czynniki-chlodnicze

https://prozon.org.pl/index.php

http://www.rynekinstalacyjny.pl/artykul/id3695,czynniki-chlodnicze-legislacja-dzis-i-jutro?gal=1

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Influence of Decreasing Supplementation to Transformation of Chemical Forms of Ni, Zn and Cu During Composting of Sewage Sludge

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Abstract: This paper pertains to the influence of decreasing supplementation to transformation of chemical forms of Ni, Zn and Cu during composting of sewage sludge. A universally used supplementing material constituting a rich source of organic carbon is straw. Addition of straw to sewage sludge is aimed at increasing C/N proportion up to at least 15 due to the risk of formation of toxic forms of nitrogen, concentration of which in sewage sludge is exceptionally high. We have presented in this paper the results of speciation research of three elements applying Tessier's sequential extraction. It's been proven that decreasing of straw share in the composted mixture with sewage sludge down to the level of C/N value below the admissible value, has a beneficial effect on the allocation of tested heavy metals towards the forms that are permanently bound in compost matrix. A systematic increase of organic (IV) and residual (V) fractions share and decrease of mobile forms of heavy metals content in bioavailable fractions i.e. ion-exchange (I) and carbonate (II) has been ascertained.

Keywords: sewage, composting, heavy metals, speciation

1. Introduction

Composting of sewage sludge originating from municipal sewage treatment, is a universally applied method of biological transformation of biodegradable waste that assures obtaining of highly fertile material i.e. compost (Curtis & Claassen 2009, Carrizo et al. 2015). Due to high content of macroelements, mainly organic carbon, nitrogen and phosphorus, mechanically dehydrated sewage sludge makes a valuable raw material for production of compost, which complies with the requirements set for soil improvers and materials substituting soil in growing media (Pinasseau et al. 2018, Regulation EU 2019). High concentration of total nitrogen in mechanically dehydrated sewage sludge generally falling into 2-7% DM (dry matter) interval (Sidełko et al. 2010, Świerczek et al. 2018) and its high humidity amounting to 85-75% (Kacprzak et al. 2017) causes that composting of sewage sludge requires use, at the compost mass formation stage, of a supplement featuring high concentration of organic carbon and low nitrogen content (Hamoda et al. 1998, Zhang et al. 2010, Doublet et al. 2010). The optimum C/N ratio at the compost formation commencement point should fall, according to various sources, within 20-30 interval (Sidełko et al. 2011, 2017) whereas value of this parameter in dehydrated sewage sludge generally does not exceed 7 (Kacprzak et al. 2017). The required C/N ratio originates, among other things, from a hazard of generation of nitrogen toxic forms – NH_3, in conditions of increased organic nitrogen concentration in sewage sludge (Gonzalez et al. 2019).

Supplementation, being an essential operation for sewage sludge composting, was a theme of many studies associated with use of various organic materials i.e. sewage sludge with green waste originating from park and garden upkeep activities, where the proportion of both components was 1:1.2 w/w (C/N = 28.9) (Gonzalez et al. 2019), sewage sludge with wood shavings and mature compost in proportion of 1:0.5:0.17 w/w (C/N = 19.3) (Zheng et al. 2018), sewage sludge with maize straw 1:1.9 w/w (C/N = 30) (Głąb et al. 2018) and sewage sludge with maize stark – 5.7% moisture content 1:0.17 w/w (C/N = 18.2) (Li et al. 2017). Research works on sewage sludge composting with supplementation below C/N = 15 proportion. due to a possibility of generation NH_3, having unfavourable impact on the kinetics of organic matter decomposition, are, however, rare. Test results for compost samples performed in laboratory conditions using a reactor of approximately 1.3 m^3 volume and proportion between dehydrated sewage sludge and barley straw being 1:0.3 respectively (C/N = 15) obtained by Kulikowska & Sindrewicz (2018), did not confirm any unfavourable impact of the increased volume of sewage sludge in composted mass on the process course. Also results of our own earlier research work on composting of sewage sludge using a dynamic reactor in industrial conditions, taking into account observed compost temperatures and timing of its maintenance as well as the change of organic substance content and C/N parameter, have indicated correct course of composting at relatively low C/N value amounting to 10 (Sidełko et al. 2020).

The research work initiated in 2018 pertained to evaluation of composting process in conditions of increased concentration of sewage sludge in its mixture with straw and comprised an analysis of change of selected physico-chemical indicators values, including also heavy metals. Total heavy metals content in compost qualified as soil improver makes, in accordance with applicable regulations, a criterion admitting compost for use in agriculture (Regulation EU 2019). The Regulation of the European Parliament and of the Council (EU) 2019/1009 of 5 June 2019 strictly defines the admissible levels of total Ni, Hg, Cr (VI), Pb and As (inorg) in organic fertiliser content. However, the recommended total copper content must not exceed 300 mg/kg DM and zinc 800 mg/kg DM.

The total heavy metals content does not allow to asses the level of hazards that the natural environment would be exposed to, which may constitute the application of composted sewage sludge to the soil. In order to determine bioavailability. mobility and reactivity of trace elements, analytical procedures based on sequential extraction are used (Janowska & Szymański 2009, Zhu 2014). The most frequently applied method is the sequential extraction developed by Tessier et al. (Zhu 2014). It consists in separation of five fractions i.e. ion-exchange, associated with carbonates and Fe/Mn oxides, with organic substance and residual fraction. It's been proved that metals in form of ion-exchange and water-soluble compounds can migrate and be accumulated in plant tissues (Zhu 2014).

The objective of our research work was to determine Ni, Zn and Cu amounts bound in specific chemical forms, also in form of complexes that are hardly available for microorganisms. It is considered that bonding of heavy metals in the solid phase during composting e.g. in humic compounds structure and argillaceous minerals compared to other chemical forms is exceptionally strong (Szymański et al. 2005). Thus the risk of liberation of heavy metals to the ground and their bioaccumulation in cultivated plants is reduced.

2. Materials and Methods

Field research was performed at Goleniów wastewater treatment plant withing a project financed under EU South Baltic programme (STEP 2018).

Before modification of the composting technique. which took place in October 2020, processing of sewage sludge originating from municipal wastewater treatment consisted in its mechanical dehydration and then composting with straw, wood chips and mature compost (inoculum) added in mass proportion of – 4:1:0.5:0.5. Composting was performed in roofed windrows 70 m in length and trapezoid cross-section dimensions being 3m – bottom base width and 1.5 m – the height. The windrows were periodically mechanically overturned at a rate of two overturns per week during the first three weeks of composting and, in the subsequent weeks, once per week on average. Composting operation comprising an intense phase and maturing lasted 4-5 months depending on the external conditions.

Two windrows differing in proportion of particular components being respectively: windrow no 1 (series 1) – 4:1:1 and windrow no 2 (series 2) – 8:1:2 (sewage sludge : straw : wood chips and inoculum) were earmarked for the research. From each windrow compost samples weighing approximately 1 kg were taken; apart from the selected physico-chemical indicators heavy metals were determined by application of a flame method using AAS atomic absorption spectrometer. The analysis of heavy metals fractions based on the multistage sequential extraction was performed using the Tessier's method (Table 1).

Table 1. Analytical procedure

Step	Fraction	Extractant	Extraction conditions	
			temperature	time
I	FR I exchangeable	10 cm^3 1 M CH_3COONH_4 pH = 7	20°C	1h
II	FR II carbonate	20 cm^3 1M CH_3COONa. pH = 5	20°C	5h
III	FR III bound with Mn and Fe oxides	20 cm^3 0.04 M $NH_2OH{\cdot}HCl$ w 25% (v/v) CH_3COOH	95°C	5h
IV	FR IV organics and sulphides	a) 5 cm^3 0.02 M HNO_3 + 5 cm^3 30% H_2O_2 . pH = 2 b) 5 cm^3 30% H_2O_2 . pH = 2 c) 10 cm^3 3.2M CH_3COONH_4 w 20% (v/v) HNO_3	a) 85°C b) 85°C c) 20°C	2h 3h 0.5h
V	FR V residue	5 cm^3 65% HNO_3 + 1 cm^3 30% H_2O_2 + 1 cm^3 75% $HClO_4$	Microwave mineralization	

*Szymański et al. 2005

3. Results and discussion

Generally, total concentrations of tested heavy metals increased in both series during the composting (Table 2-4).

Table 2. Average Ni content in fractions

Composting time day	Average Ni content in fractions. [mg/kg d.m]					
	FRI	FRII	FRIII	FRIV	FRV	sum
Windrow no. 1 – 4:1:1 (sewage sludge/straw/wood chips and innoculum)						
3	0.83	0.38	0.50	2.50	9.30	13.51
10	0.30	0.50	0.38	3.13	13.95	18.26
16	0.30	0.25	0.38	3.00	12.33	16.26
24	0.30	0.25	0.25	3.25	12.45	16.50
29	0.23	0.25	0.25	3.13	18.62	22.48
48	0.23	0.25	0.13	3.88	19.78	24.27
62	0.15	0.25	0.00	3.88	9.80	14.08
83	0.23	0.50	0.00	4.38	10.90	16.01
111	0.15	0.50	0.00	4.50	10.10	15.25
133	0.15	0.50	0.00	5.13	16.23	22.01
Windrow no. 2 – 8:1:2 (sewage sludge/straw/wood chips and innoculum)						
3	0.68	0.38	0.88	2.38	8.45	12.77
10	0.15	0.25	0.50	3.38	8.73	13.01
16	0.30	0.00	0.50	3.00	9.95	13.75
24	0.15	0.13	0.50	3.13	15.35	19.26
29	0.15	0.00	0.25	3.38	16.73	20.51
48	0.23	0.25	0.00	3.25	4.73	8.46
62	0.15	0.00	0.00	3.50	12.85	16.50
83	0.15	0.25	0.00	3.13	9.73	13.26
111	0.15	0.25	0.00	3.25	12.10	15.75
133	0.15	0.13	0.00	3.38	13.35	17.01
Sewage sludge	2.03	2.63	1.25	1.50	3.10	10.51

Table 3. Average Zn content in fractions

Composting time day	Average Zn content in fractions. [mg/kg d.m]					
	FRI	FRII	FRIII	FRIV	FRV	sum
Windrow no. 1 – 4:1:1 (sewage sludge/straw/wood chips and innoculum)						
3	14.25	124.88	162.88	90.75	48.75	441.51
10	14.93	117.00	178.50	94.38	70.45	475.26
16	16.65	115.63	183.88	97.13	69.48	482.77
24	19.43	112.38	183.63	110.50	58.58	484.52
29	14.10	109.38	205.38	106.38	74.09	509.33
48	11.93	92.13	213.25	136.50	78.70	532.51
62	9.98	82.75	208.75	167.75	79.48	548.71
83	10.80	69.25	198.63	170.00	84.83	533.51
111	10.28	62.75	195.38	170.38	123.23	562.02
133	10.43	65.25	194.38	177.13	107.83	555.02
Windrow no. 2 – 8:1:2 (sewage sludge/straw/wood chips and innoculum)						
3	16.58	117.00	160.00	62.88	49.05	405.51
10	10.28	90.75	181.88	101.75	47.10	431.76
16	13.58	102.00	177.13	85.50	60.80	439.01
24	14.40	82.00	152.63	85.88	43.60	378.51
29	14.10	88.50	186.88	94.25	39.53	423.26
48	16.20	68.50	148.50	105.50	55.05	393.75
62	13.50	63.75	169.88	112.63	40.50	400.26
83	8.85	69.50	162.75	120.50	59.40	421.00
111	9.30	67.00	157.00	141.00	54.70	429.00
133	10.80	71.63	148.25	145.50	77.33	453.51
Sewage sludge	28.95	146.63	253.25	91.13	31.80	551.76

Table 4. Average Cu content in fractions

Composting time day	Average Cu content in fractions. [mg/kg d.m]					
	FRI	FRII	FRIII	FRIV	FRV	sum
Windrow no. 1 – 4:1:1 (sewage sludge/straw/wood chips and innoculum)						
3	14.25	5.25	4.13	120.75	44.63	189.01
10	7.73	3.38	4.38	131.25	57.53	204.27
16	7.65	3.00	3.75	138.00	56.35	208.75
24	6.75	2.50	3.25	143.13	56.63	212.26
29	5.33	2.25	3.50	133.88	74.13	219.09
48	4.35	1.75	3.38	145.88	80.15	235.51
62	3.83	1.50	3.25	155.63	74.75	238.96
83	4.20	1.50	3.25	171.25	65.55	245.75
111	3.75	1.25	3.00	169.13	78.13	255.26
133	4.50	1.50	2.75	166.00	78.75	253.50
Windrow no. 2 – 8:1:2 (sewage sludge/straw/wood chips and innoculum)						
3	18.00	6.75	5.25	117.63	34.88	182.51
10	6.38	2.63	3.63	145.50	44.38	202.52
16	7.13	3.00	3.75	132.00	46.88	192.76
24	6.08	2.25	3.63	120.25	37.80	170.01
29	6.08	2.13	4.50	133.00	48.05	193.76
48	5.48	1.75	2.88	120.50	44.90	175.51
62	4.13	1.38	3.00	129.38	41.63	179.52
83	3.15	1.63	2.88	122.00	54.60	184.26
111	3.45	2.13	3.00	122.63	59.05	190.26
133	3.90	2.13	2.63	125.88	66.73	201.27
Sewage sludge	27.75	8.88	9.00	131.38	48.25	225.26

Observed increases of total contents of tested metals were associated with successive ullage of organic matter content during composting causing decrease of the dry matter content. In the reaction close to neutral (pH ≈ 7), heavy metals practically do not form any soluble compounds. Therefore, the total content of heavy metals does not change significantly but their concentration, translated into diminishing dry matter, increases. The phenomenon of increase of heavy metals concentration during composting is confirmed by values of calculated Pearson correlation coefficients defining the linear interdependence level. Data put in Table 5 show strong negative correlation between the tested metals and organic matter (OM) although in Cu case, obtaining of the result that would confirm the increasing concentration phenomenon required intervention in the data structure and removal of the so-called outlier not falling within the predefined 95% level of confidence.

Table 5. Pearson correlation coefficients values

Series	Correlation		
	Ni /*om*	Cu /*om*	Zn /*om*
No 1	-0.69	0.14/-0.38	-0.44
No 2	-0.28	-0.58/-0.65	-0.55

Following removal of one case from the available database, value of the correlation coefficient describing the force of relation between Cu and OM (organic matter) decreased from 0.14 down to -0.38 in series 1 and from -0.58 down to -0.65 in series 2. Action consisting in elimination of outliers impact, or possibly their substitution with average values, may change the force of the observed relation fundamentally and is an element of proprocessing used in statistical analysis. Figures 1 and 2 show course of the regression lines using all the data respectively and after removal of one case describing copper content in sewage sludge (Table 4).

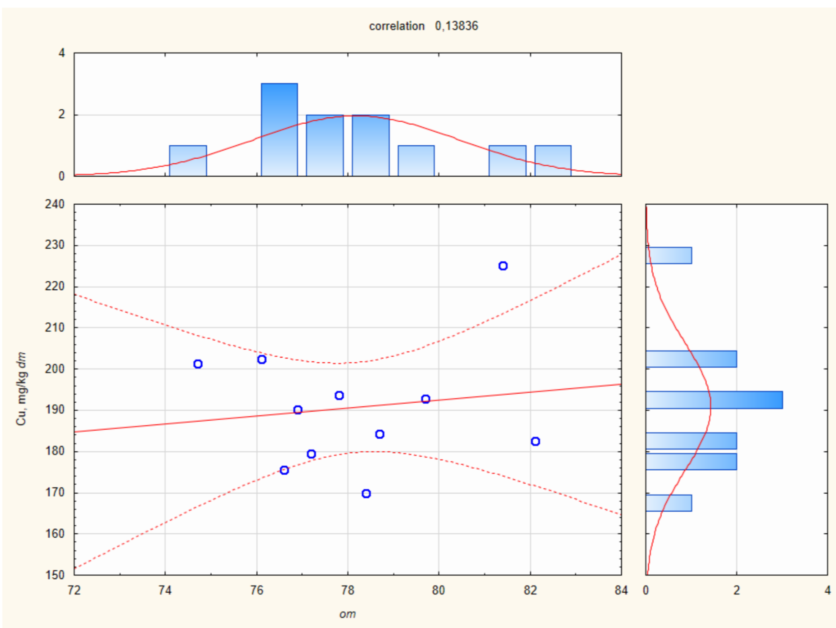

Fig. 1. Regression line and force of correlation describing Cu-*OM* association before data correction

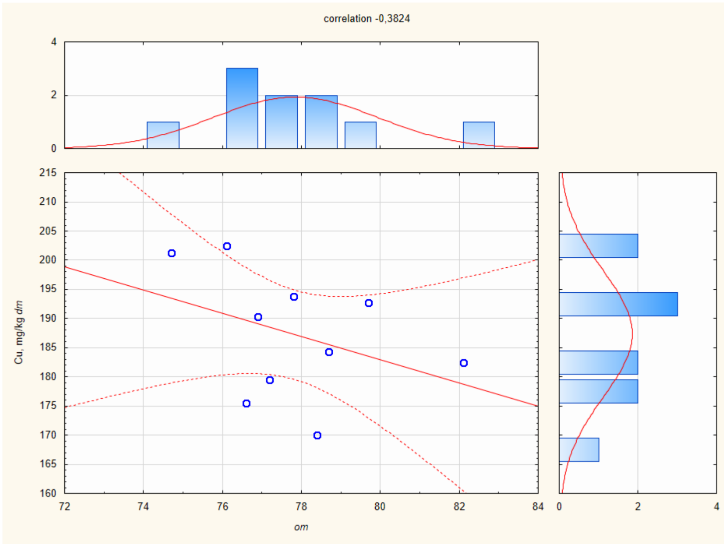

Fig. 2. Regression line and force of correlation describing Cu-*OM* association after data correction

Despite a failure to determine the admissible Cu and Zn contents in soil improver, high concentration of both elements, likewise Ni, was the main cause of fractioning operation for all three heavy metals. Metal fractioning allows for settlement of chemical forms of given element in the same compost sample. Contents of heavy metals bound in form of various compounds results from settlement of a natural equilibrium depending on the environmental conditions. A partial objective for this stage of research was the assessment of a risk originating from presence of mobile forms of nickel, copper and zinc posing a real hazard for the environment. It is considered that binding of heavy metals in the solid phase during composting, e.g. in the structure of humic compounds and argillaceous minerals, compared to other chemical forms, is exceptionally strong. Thus, the risk of heavy metals liberation to the ground and their bioaccumulation in cultivated plants is reduced.

Compost samples fractioning used to distinguish metal compounds groups featuring specific properties has been performed using the Tessier's method. According to the said method, five groups have been identified as: rechangeable metals (fraction I), carbonates bound metals (fraction II), metals bound with hydrated oxides of iron and manganese (fraction III), metals bound with organic matter (fraction IV) and metals bound with aluminosilicates (fraction V). Fractions I and II are considered unstable, liable to liberate metals to the environment. However. metals in fractions IV and V are bound in a permanent way (Szymański et al. 2005).

Test results have shown that sewage sludge composting process runs correctly even at initial proportion of C/N ≈ 10, i.e. much lower than the recommended value 15-25. When we compared test results for performed composting trials (series), it turned out that the lower the volume of sewage sludge with relation to straw per batch, the higher the temperature inside compost windrows and longer the period of the thermophilic phase (STEP 2018). Consequently, more favourable changes as to allocation of heavy metals chemical forms had been occurring. Having analysed structure of the data in terms of change of determined fractions contents with flow of composting time, it can be stated that metal contents bound in fraction I and II decreased and increased in fractions IV and V (Table 2-4).

For nickel, in both series (Table 2), total concentration values in mature compost attained the following levels respectively: 40 and 34% of the admissible value i.e., 50 mg/kg DM (Regulation EU 2019). Average nickel content in fractions IV and V in mature compost produced in each performed series constituted more than 97% of the total content. Ni contents (in mature compost) in ion-exchange fraction, carbonate bound and Fe/Mn oxides fractions did not exceed 1% of the total contents. This means that any toxic hazard originating from nickel impact, in the case of compost usage in agriculture, practically does not exist. Changes of contents of nickel bound in particular fractions in series 1 and 2 is illustrated by linear regression graphs shown in Fig. 3 and 4 respectively. Similar trend has been noted for copper and zinc.

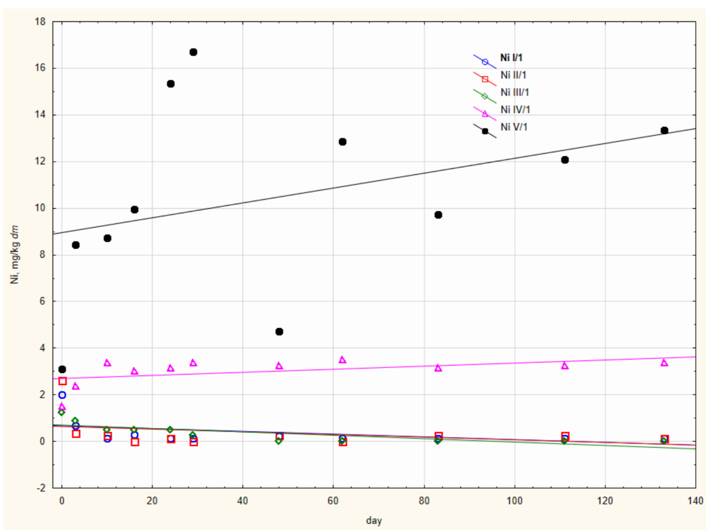

Fig. 3. Trend lines for contents of Ni bound in five tested fractions – series 1

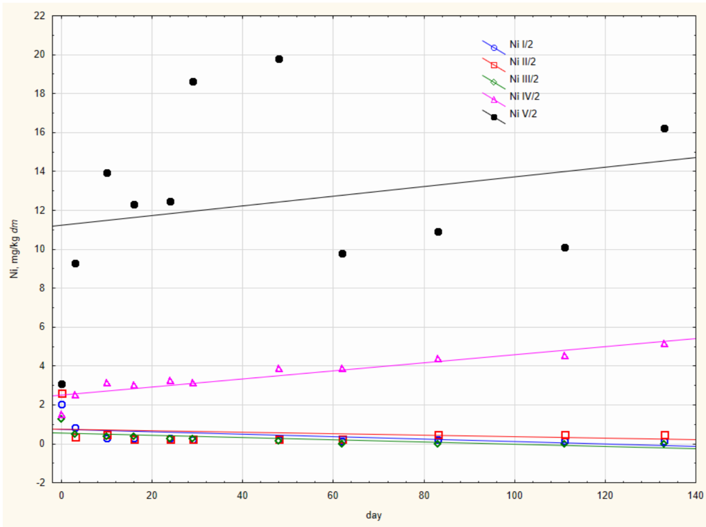

Fig. 4. Trend lines for contents of Ni bound in five tested fractions – series 2

Total zinc contents in mature compost samples in both series was 555.02 mg/kg DM and 453.51 mg/kg DM respectively and did not exceed the admissible value set in the Regulation of the European Parliament and of the Council (EU) 2019/1009 of 5 June 2019 (Regulation EU 2019) – i.e. 800 mg/kg DM (Tab. 3). Zinc occurred in tested samples mainly in the Fe/Mn oxide (FIII) and organic (FIV) fractions. Percentage of Zn in fraction FIII series 1 amounted from approximately 32% to approximately 44% whereas in series 2 from approximately 34% to 40% of total content. In both compost windrows (series 1 and 2), decrease of ion-exchange zinc compounds (FI) was observed (Table 3). Compost samples taken during the last day of series 1 process (lower sewage sludge content in the composted biomass), featured higher percentage of Zn in fraction I (2.38%) than the samples taken for series 2 (1.88%).

During the course of the process decrease of zinc compounds in carbonate fraction content was noted. Percentage of Zn, in samples taken on the 133rd day, amounted to, in this fraction, 15.79% (series 1) and 11.76% (series 2) of the total content. However, concentration in the fraction bound with organic matter (FIV) was increasing (Table 3).

Total content of Cu in the samples taken at the final composting stage amounted to 253.50 mg/kg DM (series 1) and 201.27 mg/kg DM (series 2) (Tab.4) and did not exceed the admissible value set in the Regulation of the European Parliament and of the Council (EU) 2019/1009 of 5 June 2019 (Regulation EU 2019). It has appeared from the fraction analysis that copper occurred mainly in the organic fraction (FIV). Percentage of Cu bound with organic fraction taken from windrow during composting was from 61% to 72% of total content of this element. Percentage of Cu in the residual fraction (FV) has been noted within the 19-34% interval. The lowest copper compounds contents percentage at both stages has been noted for the fraction bound with Fe/Mn oxides and with carbonates. It was 1.30% for series 1; 1.08% for series 2 and 1.06% for series 1; 0.59% for series 2 respectively. Percentage of ion-exchange copper compounds at the first composting stage (up to the third day) was approximately 9% of total content of this element whereas in mature compost samples the percentage of ion-exchange copper forms did not exceed 2% of the total content. Compost samples taken from a windrow containing higher share of sewage sludge in the composted mass (series 1) featured higher content of copper forms in fractions I, II and III than in series 2.

4. Summary

The speciation analysis results pertaining to determination of zinc, copper and nickel in sequentially separated chemical forms isolated from compost samples have shown that as composting time flows, beneficial changes as to allocation of the tested heavy metals take place. Systematic increase of the contents of tested elements in stable fractions at the expense of the fractions, which relatively easily liberate heavy metals bound with them, has been ascertained. Fractions III, IV and V, unlike fractions I and II, are treated as biologically stable. During sewage sludge composting with straw added in proportion 4/1, amount of zinc bound in three of the above-mentioned fractions increased from 271.9 to 371.1 mg/kg DM, which indicates 37% increase. For Cu and Ni, increase being estimated in similar way amounted to 24% and 43% respectively. Increase of sewage sludge volume in straw mixture up to the level having mass proportion of both components 8/1, results in higher allocation of the tested heavy metals in non-bioavailable fractions. Total contents of Zn, Cu and Ni in fractions III-V increased by 58%. 46% and 73% respectively.

Therefore, a conclusion can be drawn that decrease of supplementation consisting in lower amount of straw added to composted sewage sludge, thus reduction of C/N proportion, clearly improves the effect of heavy metals bonding in non-bioavailable chemical forms.

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References

Carrizo, M. E., Alesso, C. A., Cosentino, D. & Imhoff, S. (2015). Aggregation agents and structural stability in soils with different texture and organic carbon content. *Scientia Agricola, 72*(1)*,* 75-82. DOI: 10.1590/0103-9016-2014-0026

Curtis, M. J., & Claassen, V. P. (2009). Regenerating topsoil functionality in four drastically disturbed soil types by compost incorporation. *Restoration Ecology, 17*(1), 24-32. DOI: 10.1111/j.1526-100X.2007.00329.x

Doublet, J., Francou, F., Poitrenaud, M. & Houot, S. (2010). Sewage sludge composting: Influence of initial mixtures on organic matter evolution and N availability in the final composts. *Waste Management, 30*(10), 1922-1930. DOI: 10.1016/ j.wasman.2010.04.032.

Głąb, T., Żabiński A., Sadowska, U., Gondek, K., Kopeć, M., Mierzwa-Hersztek, M. & Taborc, S. (2018). Effects of co-composted maize, sewage sludge, and biochar mixtures on hydrological and physical qualities of sandy soil. *Geoderma, 315,* 27-35. DOI: 10.1016/j.geoderma.2017.11.034.

Gonzalez, D., Colon, J., Gabriel, D. & Sanchez, A. (2019). The effect of the composting time on the gaseous emissions and the compost stability in a full-scale sewage sludge composting plant. *Science of the Total Environment, 654,* 311-323. DOI: 10.1016//j.scitoenv.2018.11.081.

Hamoda, M. F., Abu Qdais, H. A. & Newham,. J. (1998). Evaluation of municipal solid waste composting kinetics. *Resources, Conservation and Recycling, 23,* 209-223. DOI: 10.1016/S0921-3449(98)00021-4

Janowska, B. & Szymański, K. (2009). Transformation of selected trace elements during the composting process of sewage sludge and municipal solid waste. *Fresenius Environmental Bulletin, 18*(7), 1110-1117.

Kacprzak, K., Neczaj, E., Fijałkowski, K., Grobelaka, A., Grosser, A., Worwag, M., Rorat, A., Brattebo, H., Almas, A. & Singh, B. R.. (2017). Sewage sludge disposal strategies for sustainable development. *Environmental Research, 156*, 39-46. DOI: 10.1016/j.envers.2017.03.010

Kulikowska, D. & Sindrewicz, S. (2018). Effect of barley straw and coniferous bark on humification process during sewage sludge composting. *Waste Management, 79,* 207-213. DOI: 10.1016/j.wasman.2018.07.042.

Li, S., Li, D., Li, J., Li, G. & Zhan, B. (2017). Evaluation of humic substances during co-composting of sewage sludge and corn stalk under different aeration rates. *Bioresource Technology*, *245*, 1299-1302. DOI: 10.1016/j.biortech.2017.08.177.

Pinasseau, A., Zerger, B., Roth, J., Canova, M. & Roudier, S. (2018). Best Available Techniques (BAT) Reference Document for Waste treatment Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). EUR 29362 EN. Publications Office of the European Union. Luxembourg. ISBN 978-92-79-94038-5. DOI: 10.2760/407967. JRC113018.

Regulation EU 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 (Text with EEA relevance). http://data.europa.eu/eli/reg/2019/1009/oj

Sidełko, R., Janowska, B., Walendzik, B. & Siebielska, I. (2010). Two composting phases running in different process conditions timing relationship. *Bioresources Technology, 101,* 6692-6698. DOI: 10.1016/j.biortech.2010.03.092

Sidełko, R., Seweryn, K. & Walendzik, B. (2011). Optymalizacja procesu kompostowania w warunkach rzeczywistych. *Rocznik Ochrona Środowiska, 13*, 681-692.

Sidełko, R., Siebielska, I., Janowska, B. & Skubała, A. (2017). Assessment of biological stability of organic waste processed under aerobic conditions. *Journal of Cleaner Production, 164*, 1563-1570. DOI: 10.1016/j.jclepro.2017.07.035

Sidełko, R., Walendzik, B., Smuga-Kogut, M., Janowska, B., Szymański, K., Głowacka, A. & Leśniańska, A. (2020). Impact of reduced straw content on the sewage sludge composting process. *Archives of Environmental Protection, 46*(4), 70-77. DOI: 10.24425/aep.2020.135766

STEP, Sludge Technological Ecological Progress – increasing the quality and reuse of sewage sludge. Project no. STHB.02.02.00-32-0110/17. Available: https://www.step-interreg.eu/pl/

Szymański, K., Janowska, B. & Sidełko, R. (2005). Estimation of bioavailability of copper. lead and zinc in municipal solid waste and compost. *Asian Journal of Chemistry, 17*(3), 1646-1660.

Świerczek, L., Cieślik, B. M. & Konieczka, P. (2018). The potential of raw sewage sludge in construction industry – A review. *Journal of Cleaner Production, 200,* 342-356. DOI: 10.1016/j.jclepro.2018.07.188

Zhang, J., Gao, D., Chen, T. B., Zheng, G .D., Chen, J., Ma, C., Guo, S. L. & Du, W. (2010). Simulation of substrate degradation in composting of sewage sludge. *Waste Management, 30*, 1931-1938. DOI: 10.1016/j.wasman.2010.04.004

Zheng, G., Wang, T., Niu, M., Chen, X., Liu, Ch., Wang, Y. & Chen, T. (2018). Biodegradation of nonylphenol during aerobic composting of sewage sludge under two intermittent aeration treatments in a full-scale plant. *Environmental Pollution, 238*, 783-791. DOI: 10.1016/j.envpol.2018.03.112

Zhu, N.M., Li, Q., Guo, X. J., Zhang, H. & Deng,Y. (2014). Sequential extraction of anaerobic digestate sludge for the determination of partitioning of heavy metals. *Ecotoxicology and Environmental Safety, 102*, 18-24. DOI: 10.1016/j.ecoenv.2013.12.033

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Alternative Evaluation of Olive Pomace (Pirina) as Production Waste

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Abstract: With the increasing need for energy, energy studies to be obtained from waste gain importance. In this study, it has been tried to determine the amount of biogas energy that can be obtained from olive pomace (pirina), which is produced by processing oil olives. Numerical maps of pirina amounts and potential biogas energy values and location maps of the proposed pirina processing plant were created. The necessary calculations were made by comparing the obtained results with the relevant literature information. In the study, the current potential biogas energy amount was calculated, maps were created and the electricity and gasoline energy equivalent levels of this energy were tried to be calculated using the 2015-2019 data of the Mediterranean, Aegean and Marmara Regions. The total potential amount of pirina in the research area is 1853375.7 tons and the potential biogas energy amount that can be obtained is 33360762.4 MJ. Pirina, which is the production waste after pressing the olives for oil, can be used for energy production. By using pirina to obtain biogas energy, both the utilization of pirina and the development of the regions will be provided.

Keywords: biogases, map, olive, pirina, waste

1. Introduction

Olive; it is one of the agricultural products with significant economic value in terms of oil production and utilization of its fruit and waste. For many years, studies have been carried out to recycle the wastes originating from olive processing and olive oil producing facilities. Studies focus on the purification of the "black water" that comes out during oil extraction and the utilization of "pirina" for various purposes (Başkan 2010). Our country has an important potential in terms of biogas energy originating from animal or plant products. Researchers state that biogas can prevent environmental pollution as well as the financial contribution it will provide to the country's economy (Saltuk et al. 2016, Saltuk et al. 2017, Ertop et al. 2018). For, example, when animal wastes of the province of Isparta are included in biogas production, it is calculated that a greenhouse area of 3109.51 decares can be heated at a constant 10°C greenhouse temperature and 14 hours day^{-1} heating period during the 120-days vegetative growing period (Gökdoğan 2019). Biomass energy has an important potential among renewable energy sources. Solid wastes and agricultural residues with high organic content are used as fuel for energy production (Akın 2005). In this case, it reveals that countries with higher agricultural potential such as Turkey should properly utilize their plant and animal wastes and convert them into biomass energy (Ertop et al. 2019). Pirina, which is a solid waste consisting of olive seed and pulp remaining from olive oil production, is also an important biomass used in Mediterranean countries (Akın 2005).

During the olive oil that is made intensive production in Turkey occurs of a large amount of pirina at the end of production. Pirina has taken the oil in Turkey, almost all used as fuel, there are many areas of use in other Mediterranean countries. In Mediterranean countries, pirina can be used as fertilizer, fuel, feed for cattle, or even as an additive in road construction when mixed with bitumen. However, due to its energy content, it is increasingly used for fuel purposes (Görel et al. 2004, Öcal, 2005). Pirina is often used as animal feed, additive, cultivation of horticultural crops (Dermeche et al. 2013), as a fertilizer in soil strengthening (Paredes et al. 2001) and as an alternative fuel that does not contain sulfur (Çelen et al. 2015). The use of pirina for fuel is the most common use due to its high energy content. Depending on the type of olive trees, the structure of the soil, the climate and the nutrients in the soil, the energy value of pirina varies. In Turkey, even though the change from year to year depending on the average olive production of 200-250 thousand tons year^{-1} of pirina is known to be obtained (Demirtepe 2008). Studies are carried out on the use of pirina as an organic input in agriculture, as a fertilizer, as a soil improver, to determine its effects on the soil, and to evaluate this potential in agriculture (Lopez-Pineiro et al. 2007, Gomez-Munoz et al. 2010, Diacano et al. 2012, Gomez-Munoz et al. 2013). However, the lignin in the oil and core of pirina, which has high organic matter content, cannot easily turn into humic substances. Since the pirina given to the environment increases the carbon source, a large amount of nitrogen (N) immobilization may be in question, which may have a negative effect on the nitrogen uptake required for the plants (Başkan 2010). In this case, it shows that the use of unprocessed pirina as fertilizer is limited, and if it is not used as fertilizer, it may create similar problems in the field of waste (Dermeche et al. 2013). For this reason, processing becomes a necessity as it is not possible to leave pirina directly to nature.

This study aims to map these potential energy fields by determining the amount of pirina and potential biogas energy generated as a result of olive oil production in the Mediterranean, Aegean and Marmara Regions. Also, it is to reveal the potential of an alternative energy source in order to meet the energy need by using the pirina in the production of biogas energy.

2. Materials and methods

In the calculation of oil olive biogas energy from waste the years 2015-2019 Turkey Statistical Institute of data are used. In the study, the Mediterranean, Aegean and Marmara regions were selected as the study area (Figure 1). It was taken into account that the production of olive oil production is in the forefront in selecting these regions as a study area. In the selection of olive for oil, which is an herbal product, it was taken into consideration that the amount of olive pirina that can be obtained after squeezing the olive is high.

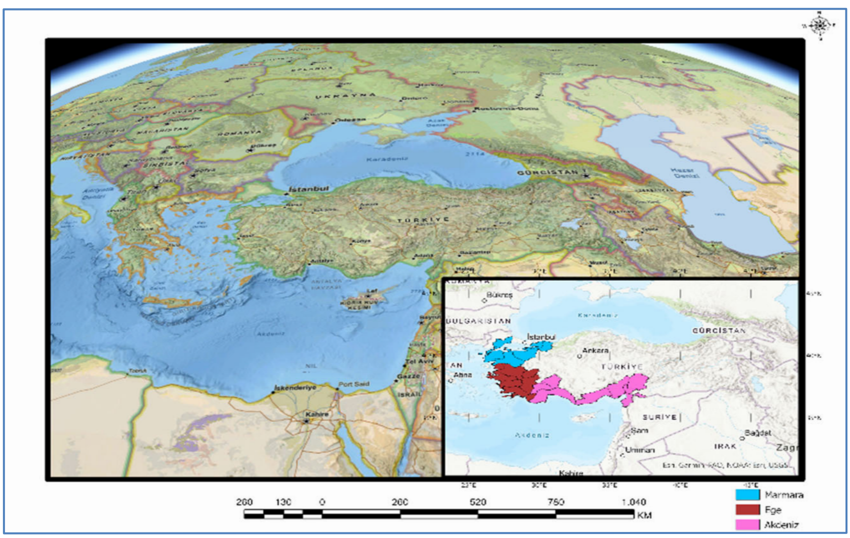

Fig. 1. General view of the study area

Pirina, which is an increased olive pulp after the pressed of olives, is an important biomass type seen in the Mediterranean countries. It can be obtained in quite large amounts at low cost. Although the amount of pirina to be obtained from olive varies depending on the cultivation technique, olive type and oil processing, on average, 15-22 kg olive oil and 35-45 kg pirina can be obtained from 100 kg olive (Kurtuluş 2003, Öcal 2005). The moisture and oil content of the obtained pirina also varies according to the production method. The production processes of the 2 phase system and the 3 phase system are the same. However, since hot water is not added to the olive paste in the 2-phase system, black water does not occur. Instead, the pirina obtained is more watery than the 3-phase system. The content of pirina produced in the 3-phase system contains 2-6% oil and 35-50% moisture. These values must be reduced to be used as a pirina fuel. According to the Communiqué on the Control of Solid Fuels, the oil ratio of fuel oil must be below 1.5% and humidity below 15%. Taking these values into account, the amount of pirina that can be evaluated as fuel can be determined by taking the pirina yield coefficient at an average of 0.3 (Karaca et al. 2005).

For the research area, the data obtained from the Turkish Statistical Institute multiplied by 0.3, which is the yield coefficient of pirina, and the potential of pirina that can be used as fuel was calculated. 18 MJ kg^{-1}, which is the lower thermal value of pirina with the calculated pirina potential (Karaca et al. 2005) multiplied by the total energy potential was determined. After determining the potential biogas energy that can be obtained from pirina, comparisons with electricity and gasoline equivalent energy have been made. Zan Sancak et al., 2014; Baran et al., 2017; Atilgan et al., 2020a; Atilgan et al., 2020b; they stated in their studies that the amount of energy obtained from 1 m^3 of biogas is equivalent to 4.7 kWh of electricity and 0.8 liters of gasoline. These values were used in calculations. In the selection of the provinces envisaged for the facility where the obtained pirina will be processed and the provinces where the pirina is located, the smallest locations in kilometers have been chosen to benefit from time, transportation, work and labor factors. While choosing these locations, the distance between provincial centers was taken into account (Anonymous 2021).

Geographic Information systems software ArcGIS Pro was used in the study. Maps were produced with GIS software for spatial interpretation and inferences and these parts were discussed. Classification method was used in the production of maps. "Potential Pirina Amount (tone) and Potential Energy Amount (MJ)" classification maps for each region were produced with the Geographical Information Systems software. The number of classes in each region is equal to the number of provinces. In this way, the province ranking of the region in terms of the criteria addressed was made. Thanks to these spatial bases, maps for the positioning of pirina facilities were created and interpreted (Aksoy & San 2019). In the study, nonparametric Kruskal Wallis test was applied to determine the difference between provinces according to the number of olive trees for oil and the amount of olives. Dunn's multiple comparison test was used for statistically significant results (Cebeci 2019).

3. Results and discussion

The number of olive trees available in the Mediterranean Region for 2015-2019, the amount of olives collected from existing trees, the potential amount of pirina that can be obtained by squeezing the olives for oil and the potential energy amount that can be obtained are given in Table 1. The difference between provinces according to the number of olive trees for oil and the amount of olives was statistically significant ($p < 0.01$). The grouping obtained as a result of the application of Dunn's multiple comparison test is given in Table 1.

Table 1. The potential amount of pirina and energy that can be obtained in the Mediterranean Region

Province	Number of olive trees for oil (piece)	Olives for oil (tons)	Amount of potential pirina (tons)	Amount of potential energy (MJ)
Adana	8616832	147770	44331	797958
Antalya	12557916	294889	88466.7	1592400.6
Burdur	169926	1012	303.6	5464.8
Hatay	48353822	611161	183348.3	3300269.4
Isparta	19416	123	36.9	664.2
Kahramanmaraş	5104480	51969	15590.7	280632.6
Kilis	18605898	146679	44003.7	792066.6
Mersin	24625585	459131	137739.3	2479307.4
Osmaniye	7101696	187662	56298.6	1013374.8
Total	125155571	1900396	570118.8	10262138.4

When Table 1 is examined, it is seen that there are a total of 125155571 olive trees for olive oil production in the Mediterranean Region and a total of 1900396 tons of olives are collected for olive oil production. It was determined that the province of Hatay ranked first with 38.63% and Isparta province ranked last with 0.02% in the total tree presence in the region. Besides, it was determined that the province of Hatay ranked first with 32.16% in terms of the amount of olives grown in the region, and Isparta province ranked last with 0.006%. Although there are fluctuations in the number of trees and olive production on an annual basis, it can be said that the number of trees and olive production varies in proportion to the long period. However; it has been determined that the potential amount of pirina that can be obtained in the region is 570118.8 tons and the potential energy amount that can be obtained from this amount of pirina is 10262138.4 MJ. It is seen that the amount of potential pirina and energy that can be obtained in the olive tree and olive production is in the first place in the province of Hatay and the last place in Isparta. There is 32.16% of the total amount of pirina in Hatay province and 0.006% in Isparta. It has been calculated that 32.16% of the potential energy amount that can be obtained is located in the province of Hatay and 0.006% in the province of Isparta. Therefore, it can be thought that the amount of olive production and the potential amount of pirina and energy that can be obtained show a proportional change. The map of the potential amount of pirina that can be obtained in the Mediterranean Region is shown in Figure 2 and the map of the potential energy amount is shown in Figure 3.

When figures 2 and 3 are examined; it is seen that the province of Hatay has the highest level of pirina amount and energy potential in the Mediterranean Region, while Mersin is the second in the region and Antalya is the third. It was determined that the province with the lowest pirina and energy level was Isparta. Ertop and Atilgan (2019) stated in their study that Antalya and Mersin provinces are at the forefront in potential biogas energy planning. It can be said that Antalya and Mersin provinces in the Mediterranean region are in parallel with this study in terms of their biogas energy potential.

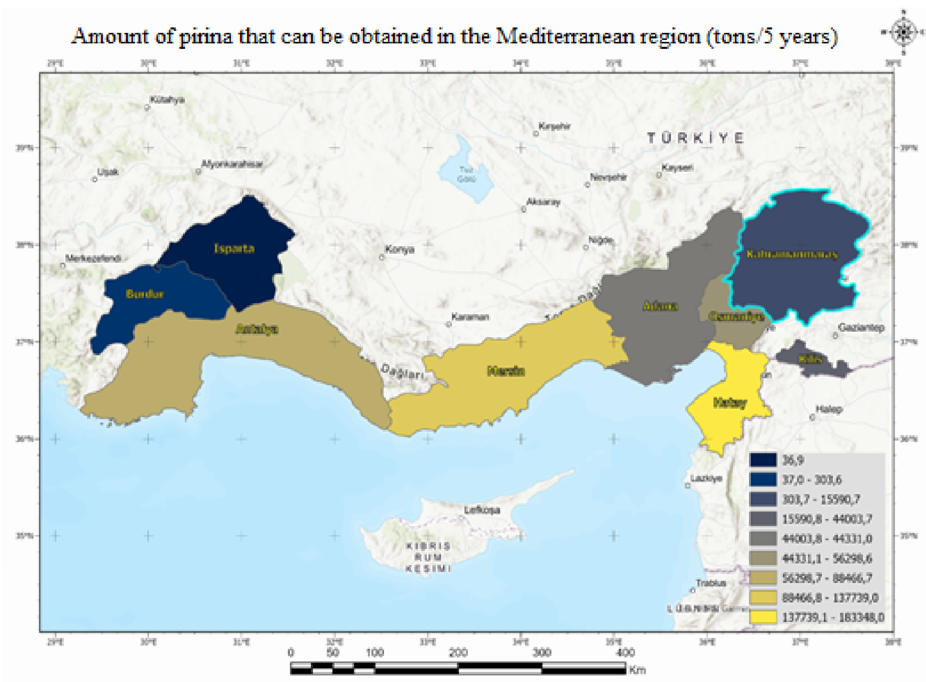

Fig. 2. Amount of pirina that can be obtained in the Mediterranean region (tons 5 years^{-1})

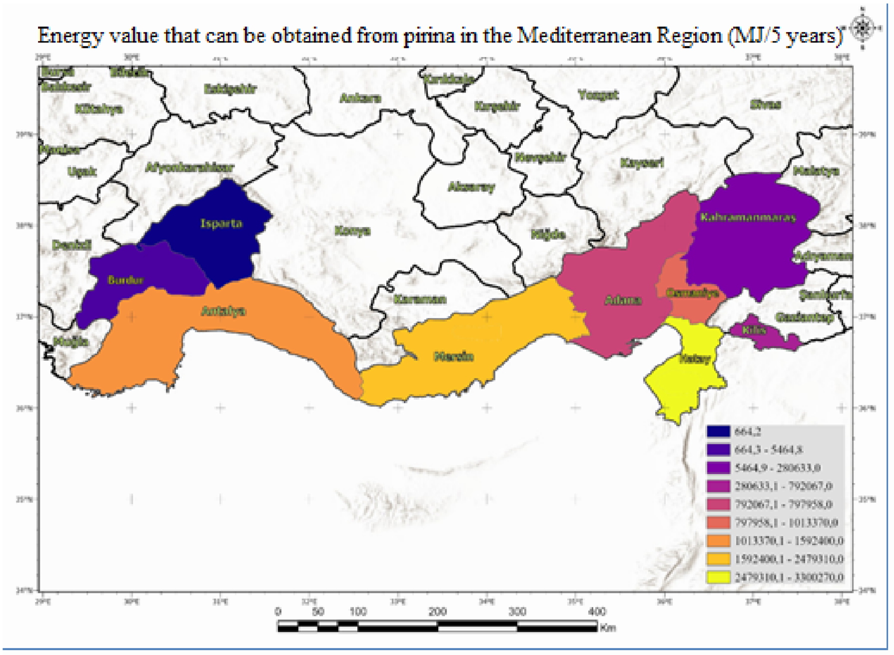

Fig. 3. Energy value that can be obtained from pirina in the Mediterranean Region (MJ 5 years^{-1})

In Table 2, the province where the olive pirina facility is proposed and the raw material capacities of the pirina plant and Figure 4 shows the location and distance of the proposed pirina facility in the region and provinces where raw materials can be supplied.

Table 2. Suggested pirina facilities for the Mediterranean Region and pirina capacity of the provinces

Province where pirina Facility is suggested	The province with pirina raw material	5-Year Pirina Capacity of Provinces (Tons)	The distance of the suggested pirina facility to the provinces (km)
Antalya	Antalya	88466.7	0
	Isparta	36.9	131
	Burdur	303.6	122
Osmaniye	Osmaniye	56298.6	0
	Mersin	137739.3	158
	Adana	44331	89
	Kahramanmaraş	15590.7	105
	Kilis	44003.7	145
	Hatay	183348.3	129

When Table 2 is examined; it can be thought that a pirina facility to be established in Antalya province may cover the provinces of Antalya, Isparta and Burdur. The total amount of pirina in these three cities is 88807.2 tons and the potential energy amount that can be obtained is 1598529.6 MJ. The amount of potential energy that can be obtained is equal to 7513089.12 kWh of electricity equivalent energy and 1278823.68 L of gasoline-equivalent energy. When Figure 4 is examined, it can be thought that Antalya is the province where the most suitable pirina facility will be built for Antalya, Isparta and Burdur provinces. It is seen that the closest cities where Antalya province can supply raw materials are Burdur, which is 122 km away, and Isparta, which is 131 km away. However, as seen in Table 2; it is seen that the raw material of pirina in Burdur and Isparta provinces is 340.5 tons in total. Therefore, considering the distance of Antalya province to other provinces in the region, it can be said that a facility for obtaining energy by processing pirina alone cannot be a profitable investment. Atilgan et al. (2020c) stated in their study in Antalya that greenhouse wastes can be used in the use of biogas energy. It may be thought that in Antalya, where greenhouse cultivation activities are carried out intensively, pirina should be used in greenhouse waste and energy planning.

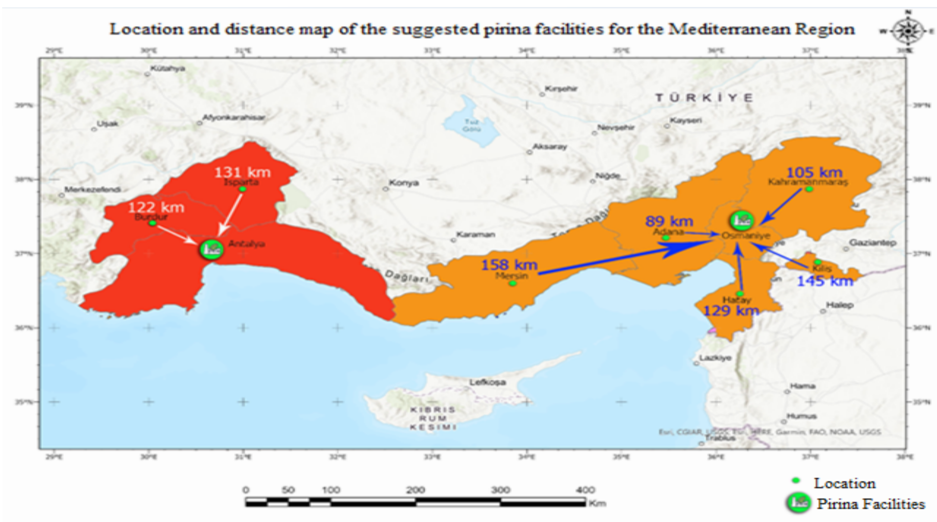

Fig. 4. Location and distance map of the suggested pirina facilities for the Mediterranean Region

Similarly, when Table 2 is examined, it is thought that a pirina facility to be established in Osmaniye province may cover the provinces of Osmaniye, Mersin, Adana, Kahramanmaraş, Kilis and Hatay. When Figure 3 is examined, the closest city where Osmaniye can obtain raw materials is Adana with 89 km, while the furthest city for raw material supply is Mersin with 158 km. As seen in Table 2; it is seen that the city with the highest potential in terms of pirina amount is Hatay. However, since transportation and labor costs between cities may be high, it is predicted that it would be more beneficial to consider a pirina facility that will be planned to be established in the eastern part of the Mediterranean Region in Osmaniye, as shown in Figure 4. The five-year raw material processing capacity of a pirina processing plant to be established in Osmaniye province will be 481311.6 tons. The amount of biogas energy that can be obtained from this facility is 8663608.80 MJ and this potential energy amount is equal to 40718961.36 kWh electricity equivalent energy and 6930887.04 L gasoline-equivalent energy.

The number of olive trees available in the Aegean Region for 2015-2019, the amount of olives collected from existing trees, the potential amount of pirina that can be obtained by squeezing the olives for oil and the potential energy amount that can be obtained are given in Table 3.

Table 3. The potential amount of pirina and energy that can be obtained in the Aegean Region

Province	Number of olive trees for oil (piece)	Olives for oil (tons)	Amount of potential pirina (tons)	Amount of potential energy (MJ)
Aydın	88628736	1325366	397609.8	7156976.4
Denizli	2669196	33499	10049.7	180894.6
Manisa	28144477	468659	140597.7	2530758.6
Muğla	76185566	705996	211798.8	3812378.4
Uşak	4311	20	6	108
İzmir	73695974	733115	219934.5	3958821
Total	269328260	3266655	979996.5	17639937

When the values of the Aegean Region are examined, it is seen that there are 269328260 olive trees and a total of 3266655 tons of olives are collected for olive oil production (Table 3). It was determined that Aydın province ranks first with 32.91% of the total tree presence and Uşak province ranks last with 0.002%. Also, it was determined that Aydın was the first with 40.57% in terms of the amount of olives grown in the region, and Uşak was the last with 0.0006%. It is seen in Table 3 that the potential amount of pirina that can be obtained in the region is 979996.5 tons and the potential energy amount that can be obtained from this amount of pirina is 17639937 MJ. It was determined that the potential amount of pirina and energy that could be obtained was also the first place of Aydin province and the last place of Uşak province. 40.57% of the total amount of pirina is in Aydın province and 0.006% is in Uşak province. It was calculated that 40.57% of total energy was in Aydın province and 0.0006% was in Uşak province. The map of the potential amount of pirina that can be obtained in the Aegean Region is shown in Figure 5 and the map of the potential energy amount is shown in Figure 6.

When Figure 5 and Figure 6 are examined; it is seen that Aydın Province has the highest level in Aegean Region in terms of pirina amount and energy potential and Izmir province is in second place in the region. It was determined that the province with the lowest pirina and energy level was Uşak. In Table 4, the province where the pirina facility is proposed and the raw material capacities of the pirina plant and Figure 7 shows the location and distance of the proposed pirina facility in the region and provinces where raw materials can be supplied.

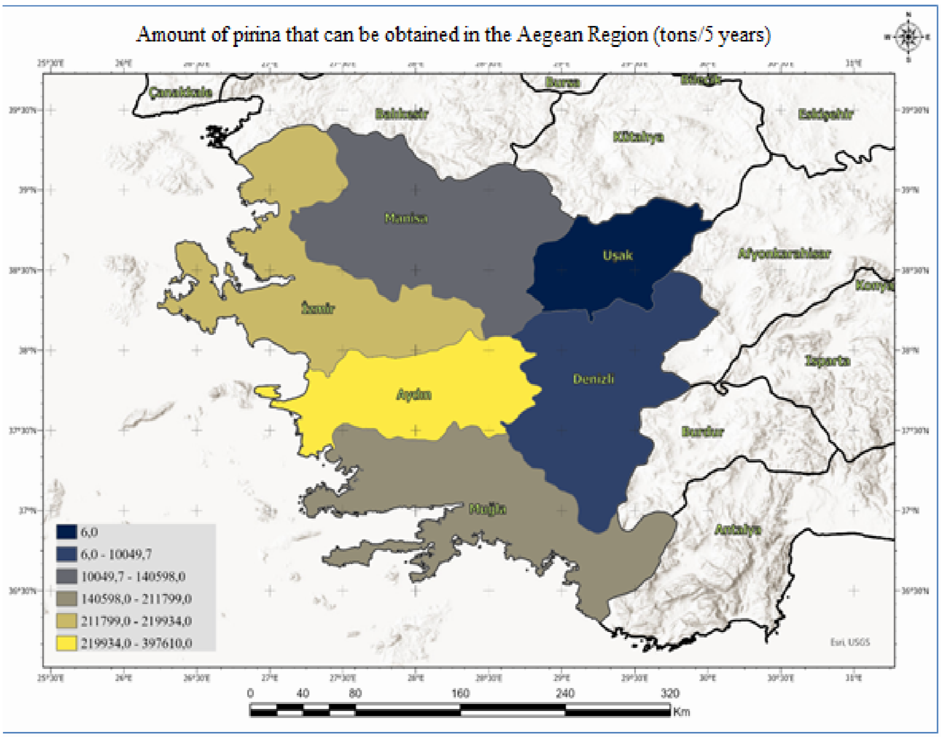

Fig. 5. Amount of pirina that can be obtained in the Aegean Region (tons 5 years^{-1})

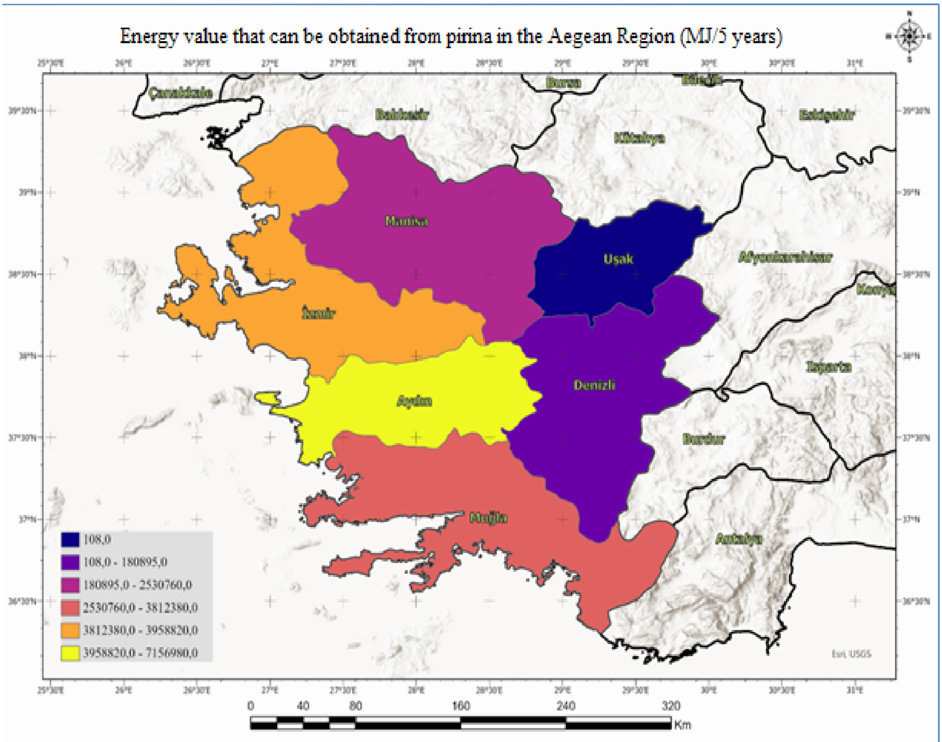

Fig. 6. Energy value that can be obtained from pirina in the Aegean Region (MJ 5 years^{-1})

Table 4. Suggested pirina facilities for the Aegean Region and pirina capacity of the provinces

Province where pirina facility is suggested	Province with pirina raw material	5-Year Pirina capacity of provinces (Tons)	The distance of the suggested pirina facility to the provinces (km)
Aydın	Aydın	397609.8	0
	Muğla	211798.8	98
	İzmir	219934.5	128
	Denizli	10049.7	124
	Manisa	140597.7	152
	Uşak	6	216

When Table 4 is examined, it can be thought that a pirina facility to be established in Aydın province may include Aydın, Muğla, Izmir, Denizli, Manisa and Uşak provinces. However, considering the very low amount of pirina in Uşak and its distance to Aydın, it can be said that there may be problems in raw material supply and therefore, the province of Uşak may not benefit from the facility to be established. When Figure 7 is examined, it can be said that Aydın is the most suitable province for the establishment of the Aegean Region pirina facility. In raw material supply for Aydın, it is seen that the closest province is Muğla with 98 km and the farthest province is Uşak with 216 km. However, it may be thought that it will not be economical to choose it due to the scarcity of raw materials in Uşak. For this reason, it can be said that the furthest raw material supply for Aydın province is Manisa, 152 km away. The total amount of pirina for the facility planned to be built in Aydın is 979996.5 tons and the potential energy amount that can be obtained is 17639937 MJ. The amount of potential energy that can be obtained is equal to 82907703.9 kWh of electrical energy and 14111949.6 L gasoline equivalent energy.

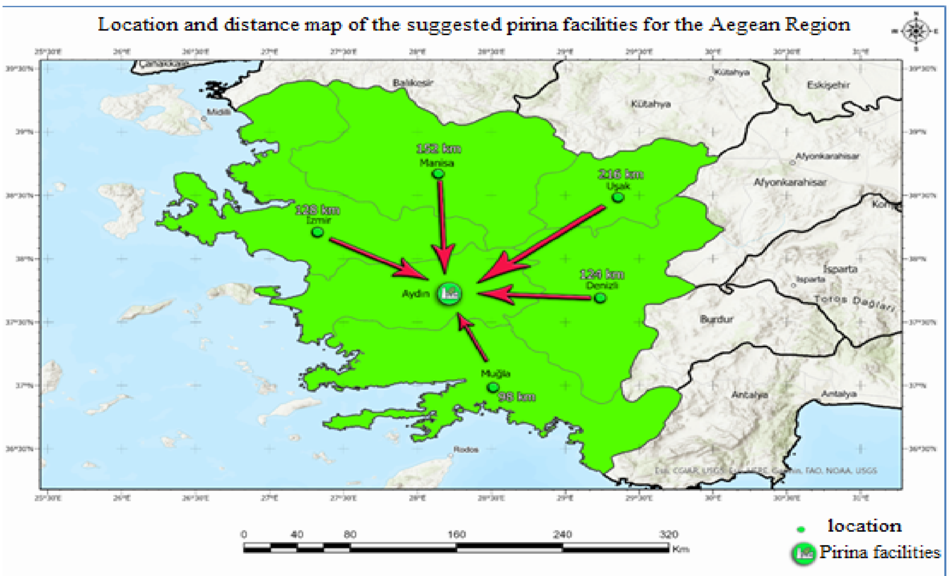

Fig. 7. Location and distance map of the suggested pirina facilities for the Aegean Region

The number of olive trees available in the Marmara Region for 2015-2019, the amount of olives collected from existing trees, the potential amount of pirina that can be obtained by squeezing the olives for oil and the potential energy amount that can be obtained are given in Table 5.

Table 5. The potential amount of pirina and energy that can be obtained in the Marmara Region

Province	Number of olive trees for oil (piece)	Olives for oil (tons)	Amount of potential pirina (tons)	Amount of potential energy (MJ)
Balıkesir	43886559	644068	193220.4	3477967.2
Bursa	3524076	44655	13396.5	241137
Kocaeli	3964	37	11.1	199.8
Sakarya	709012	10794	3238.2	58287.6
Tekirdağ	600935	8990	2697	48546
Yalova	12073	82	24.6	442.8
Çanakkale	22831281	302242	90672.6	1632106.8
Total	71567900	1010868	303260.4	5458687

It has been determined that there are a total of 71567900 olive trees for olive oil production in the Marmara Region and a total of 1010868 tons of olives are collected for olive oil production (Table 5). It is seen that Balıkesir province ranks first with a rate of 61.32% in terms of total tree presence in the region. In addition, it has been determined that Balıkesir is in the first place with 63.72% in terms of the amount of olives grown in the region and Kocaeli province is in the last place with 0.004%. However; It has been determined that the potential amount of pirina that can be obtained in the region is 303260.4 tons and the potential energy amount that can be obtained from this amount of pirina is 5458687 MJ. It is seen that the amount of potential pirina and energy that can be obtained in olive tree and olive production is in the first place in the province of Balıkesir and similarly in the last place in Kocaeli (Figure 8). There is 63.71% of the total amount of pirina in Balıkesir province and 0.004% in Kocaeli. It has been calculated that 63.71% of the potential energy amount that can be obtained is in Balıkesir and 0.004% is in Kocaeli. The map of the potential amount of pirina that can be obtained in the Marmara Region is shown in Figure 8 and the map of the potential energy amount is shown in Figure 9.

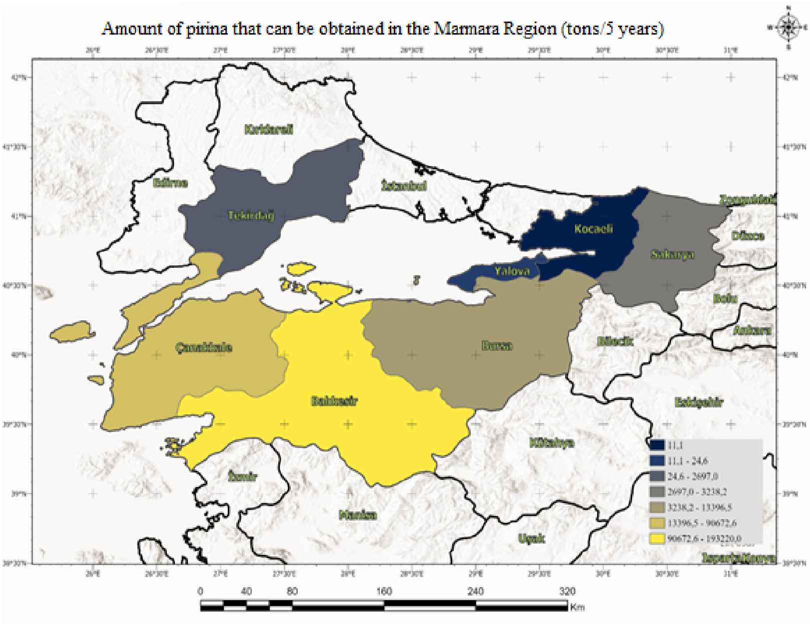

Fig. 8. Amount of pirina that can be obtained in the Marmara Region (tons 5 years^{-1})

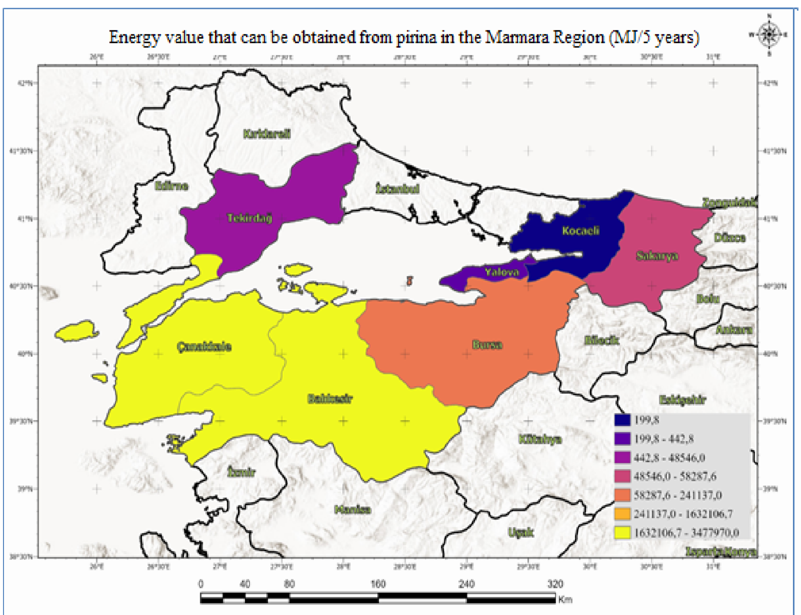

Fig. 9. Energy value that can be obtained from pirina in the Marmara Region (MJ 5 years^{-1})

When figures 8 and 9 are examined; It is seen that the pirina amount and energy potential of Balıkesir Province, which is expressed in yellow, is at the highest level, while Çanakkale is the second in the region. In Table 6, the province where the pirina facility is proposed and the raw material capacities of the pirina plant and Figure 10 shows the location and distance of the proposed pirina facility in the region and provinces where raw materials can be supplied.

Table 6. Suggested pirina facilities for the Marmara Region and pirina capacity of the provinces

Province where pirina Facility is suggested	The province with pirina raw material	5-Year Pirina Capacity of Provinces (tons)	The distance of the suggested pirina facility to the provinces (km)
Balıkesir	Balıkesir	193220.4	0
	Bursa	13396.5	152
	Kocaeli	11.1	275
	Sakarya	3238.2	308
	Tekirdağ	2697	370
	Yalova	24.6	212
	Çanakkale	90672.6	221

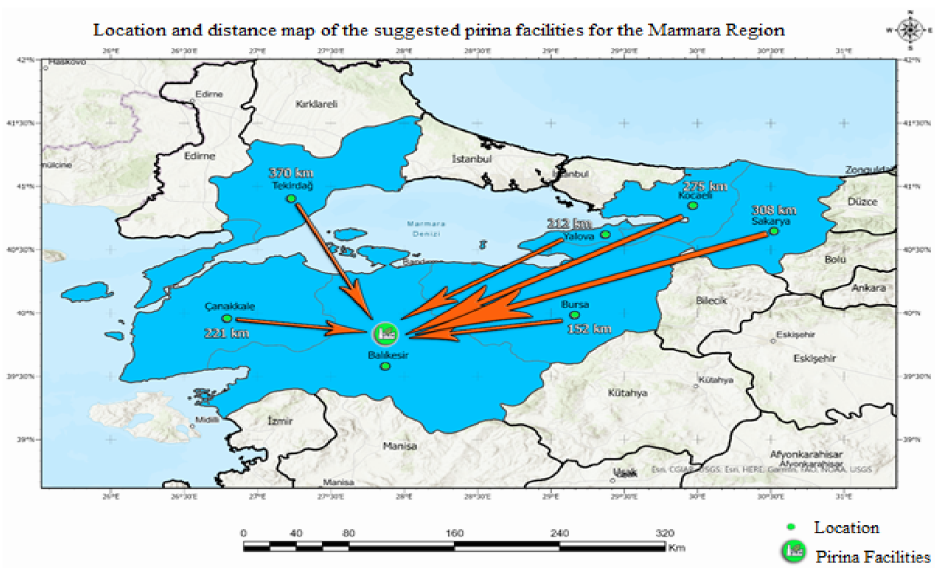

Fig. 10. Location and distance map of the suggested pirina facilities for the Marmara Region

We can easily say that a pirina facility to be established in Balıkesir province may include Balıkesir, Bursa, Kocaeli, Sakarya, Tekirdağ, Yalova and Çanakkale provinces. It can be said that in Kocaeli and Yalova provinces there may be problems in the supply of pirina raw materials and it may be appropriate to process different agricultural wastes and prina together in these provinces due to the long distance to Balıkesir (Table 6). When Table 6 and Figure 10 are examined together, it can be said that the distance of Tekirdağ to the facility planned to be built in Balıkesir is 370 km and it will not be a profitable investment due to the geographical location of Tekirdağ province. Also; Aktaş et al. (2015) stated in their study that using animal wastes would be beneficial in the biogas energy potential of Tekirdağ province. It is thought that this benefit will increase if animal wastes and pirina are processed together in Tekirdağ province. It can be said that there is a similar situation in the province of Sakarya as in Tekirdağ. Karabaş (2019) stated that different agricultural wastes should be used in the biogas energy potential of Sakarya. It has been concluded that in Sakarya, as in Tekirdağ, processing pirina together with different agricultural waste will increase the benefit rate. Therefore, it is seen that Balıkesir province can serve Bursa and Çanakkale provinces more beneficially as a pirina processing facility in the Marmara Region. The amount of pirina that can be processed in this facility is 297325.2 tons and the potential energy amount that can be obtained is 5351853.6 MJ. The amount of potential energy that can be obtained is equal to 25153711.92 kWh of electricity and 4281482.88 L of gasoline-equivalent energy. Turkey, which is an important agricultural country with high potential in terms of both crop production and animal production. Despite the high potential of organic waste, biogas management, known as the energy production method, is not used properly. When biogas management is implemented correctly, an economical input will be provided in terms of energy, and rural development can be achieved by providing a sustainable quality environment by reducing harmful wastes in terms of environment.

4. Conclusions

Organic waste material, which will be obtained from olive oil in the research area and is called pirina, has been taken into consideration. In this context, maps were created by revealing potential biogas energy. In which provinces the biogas plants to be planned in the future will be advantageous, it has been examined and the most suitable scenarios have been created. The total amount of potential biogas energy that can be obtained from pirina is 33360762.4 MJ. In the regions; it has been determined as 10262138.4 MJ in the Mediterranean Region, 17639937 MJ in the Aegean Region, and 5458687 MJ in the Marmara Region. It has been calculated that the highest energy amount that can be obtained in the regions is Hatay with 3300269.4 MJ in the Mediterranean Region, Aydın with 7156976.4 MJ in the Aegean Region and Balıkesir with 3477967.2 MJ in the Marmara Region. In our country where olive consumption is high, it has been concluded that the use of pomace produced from olives as a raw material source for biogas production instead of using it as a fuel can be used both in the utilization of organic materials and in obtaining energy. Thanks to these studies, by drawing attention to the utilization of agricultural wastes, this study was carried out to protect our environment as well as to evaluate the wastes as the biggest energy sources in the future.

References

Acaroğlu, M. (2007). Alternative Energy Sources. *Nobel Yayın, 1253*, 609, Ankara (in Turkish).

Akbulut, A., Dikici, A. (2004). *E Biogas Potential of Elazıg Province and Cost Analysis*. Doğu Anadolu Bölgesi Araştırmaları (in Turkish).

Akın, S. (2005). *Using Pomace as Biomass in Energy Production*. Balıkesir Üniversitesi Fen Edebiyat Fakültesi Kimya Bölümü, Balıkesir (in Turkish).

Aksoy, E., San, B. T. (2019). Geographical Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) Integration for Sustainable Landfill Site Selection Considering Dynamic Data Source. *Bulletin of Engineering Geology and the Environment, 78*(2), 779-791.

Aktaş, T., Özer, B., Soyak, G., Ertürk, M.C. (2015). Determination of the Electricity Generation Potential from Animal Biogas in Tekirdag City. *Tarım Makinaları Bilimi Dergisi, 11*(1), 69-74 (in Turkish).

Anonymous, (2006). Turkey's Renewable Energy Resources. *Türkiye Çevre Vakfi*, *Yayın 175*, 368, Ankara (in Turkish).

Anonymous, (2021). *General Directorate of Highways*. Distance Inquiry, Distance from District to District. https://www.kgm.gov.tr/Sayfalar/KGM/SiteTr/Uzakliklar/ilcedenIlceyeMesafe.aspx (Date of Access 24.01.2021) (in Turkish).

Atilgan, A., Saltuk, B., Ertop, H., Yücel A. (2020a). *Determination of Potential Biogas, Electricity and Natural Gas Energy Value That Can Be Obtained From Animal Wastes*. 4. Asia Pacific International Congress on Contemporary Studies, December 12-13, Montesorri, 1-14.

Atilgan, A., Saltuk, B., Ertop, H., Aksoy E. (2020b). *Determination of Potential Energy Values That Can Be Obtained From Cereal Residues*. 4. Asia Pacific International Congress on Contemporary Studies, December 12-13, Montesorri, 15-31.

Atilgan, A., Saltuk, B., Ertop, H., Aksoy, E., (2020c). Determining the Biogas Energy Potential from Greenhouse Wastes and Creating Maps: The Case of Antalya Province. *Euroasia Journal of Mathematics, Engineering, Natural & Medical Sciences*, 7(12), 19-30. International Indexed & Refereed ISSN: 2667-6702 (in Turkish).

Baran, M.F., Lüle, F., Gökdoğan O. (2017). Energy Potential Can Be Produced by Animal Waste of Adiyaman Province. *Türk Tarım ve Doğa Bilimleri Dergisi, 4*(3), 245-249 (in Turkish).

Başkan, A.E. (2010). *Waste and Evaluation Ways in Olive Oil Enterprises*. T.C. Güney Ege Kalkınma Ajansı, Denizli (in Turkish).

Boztepe, E., Karaca, A., (2009). *Agricultural Wastes as a Renewable Energy Source*. Enerji Kongresi. 21-23 Ekim 2009. İzmir (in Turkish).

Cebeci, Z., (2019). Non-Parametric Statistical Analysis with R. Abaküs Kitap Yayın Evi. İstanbul (in Turkish).

Çelen, S., Aktaş T, Karabeyoğlu S, Akyıldız A. (2015). Drying of Prina Using Microwave Energy and Determination of Appropriate Thin Layer Drying Model. *Journal of Tekirdag Agricultural Faculty. 12*(2), 21-31 (in Turkish).

Demirtepe, M. (2008). Studies on using of olive pomace and olive pomace oil in fish feeding MSc. Thesis, Ege Üniversitesi, Fen Bilimleri Enstitüsü, İzmir. (in Turkish)

Dermeche, S., Nadour, M., Larroche, C., Moulti-Mati, F., Michaud, P. (2013). Olive Mill Wastes: Biochemical Characterizations and Valorization Strategies. *Process Biochemistry, 48,* 1532-1552.

Diacono, M., Donato, F., Corrado, C., Tittarelli, F., Ceglie, F., Verrastro, V., Ventrella, D., Vitti, C., Montemurro, F. (2012). Bioassays and Application of Olive Pomace Compost on Emmer: Effects on Yield and Soil Properties in Organic Farming. *Acta Agriculturae Scandinavica, Section B-Soil & Plant Science. 62*(6), 510-518.

Ertop, H., Atilgan, A., Yücel, A., Saltuk, B. (2018). Management and Potential Biogases Quantities of Waste from Animal Breeding Enterprises Antalya Case. *Scientific Works. Series C. Veterinary Medicine, 2*(LXIV), 97-104.

Ertop, H., Atilgan A. (2019). *Determination of Potential Biogas Energy Values of Wastes Generated in Crop Production: Greenhouse Cultivation Case*. 3. Uluslararası Tarım, Hayvancılık ve Kırsal Kalkınma Kongresi 20-22 Aralık, Van, 961-971 (in Turkish).

Ertop, H., Atilgan A., Yücel A. (2019). *Determination of Biogas and Electricity Generatıon Potential Obtained From Animal Wastes: The Case of Layıng Hens.* 3. Uluslararası Tarım, Hayvancılık ve Kırsal Kalkınma Kongresi 20-22 Aralık, Van, 948-960 (in Turkish).

Fanchi, J. R., Fanchi, C. J. (2011). *Energy in the 21st Century*. World Scientific Publishing Co. Pte. Ltd. 5 Toh Tuck Link, Singapore 596224.

Gomez-Munoz, B., Hatch, DJ., Bol, R., Garcia-Ruiz, R. (2013). Agrochemical Characterization, Net N Mineralization and Potential N Leaching of Composted Olive-mill Pomace Currently Produced in Southern Spain. *J. Plant Nutr. Soil Sci., 176*, 655-664.

Gomez-Munoz, B, Hatch, DJ, Bol, R, Dixon, ER, Garcia-Ruiz, R. (2010). Gross and Net Rates of Nitrogen Mineralization in Soil Amended with Composted Olive Mill Pomace. *Rapid Communications in Mass Spectrometry, 25*, 1472-1478.

Gökdoğan, O. (2019). Greenhouse heating with the Energy that can be Acquired from Isparta Province's Animal Waste. *Akademia Doğa ve İnsan Bilimleri Dergisi, 5*(1), 27-34 (in Turkish).

Görel, Ö., Doymaz, İ., Akgün, N.A (2004). *Energy Use of Olive Oil Factory Wastes*, Yıldız Teknik Üniversitesi, Kimya Mühendisliği Bölümü, İstanbul (in Turkish).

Karaca, C., Bozoğlu, B., Polat., O, (2015). Mapping of Waste Quantity and Energy Potential of Olive Oil Cake in Hatay Province. *Uludağ Üniversitesi Ziraat Fakültesi Dergisi, 29*(2), 55-60 (in Turkish).

Karabaş, H., (2019). Investigation of Waste Amount and Energy Potential of Sakarya Province by Vegetative Biomass. *Ulusal Çevre Bilimleri Araştırma Dergisi, Sayı 2*(1), 35-43 (in Turkish).

Kurtuluş, E., (2003). *The Use and Production of Pirina as a Fuel*. Yeni ve Yenilenebilir Enerji Kaynakları Sempozyumu ve Sergisi Bildiriler Kitabı, Kayseri, 3-4 Ekim, 105-108 (in Turkish).

Lopez-Pineiro, A., Murillo S., Barreto C., Munoz A, Rato JM, Albarran A, Garcia A. (2007). Changes in Organic Matter and Residual Effect of Amendment with Two-phase Olive-mill Waste on Degraded Agricultural Soils. *Science of the Total Environment, 378,* 84-89.

Öcal, A, (2005). *Investigation on Using Olive Oil Wastewater and Prina for The Purpose of Plant Growing*. MSc. Thesis, Çukurova Üniversitesi, Fen Bilimleri Enstitüsü, 58 (in Turkish).

Öztürk, H. H., (2008). Renewable Energy Sources and Uses. *Teknik Yayınevi, 367*, Ankara (in Turkish).

Paredes, C., Bernal, M.P., Roig, A., Cegarra, J. (2001). Effects Of Olive Mill Wastewater Addition in Composting Of Agro-Industrial and Urban Wastes. *Biodegradation, 12*, 225-234.

Saltuk, B., Atilgan, A., Aydın, Y., Koca, Y. K., Köse, N. (2016). Manure from Livestock Farming in the Euphrates Basin and Its Potential Environmental Impact on Water Resources. Scientific Papers. Series D. *Animal Science, 59*(1), 251-257.

Saltuk, B., Artun, O., Atilgan, A. (2017). Determination of the Areas Suitable for Biogas Energy Production by Using Geographic Information Systems GIS Euphrates Basin Case. *Scientific Papers-Series E-Land Reclamation Earth Observation Surveying Environmental Engineering, 6*(1), 57-64.

Yürük, F., Erdoğmuş, P., (2015). Bıogas Potentıal of Düzce Whıch Can Be Produced by Animal Waste and Determination of Optimum Plant Location With K-Means Clustering. *Fen Bilimleri Enstitüsü, İleri Teknoloji Bilimleri Dergisi 4*(1), 47-56 (in Turkish).

Zan Sancak, A., Sancak, K., Demirtaş, M., Dönmez, D., Kalanlar, Ş., Arslan, S. (2014). *The Biogas Production Potential Produced From Bovine Animal Waste in Turkey*. 11. Tarım Ekonomisi Kongresi, 3-5 Eylül, Samsun (in Turkish).

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Environmental Loads Resulting from Manufacturing Technology

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Abstract: The study of environmental loads resulting from manufacturing technology is of great importance for environmental protection. Applying the principles of sustainable development means "a way of farming in which meeting the needs of the present generation will not reduce the chances of meeting the needs of future generations." Faced with such a challenge, the product must be assessed throughout its entire life cycle (LCA). From the available technologies and materials, one should choose those that are least harmful to the environment. In order to make a correct choice, it is necessary to know and understand the technological processes and phenomena that take place in them. Using *off-the-shelf* LCA applications, without knowing basic knowledge of manufacturing technology, can bias the results. The aim of the article is to present benefits resulting from the environmental assessment of manufacturing processes.

Keywords: Fe-C alloys, technological process, environmental assessment

1. Introduction

Iron alloys are materials with versatile applications. Products from the steel, metallurgy and foundry industries are indispensable in the automotive sector, in construction, for the production of household appliances and in many other industries.

Until some time ago, it was only possible to invent a new substance or technology and the choice was based on operational, technical and economic criteria (Filipiak et al. 2018, Gabryelewicz et al. 2021). No environmental consequences were presented, for example with asbestos, freon or leaded naphtha. Technical progress and the progress in civilization were understood as an increase in production. The concept of quality did not include ecological standards, but technical and utility standards only (Adamczyk 2004). This situation is changing radically today. Assessing innovation from an ecological point of view is becoming the standard (Loucanova & Olsiakova 2020).

The production technology used has the greatest impact on the environment and determines what happens to the product after its useful life, vis-à-vis recovery, recycling, disposal and storage (Wędrychowicz et al. 2019, Wędrychowicz et al. 2021, Chamier-Gliszczynski & Krzyzynski 2005, Chamier-Gliszczyński 2011a, Chamier-Gliszczyński 2011b, Czwajda et al. 2019, Jajczyk et al. 2020, Straka et al. 2020). The choice of production technology and methodology for its optimization, taking into account ecological aspects, is made intuitively or based on the experience of the designer and technologist. (Adamczyk 2004, Sabadka et al. 2017). Commercial software, such as SimaPro, can be used to assess sustainable development and life-cycle (Burchart-Korol et al. 2020). This software has quantitative and qualitative databases on environmental pressures. In order to use them correctly, it is necessary to know the course of the technological process of the product assessed. Without knowledge of the manufacturing technology, it is easy to make a mistake in assessing environmental loads. Environmental research should be concerned with (Adamczyk 2004):

- achieving a certain quality of product – the level of individual features in the analysis of ecological effects in the entire or defined part of the product life cycle;
- and selection of manufacturing methods to meet the assumptions with a minimal negative environmental impact.

One method to motivate entrepreneurs to protect the environment is the introduction of environmental fees. Since 1 January 2018, the obligation to pay fees for polluting the environment under Environmental Protection Legislation applies only to the fees for the release of gases or dust into the air and the storage of waste. On the other hand, the rules for paying fees for discharging sewage into water or soil and water uptake are regulated by the provisions of the

Water Legislation and of the Regulation of the Council of Ministers of 22nd. December 2017 on Unit Rates of Charges for Water Services.

Fee rates for polluting the environment are getting higher every year, as shown in Table 1 with knowledge of the impact of a given technology on the environment seeming to be all the more beneficial for enterprises (Announcement of the Minister of Climate of 9 September 2020, Announcement of the Minister of the Environment of 18 August 2009, Announcement of the Minister of the Environment of 3 October 2018).

Table 1. Fees for selected iron and steel waste in 2010, 2019 and 2021

Type of substance	Fee in [PLN/Mg]		
	2010	2019	2021
Waste from tools used for turning and sawing and its alloys	10.94	12.92	13.43
Emission of CO_2	0.25	0.30	0.31
Waste from the iron and steel industries:			
Slag from smelting processes (blast furnaces, steel production)	16.95	20.03	20.82
Untreated slag from other processes	16.95	20.03	20.82
Solid waste from gas treatment containing hazardous substances	54.40	64.29	66.82
Rolling scale	16.95	20.03	20.82
Waste from cooling-water treatment containing oils	54.40	64.29	66.82
Dribbles from iron metallurgy	16.95	20.03	20.82
Waste ferrous sulphate	16.95	20.03	20.82

2. Environmental assessment method

The application of value analysis to the environmental assessment of production technology is aimed at finding the optimal solution from the ecological point of view, while maintaining quality, efficiency and low own costs.

Value analysis is (Crum 1973) a planned procedure aimed at achieving the necessary functionality of a product at the lowest cost without compromising the level of quality, reliability and without compromising the operating and delivery conditions. It is a procedure which gradually attains its goal by means of tried and tested techniques and new methods combined into one logical ensemble.

It is possible to evaluate the entire technological process as well as individual stages of its life (Chamier-Gliszczyński 2010, Chamier-Gliszczyński 2011) or its fragments (Clift 1997). The assessment is facilitated by comparing a given technology with similar ones, distinguished by a high level of environmental friendliness and proven in industrial conditions (Ekvall et al. 2005, Guinee et al. 2001). Often, there is a need to evaluate and select the optimal manufacturing technology from among several possibilities. (Hochschorner & Finnveden 2003, Jajczyk 2016). In order to conduct a reliable assessment of manufacturing technology, extensive experience, along with a complete knowledge, thereof, based on the manufacturing technology being assessed, as well as appropriate knowledge about possible solutions, are necessary. Value analysis can be applied to products at any stage of their development, such as in the design, production and use). This method can be used to test design or operating systems.

3. Environmental assessment of a manufacturing technology

The manufacture of the product involves the choice of material and technology. Generally, there is a choice between different materials and manufacturing technologies. The shape and / or dimensions of the product may vary, but the function and quality of the product remain unchanged (Ashby 1998).

In the case of the environmental assessment of iron alloy products, a difference analysis can be applied. Only those production stages that differ from the analysed products are analysed and assessed (Nielsen & Weidema 2001). In the case of products made of iron alloys, the stage under analysis is the manufacturing process. This means that acquisition of the raw material, its use and its disposal are omitted. It was assumed that these stages have an equal effect on the environment. Such a simplification can be accepted because these products are made of the same, or very similar, raw materials. The stage of use of machine parts does not affect the environment and the utilisation stage, in the case of iron-alloy products, in most cases, consists of landfilling or recycling, which is the same for all the above-mentioned groups of products. Graphically, the concept of defining a system's boundaries is shown in Figure 1.

The manufacturing process has been divided into three main stages:

– preparation stage for the input material, i.e. the amount of input material,
– preparation stage of a semi-finished product,
– completion stage.

Only processes influencing further unit processes are included in a system's boundaries. When determining a system's boundaries, attention should be paid to the availability and validity of the data assigned to each production stage (Weidema 1993). All the data used for environmental assessment in this study was obtained and compiled on the basis of the literature, primarily the data from the Reference Document on Best Available Techniques (BREF) and the literature on environmental problems in machining were used (Pieńkowski 2005, Srinivasan & Sheng 1999, Schulz & Schiefer 1986). The method for analysing the manufacturing process reflects the sequence of successive technological operations leading to the production of the product tested (Fig. 1).

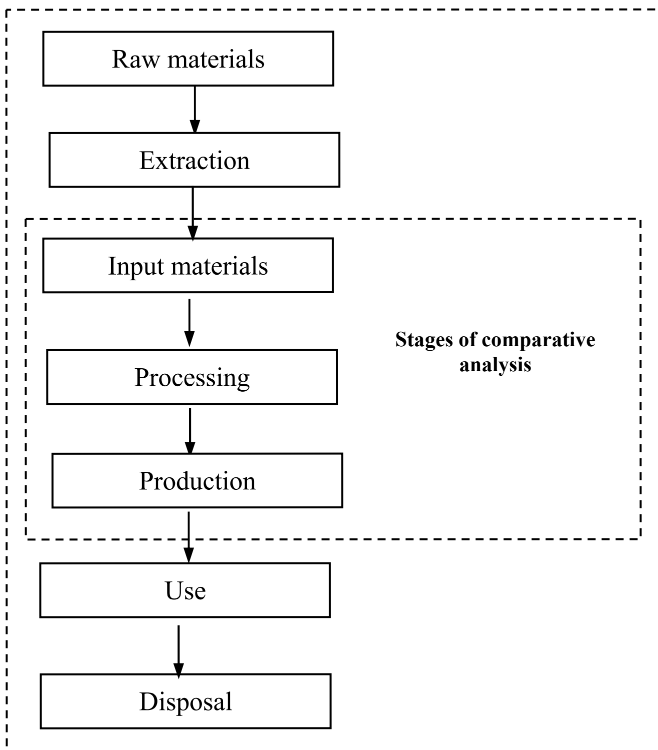

Fig. 1. Graphical concept illustrating the scope of the analysis

Numerical data used for calculations i.e., data on energy inputs, the number of pollutants emitted, water used and the amount of sewage, the amount of waste, the amount of raw materials, the semi-finished products and materials used, can be presented in two ways (Sala 1986, 1996, Sheng & Munoz 1995, Gabryelewicz et al. 2020). Firstly, they can be given either in a natural, physical form, i.e., in units of energy, mass and volume and so on; this type of calculation is 'technological'; or it can be given in the form of value, as in economic value, in terms of cost or price; this type of calculation is 'economic'. In order to analyse the impact on the environment of the technology of manufacturing products from iron alloys, the methodology based on the value analysis was followed, that is:

- determination of the object of the test,
- determination of the system's boundaries, i.e. the stages of the manufacturing process,
- determination of the unit processes, that is, the links between them and the assignment of quantitative data related to the functional unit, which will be the pulley,
- data analysis.

3.1. Determination of the object of the test

This analysis concerns the environmental assessment of two production technologies: machining and die forging. The manufacturing technology was assessed using, as an example, a pulley treated as a functional unit (Fig. 2) and made as:

− a pulley, machined from a cylindrical bar,
− a die-forged and machined pulley.

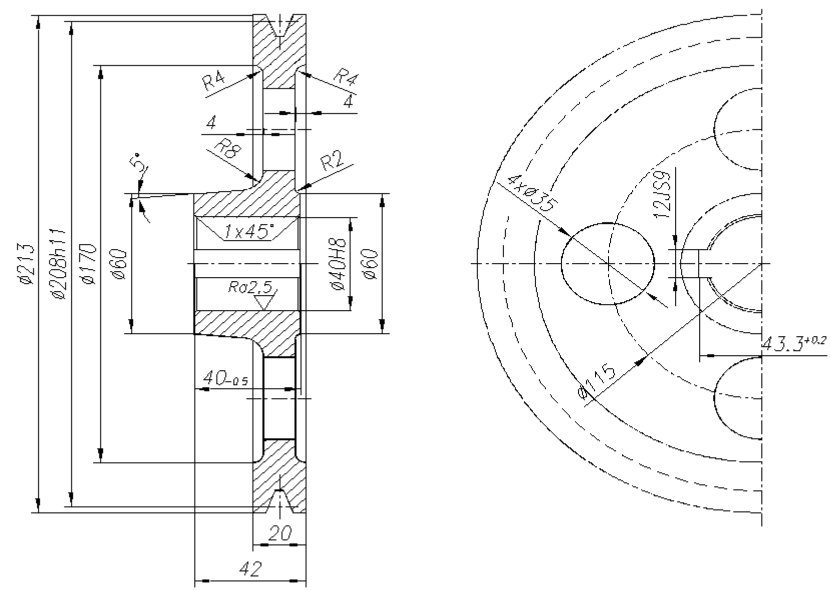

Fig. 2. Pulley – a functional unit

Due to the needs of the analysis of manufacturing technology, the same concept regarding the pulley structure was adopted, despite knowing about the possibility of giving different shapes to a given part, fulfilling the same function but made with different technologies. However, for the sake of comparability, the possibility of obtaining the same shape for a given pulley, obtained by different manufacturing techniques, was taken into account.

3.2. Definition of a system's boundaries

The boundaries of the system being tested are the technological processes that make up the production of a given pulley. The processes that make up the analysis are shown in Fig. 3 for a pulley produced by machining from a steel bar and Fig. 4 for a drop-forged and machined pulley.

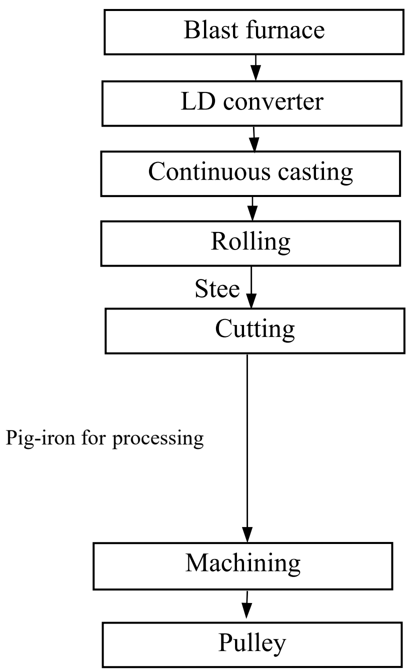

Fig. 3. System boundaries for the environmental analysis of a pulley; steel rod

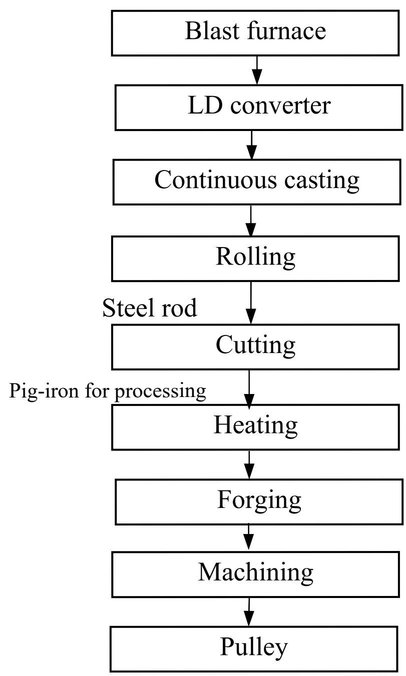

Fig. 4. System boundaries for the environmental analysis of a pulley; drop-forged

3.3. Environmental loads – a pulley machined from a cylindrical rod

The starting material for the production of the pulley is a steel rod: ∅225 x 45 mm.

Table 2. Data for analysing a pulley produced by the machining method

	Pulley	Pig-iron for making the pulley. Steel rod ∅225 by 45 mm
Volume	481,823.4 mm^3	1,788,328.0 mm^3
Mass	3.782 kg	14.038 kg

The mass is calculated by assuming the density of steel: g = 0.00785 g/mm^3

Table 3. Physical quantities of environmental aspects per functional unit

Process	Energy consumption MJ/pc.	Emissions generated into the atmosphere kg/pc.		Waste kg/pc.	Sewage dm^3/pc.
		total	in that CO_2		
Pig-iron production	192.450	11.824	11.467	10.661	58.64
Melting of cast steel in the LD converter	11.764	2.817	2.807	1.9772	7.440
Continuous casting	3.875	0.222	0.218	0.0296	1.196
Rolling	109.398	10.578	10.449	2.076	98.266
Cutting	0.282	–	–	1.3	no data
Machining	22.21	–	–	10.256	no data
Total:	339.979	25.441	24.941	26.2998	165.542

In figures 12 to 15 the environmental unit assessment is shown as bars while the cumulative environmental load is shown as a curve.

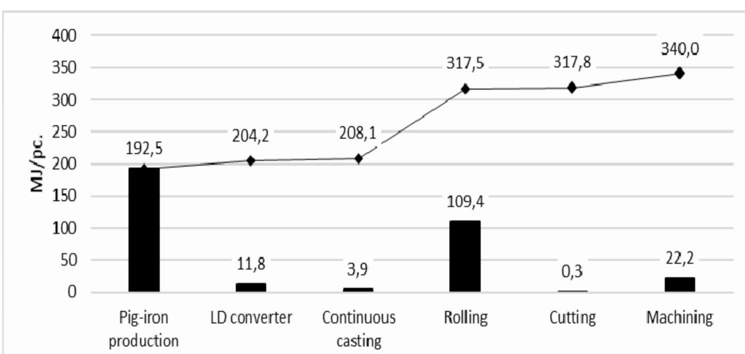

Fig. 5. Energy consumption in the production of a pulley made by machining a cylindrical rod [MJ/pc.]

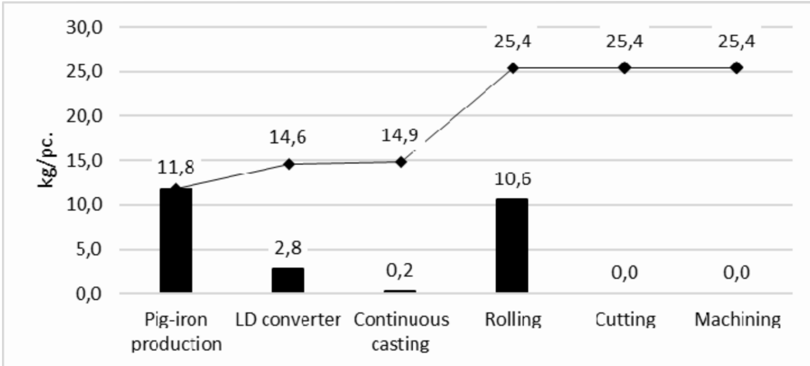

Fig. 6. Emissions generated into the atmosphere, in the production of a pulley made by cutting a cylindrical rod [kg/pc.]

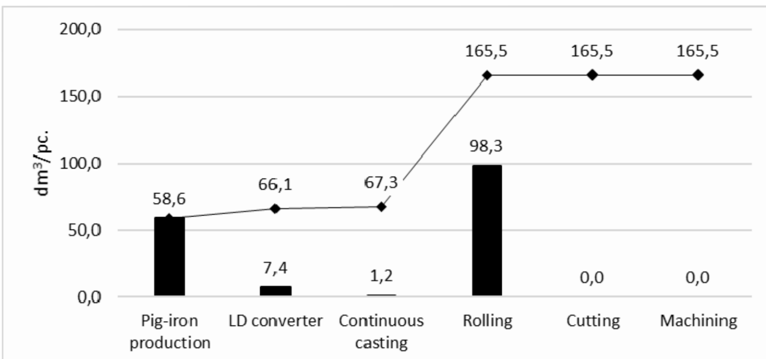

Fig. 7. Waste water generated in the production of a pulley made by machining from a steel bar [dm^3/pc.]

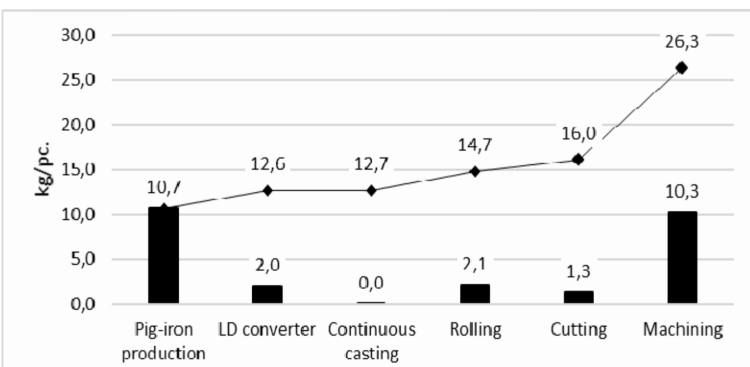

Fig. 8. Waste generated in the production of a pulley made by cutting from a steel bar (in kg/piece)

3.4. Environmental assessment – forged and machined pulley

As starting material, we take 68 rods, 161 mm long.

Table 4. Data for the environmental analysis of a drop-forged pulley

	Pulley	Pig-iron for making the pulley. Steel rod ∅ 68 to 161 mm	Forging
Volume	V = 481.823 cm^3	V = 74,446.4 mm^3	V = 592.9 cm^3
Mass	m = 3.782 kg	m = 5.844 kg	m = 4.654 kg

The mass is calculated by assuming the density of steel: g = 0.00785 g/mm^3.

Table 5. Levels of environmental aspects for the technology of manufacturing a die-forged pulley

Process	Energy consumption MJ/pc.	Emissions generated into the atmosphere kg/pc.		Waste kg/pc.	Sewage dm^3/pc.
		total	in that CO_2		
Pig-iron production	80.111	4.918	4.770	4.435	24.413
LD converter	5.425	1.172	1.168	0.823	3.097
Continuous casting	1.788	0.092	0.091	0.0123	0.498
Rolling	14.181	4.400	4.346	0.864	40.91
Cutting	0.258	no changes	no changes	0.546	no data
Heating	1.377	no data	no data	–	–
Forging	2.152	no data	no data	2.062	no data
Machining	1.482	no data	no data	0.872	no data
Total:	106.774	10.582	10.375	9.6143	68.918

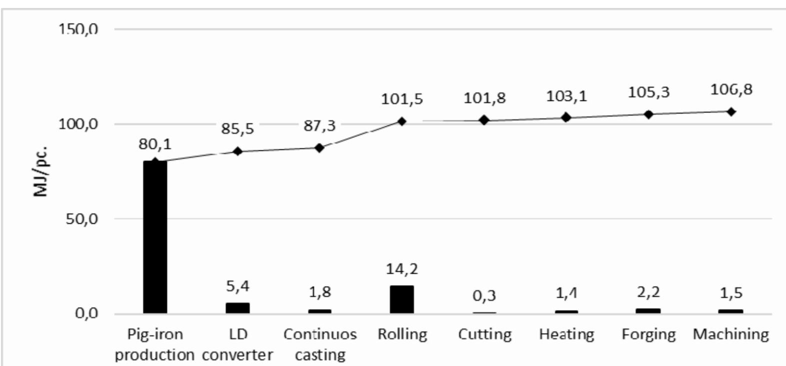

Fig. 9. Energy consumption in the production of a die-forged pulley [MJ/pc.]

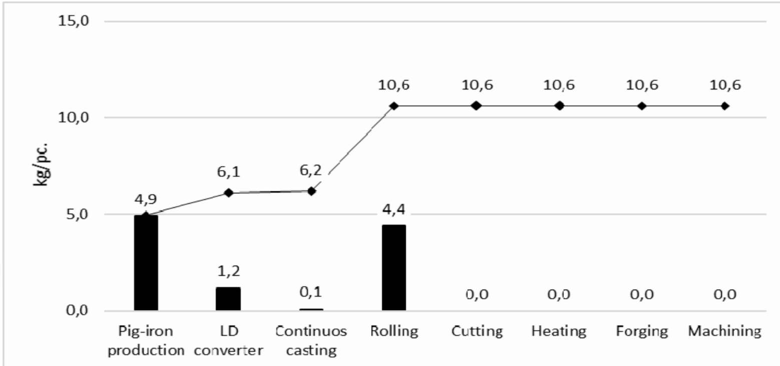

Fig. 10. Emissions generated into the atmosphere, in the die-forging of a pulley [kg/pc.]

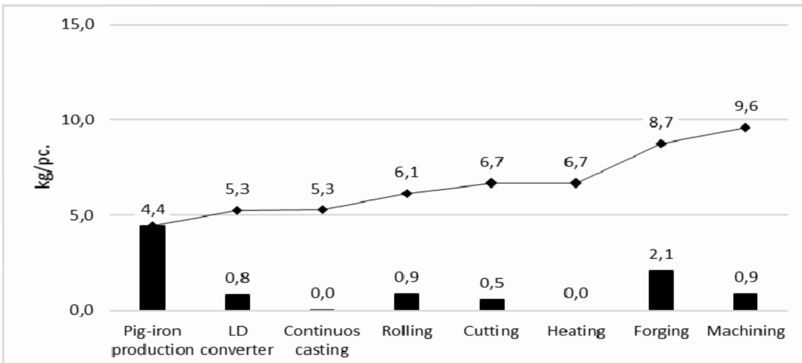

Fig. 11. Waste generated in the die-forging of a pulley [kg/pc.]

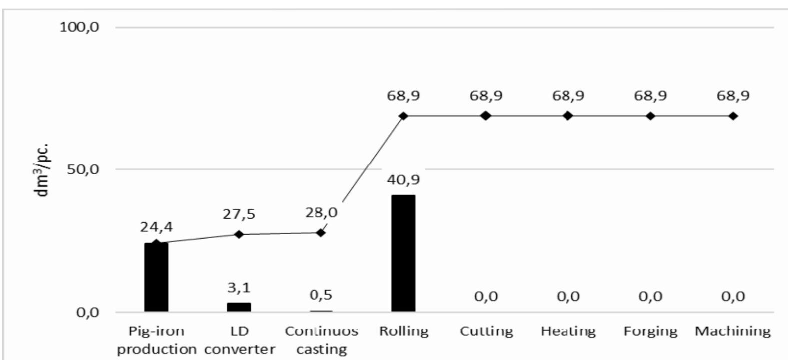

Fig. 12. Waste water generated in the die-forging of a pulley [dm^3/pc.]

4. Analysis of environmental data for selected production technologies

The compilation of environmental aspects, together with the physical quantities relating to individual manufacturing technologies, allows the impact of individual technologies on the environment to be analysed. The results obtained are summarised in the Table 6 and in the graphs from 13 to 16.

Table 6. Environmental aspects for the pulley depending on the manufacturing technology employed

	Energy consumption [MJ/pc.]	Emissions generated into the atmosphere [kg/pc.]	Waste [kg/pc.]	Wastewater [dm^3/pc.]
Machining	339.98	25.44	26.3	165.54
Die forging	106.77	10.58	9.61	68.92

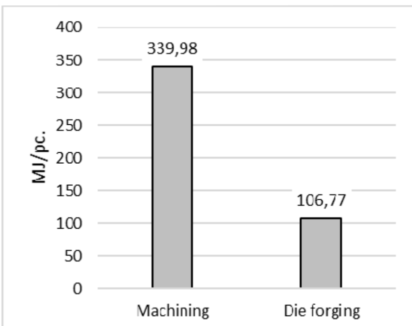

Fig. 13. Energy consumption for a pulley, depending on the technology employed in its construction

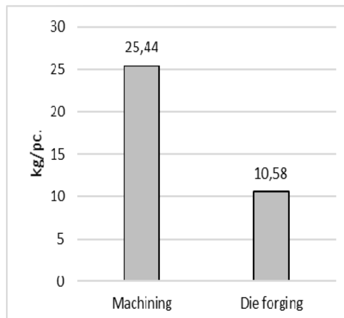

Fig. 14. Emissions generated into the atmosphere for a pulley, depending on the technology employed in its construction

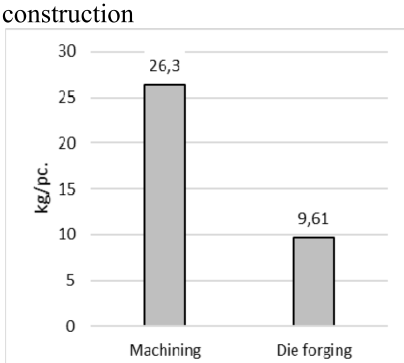

Fig. 15. Waste generated for a pulley depending on the technology employed in its construction

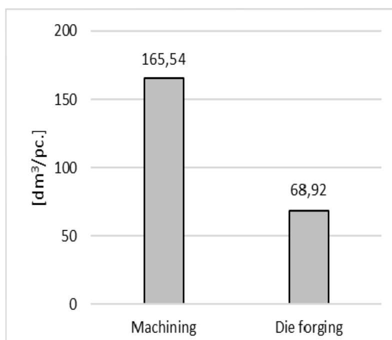

Fig. 16. Wastewater generated for a pulley depending on the technology employed in its construction

5. Conclusions

In an era of global environmental crisis, the overriding objective should be to meet the demand for products produced in balance with the environment, i.e., using renewable, non-hazardous materials and energy sources, while protecting biodiversity. Production systems should not be linear, but closed and cyclical, in order to consume fewer materials, less water and less energy. We should question the need for many products and look for other ways of meeting or reducing needs. A holistic and integrated product-centred approach to environmental issues should be implemented. Most environmental problems such as global warming, toxic contamination, or loss of biodiversity are caused by the way in which natural resources are produced and consumed and also at the pace at which natural resources are produced and consumed.

When analysing the environmental friendliness of the manufacturing technology of a machine part, account should be taken of the task it is intended to perform in the operation of the machine as well as the functionality, reliability and durability criteria thereof. All other considerations must be subordinated to these overriding objectives and therefore also to the environmental friendliness of the technology used in the manufacture of machine parts. Based on the analysis of the issue, the following conclusions were drawn:

- the end result for a given technology allows the environmental load to be tracked;
- knowledge of the unit size of environmental load allows the critical points of the process to be identified;
- the holistic process analysis makes it possible to avoid transferring environmental loads from one unit process to another;
- only when taking into account cumulative environmental loads is it possible the assess the full scope of environmental risks and then identify the most environmentally friendly technologies;
- the environmental burden can be reduced by changing the manufacturing technology, changing the material used or by changing the design of the product;
- the number of research methods for environmental analysis is extensive and there is a serious problem to be overcome in order to select them properly. There is a clear conflict between substantive and practical reasons when making a choice.
- new products and technologies should be brought to life on the basis of an analysis of the environmental costs of their entire life cycle.

Common sense requires energy and environmental protection to be managed rationally at every stage of a product's life. Various indicators can be used to assess the impact of human activity on the environment. By carrying out a variant evaluation of projects, it is possible to clearly identify a better or worse variant of the solution. The second recommendation for assessing the state of the environment is the use of quantitative indicators. Quantitative indicators, expressed in physical quantities *per* functional unit, seem to be more suited to the analysis of manufacturing technology. They give a picture of the actual impact of the technology under analysis on the environment. Having the actual data relating to a given unit process, can be converted into a monetary unit, for example.

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References

Adamczyk, W. (2004). *Ekologia wyrobów*. PWE, Warszawa

Ashby, M.F. (1998). *Dobór materiałów w projektowaniu inżynierskim.* WNT, Warszawa (in Polish).

Best Available Techniques (BAT) Reference Document for the Ferrous Metals Processing Industry 2010, Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention And Control)

Best Available Techniques (BAT) Reference Document for the Ferrous Metals Processing Industry 2019.

Best Available Techniques (BAT) Reference Document for the Smitheries and Foundries Industry 2004.

Best Available Techniques (BAT) Reference Document for the Smitheries and Foundries Industry 2005.

Best Available Techniques Reference Document on the Production of Iron and Steel 2001.

Burakowski, T., Sala, A. (1980). *Racjonalizacja zużycia energii w obróbce cieplnej metali.* Publishing House of the Institute of Precision Mechanics (in Polish).

Burchart-Korol, D., Jursova, S., Folega, P., Pustejovska, P. (2020). Life Cycle Impact Assessment of Electric Vehicle Battery Charging in European Union Countries. *Journal of Cleaner Production, 257*, (120476), DOI: 10.1016/j.jclepro.2020.120476.

Chamier-Gliszczynski, N., Krzyzynski, T. (2005). *On modelling three-stage system of receipt and automotive recycling*. REWAS'04, Global Symposium on Recycling, Waste Treatment and Clean Technology 2005, 2813-2814, Madrid, Spain, 26-29 September 2004, Conference Paper, ISBN: 8495520060.

Chamier-Gliszczyński, N. (2010). Optimal Design for the Environment of the Means Transportation: a Case Study of Reuse and Recycling Materials. *Sold State Phenomena, 165*, 244-249. DOI: 10.4028/www.scientific.net/SSP.165.244

Chamier-Gliszczyński, N. (2011). Environmental aspects of maintenance of transport means, end-of life stage of transport means. *Eksploatacja i Niezawodność – Maintenance and Reliability, 50*(2), 59-71. http://ein.org.pl/podstrony/wydania/50/pdf/07.pdf

Chamier-Gliszczyński, N. (2011a). Reuse, Recovery and Recycling System of End-of Life Vehicles. *Key Engineering Materials, 450*, 425-428. DOI: 10.4028/www.scientific.net/KEM.450.425

Chamier-Gliszczyński, N. (2011b). Recycling Aspect of End-of Life Vehicles. Recovery of Components and Materials from ELVs. *Key Engineering Materials, 450*, 421-424. DOI: 10.4028/www.scientific.net/KEM.450.421

Clift, R. (1997). *Life cycle assessment*. University of Surrey.

Crum, L., W. (1973). *Analiza wartości*. PWE, Warszawa (in Polish).

Czwajda, L., Kosacka-Olejnik, M., Kudelska, I., Kostrzewski, M., Sethanan, K., Pitakaso, R. (2019). Application of prediction markets phenomenon as decision support instrument in vehicle recycling sector. *Logforum, 15*(2), 265-278. DOI: 10.17270/J.LOG.2019.329

Ekvall, T., Tillman, A.M., Molander, S. (2005). Normative Moral Philosophy and Methodology for Life Cycle Assessment. *Journal of Cleaner Production, 13.*

Filipiak, M., Jajczyk, J., Dobrzycki, A. (2018). The economics of use of wireless power supply in electric buses, *ITM Web of Conferences, 19*(01034), DOI: https://doi.org/10.1051/itmconf/20181901034.

Gabryelewicz, I., Stryjski, R., Wędrychowicz, M., Dąbrowski, T. (2020). The State Of The Air Quality In Poland, *Rocznik Ochrona Środowiska, 22*(2), 998-1013.

Gabryelewicz, I., Wędrychowicz, M., Pántya, P., Krupa, P. (2021). *Raw material and environmental safety of industrial processes 2021*, W: I. Gabryelewicz, M. Wędrychowicz (red.). Environmental safety – non-energy and raw materials: scientific monograph (11-37). Zielona Góra: Oficyna Wydawnicza Uniwersytetu Zielonogórskiego (in Polish).

Guinee, J.B. (2002) Handbook on Life Cycle Assessmennt: Operational Guide to the ISO Standard. Part 1,2,3. Kluwer Academic Publishers, Dordrecht Boston London.

Hochschorner, E., Finnveden, G. (2003). Evaluation of Two Simplified Life Cycle Assessment Methods. *The Interactional Journal of Life cycle Assessment, 8*(3).

Jajczyk, J. (2016). Use of Personal Computers with Multi-core Processors for Optimisation Using the Genetic Algorithm Method, *IEEEXplore Electronic*, DOI: https://doi.org/10.1109/CPEE.2016.7738731.

Jajczyk, J., Filipiak, M., Dąbrowski, T. (2020). Reducing the Use of Electrochemical Sources of Electricity Through the Use of Wireless Power Supply. *Rocznik Ochrona Środowiska, 22*(1), 444-455. http://ros.edu.pl/images/roczniki/2020/033_ROS_V22_R2020.pdf

Loucanova, E., Olsiakova, M. (2020). Logistics, Eco-innovations and Pandemic. *Acta logistica*, *7*(3), 187-193, DOI: 10.22306/al.v7i3.175.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W. (1973) Granice wzrostu. PWE, Warszawa (in Polish).

Nielsen, A.M., Weidema, B.P. (2001). Input/Output analysis – Shortcuts to Life Cycle Data. LCA Consultants, Environmental Project No. 581, Copenhagen.

Obwieszczenie Ministra Klimatu z dnia 9 września 2020 r. w sprawie wysokości stawek opłat za korzystanie ze środowiska na rok 2021

Obwieszczenie Ministra Środowiska z dnia 18 sierpnia 2009 r. w sprawie wysokości stawek opłat za korzystanie ze środowiska na rok 2010

Obwieszczenie Ministra Środowiska z dnia 3 października 2018 r. w sprawie wysokości stawek opłat za korzystanie ze środowiska na rok 2019

Pieńkowski, G., Krzyżanowski, J. (2005). Mączka J., *Problemy oceny energochłonności wyrobów wytwarzanych metodami obróbki ubytkowej*. Przegląd Mechaniczny 2005, nr 11 (in Polish).

Rozporządzenie Ministra Środowiska z dnia 26 lipca 2002 r. w sprawie rodzajów instalacji mogących powodować znaczne zanieczyszczenie poszczególnych elementów przyrodniczych albo środowiska jako całości. (Dz. U. z dnia 1.08.2002) (in Polish).

Sabadka, D., Molnár, V., Fedorko, G., Jachowicz, T. (2017) Optimization of production processes using the yamazumi method. *Advances in Science and Technology Research Journal, 11*(4), 175-182.

Sala, A. (1996). *Koncepcja systemu normatywów energochłonności*. Normalizacja 9/1996.

Sala, A. (1986) *Zasady energooszczędnego konstruowania*. Część I., Zastosowanie rachunku energochłonności skumulowanej oraz wybór właściwej strefy nakładów energetycznych. Przegląd Mechaniczny 12/1986 (in Polish).

Sala, A., (1986) *Zasady energooszczędnego konstruowania*. Część II. Minimalizacja energochłonności produkcji i eksploatacji, przykłady jej obniżania oraz zalecenia postępowania., Przegląd Mechaniczny 13/1986 (in Polish).

Schulz, H., Schiefer, E. (1986). Optimierung von Prozessen, Prozebfuhrung und Energiebedarf bei spanenden Fertigungsverfahren.

Sheng, P., Munoz, AA., (1995). An analytical approach for determining the environmental impact of machining processes. *Journal of Materials Processing Technology, 53*.

Srinivasan, M., Sheng, P. (1999). Feature-based process planning for environmentally conscious machining – Part 2; macroplanning. *Robotics and Computer Integrated Manufacturing, 15*.

Srinivasan, M., Sheng, P. (1999). Feature-based process planning for environmentally conscious machining – Part 1: microplanning. *Robotics and Computer Integrated Manufacturing, 15*.

Straka, M., Tausova, M., Rosova, A., Cehlar, M., Kacmary, P., Sisol, M., Ignacz, P., Farkas, C. (2020). Big Data Analytics of a Waste Recycling Simulation Logistics System. *Polish Journal of Environmental Studies, 29*(3), 2355-2364, DOI: 10.15244/pjoes/108684

Weidema, B.P. (1993). Envronmental Assessment of Produkt. A textbook on life cycle assessment. UETP-EEE, Helsinki

Wędrychowicz, M., Bydałek, A., Migas, P., Skrzekut, T., Noga, P., Madej, P., Kałasznikow, A. (2021). The effect of adding iron powder from plasma cutting on the microstructure, mechanical properties of the composite based on aluminum powder matrix made using powder metallurgy. *Archives of Metallurgy and Materials 66*(1), 273-279.

Wędrychowicz, M., Bydałek, A., Skrzetut, T., Noga, P., Gabryelewicz, I., Madej, P. (2019). Analysis of the mechanical strength, structure and possibilities of using waste phosphogypsum in aluminum powder composites. *SN Applied Sciences, 1*.

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Numerical Calculations with a Multi-layer Model of Mixed Sand Transport Against Measurements in Wave Motion and Steady Flow

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Abstract: A multi-layer model is used to calculate time-dependent sediment velocity and concentration vertical profiles. This model, in which the differences in sediment transport at different distances from the bed are considered is intended both for the wave motion and steady flow. Numerical calculations were carried out for sediment transport during the wave crest and trough and total sediment transport as a sum of their absolute values. The model concept of variation in shear stress from the skin stress value above the bed to the stress value at the bed previously proposed for steady flow is extended here for the wave motion and verified by direct stress measurements. The calculations were carried out for mixed sand sediments with different grain size distributions including semi-uniform and poorly sorted grains. Comparison with the available small- and large -scale data from flumes and oscillating tunnels yields agreement typically within plus/minus a factor two of measurements.

Keywords: wave motion, steady flow, sediment transport, transport during the wave crest and trough

1. Introduction

There are several works representing a multi-phase approach to sediment transport modelling. Berzi and Fraccarollo (2016) present an interesting description of multilayer sediment transport for steady flow, based on the granular gases theory for the particle phase and the turbulent mixing length approach for the fluid phase. Hsu et al. (2004) present a two-phase sediment transport description, developed for strong turbulent shear flows over mobile beds.

Many recent works present a probabilistic approach to bedload transport, in which the motion of particles is modelled on the basis of probability density functions for velocities and grain accelerations, as well as grain path lengths and travel times (e.g. Furbish et al. 2012). However, Lagrangian modelling, although very precise and capable of determining exact paths of separate particles, is less effective when large datasets are considered. Therefore, DAM (Double-Averaging Methodology) methods are employed (e.g. Vowinckel et al. 2017a and 2017b).

The majority of models for wave-induced sediment transport calculate sediment transport at specified grain mobility conditions as averaged over the wave period. Although the quasi-steady approach may give reasonable predictions of the net sediment transport, many researchers (Van Rijn et al. 2007a, 2007b, 2007c, 2007d, Briganti et al. 2018) found, that unsteady behavior of the oscillatory flow significantly influences the sediment concentration and the resulting net transport. Both velocity and sediment concentration vary in time, being not necessarily in phase with each other. Hence, the prediction of sediment transport is a complex problem. The most advanced theoretical models (Hsu et al. 2004, Kaczmarek et al. 2004, Silva et al. 2006, Cheng et al. 2017), as well as experimental investigations (Ribberink & Al-Salem 1995, Cloin 1998, O'Donoghue & Wright 2004a, Dohmen-Janssen & Hanes 2002, Hassan & Ribberink 2003, van der A. et al. 2010, Schretlen 2012, Kaczmarek et al. 2015) describe the unsteady sediment transport by equations for wave-induced sediment velocities and concentrations.

The concept of vertical shear stress variation, recently introduced by Kaczmarek et al. (2019) for steady flow is extended here for a wave motion. The proposed description of vertical shear stress variation is also verified here by comparison of the numerical calculation results of the maximum shear stress at the bed during the wave period versus the results of direct stress measurements (Rankin & Hires 2000, Jiang & Baldock 2015). In order to explain the model modification a short discussion of the basic model equations and the calculation procedure are included in this paper. Further, like the previous numerical calculations for the wave motion, the present calculations are not limited to the resulting net sediment transport. Here, a multi-layer approach is used to calculate both progressive and reverse sediment transport streams with a full vertical structure of instantaneous concertation and velocity. The calculations were carried out for different grain size distributions. The calculation results were compared with the wave data including acceleration-skewed oscillatory flows and flows described by Stokes' first and second approximations.

2. Description of the multi-layer model

The multi-phase approach is used in present model. Considering a different physical processes that rule sediment transport at various distances above an immobile bed. The specification of layers up to water surface elevation is proposed as follows (Fig. 1): a dense layer with immobile Coulomb friction sublayer and upper dense mobile sublayer dominated by grain collisions. Further, a contact layer, in which particle collisions and turbulent lift cooperate in momentum exchange and suspended sediment zone.

Under conditions of high grain mobility the transport of concentrated sediment takes place at the entire layer of the dense mixture, in the form of a grain flow with a specific velocity and concentration profile. Under conditions of low grain mobility, the active layer is reduced to the upper sublayer, consisting of single grains being rolled and dragged over the bed surface, as in a typical bedload regime. Since it is assumed that both water and grains move in both regions (i.e. at the mobile dense layer and in the layer of suspended sediment), therefore, there must be a transitional zone between these two regions, in which both instantaneous velocity and concentration profiles of each fraction of the sediment mixture (Fig. 1a) and the shear stress profile (Fig. 1b) represent continuous shape. This transition zone is called the contact layer after Kaczmarek et al. (2004), Kaczmarek et al. (2017) and Kaczmarek et al. (2019).

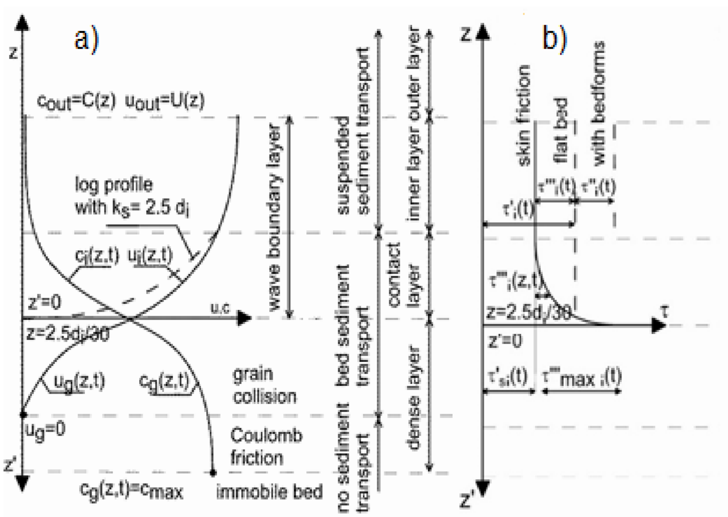

Fig. 1. Vertical structure of: a – instantaneous sediment transport (during the wave period) with velocity and concentration of the i-th fraction of sediment;
b – the instantaneous shear stress profile of the i-th fraction of sediments

The suspended sediment zone is divided into inner and outer flow regions. The inner flow region is characterized by a logarithmic velocity profile. The outer region of pure suspension is characterized by a very small concentration, where the process of sediment distribution may be considered as a convective or diffusive process. In contrast, the dense layer is characterized by very high concentrations, where inter-granular resistance is predominant.

The following mechanism of transmission of a tractive shear stress from the fluid to the immobile bed is proposed both for the wave motion and steady flow. The declining part of particle stresses in the upper dense sublayer is transferred directly to the moving grains. The increasing residual part as the rate-independent component is transferred further to the fixed bed. The concept of shear stress variation proposed originally for steady flow (Kaczmarek et al. 2019) is extended here for a wave motion. Shear stress increases from the skin stress value above the bed to the maximum value at the bed, and then, the viscous part of this stress decays in the bed. However, while the skin shear stress above the bed as an input data is identified with the value obtained from experiments at steady flow conditions, it must be calculated in the case of wave flow.

It is assumed (after Kaczmarek et al. 2004), that in the moving layer of densely concentrated sediments, all sediment fractions move at the velocity equal to the velocity of the mixture (at specified elevation). Therefore, it is assumed that interactions between the sediment fractions are so strong, that the finer fractions are slowed down by the thicker ones and all the fractions are characterised by the same vertical instantaneous velocity $u_g(z',t)$ and concentration $c_g(z',t)$ distributions. The model also takes into account, that the most intensive sorting of sediment occurs in the grain scattering process in the contact layer and in turbulent flow region, which brings the sediment into suspension. In the contact layer, instantaneous velocities $u_i(z,t)$ and concentrations $c_i(z,t)$ vary for individual fractions, due to turbulent fluid pulsations and chaotic collisions of grains.

The instantaneous grain stress components $\tau_i'''(z,t)$ of individual sediment fractions, which are all related to grain movement throughout the entire contact layer, change from zero at the upper boundary of the contact layer to the maximum value at the upper boundary of the dense layer (Fig. 1b). Hence, the maximum stresses during the wave period representative of the sediment mixture may vary from the stresses τ_r' at the upper boundary of the contact layer to τ_{0r} at the top of the dense layer. The maximum stresses τ_r' during the wave period at the upper boundary of the contact layer are the sum of skin shear stresses τ_{sr}' and stresses τ_r''', averaged over the depth, which result from grain movement across the entire contact layer. The skin shear stresses $\tau_{si}'(t) = \rho u_{fsi}'^2(t)$, where ρ is the density of water, and $u_{fsi}'(t)$ is the friction velocity, are described here by the logarithmic profile with the skin hydraulic roughness, k_{si}= 2,5d_i/30. They are calculated by the Fredsøe (1984) model.

3. Basic equations and calculation procedure

Temporary profiles of the velocity $u_g(z',t)$ and concentration $c_g(z',t)$ in the dense layer are calculated using the equations Eq. (1) and Eq. (2) in a system of coordinates with the vertical axis z' directed downwards (Fig. 1a):

$$\alpha^0\left(\frac{c_g-c_0}{c_m-c_g}\right)\sin\varphi\sin 2\psi+\mu_1\left(\frac{\partial u_g}{\partial z\prime}\right)^2=\tau_{0r} \tag{1}$$

$$\alpha^0\left(\frac{c_g-c_0}{c_m-c_g}\right)(1-\sin\varphi\cos 2\psi)+\mu_2\left(\frac{\partial u_g}{\partial z\prime}\right)^2=\left(\frac{\mu_2}{\mu_1}\right)\Big|_{c_g=c_0}\tau_{0r}+(\rho_s-\rho)\,g\int_0^{z'}c_g dz' \tag{2}$$

where $\tau_{0r}(t)=\rho u_{f0r}^2(t)$; u_{f0r} is the friction velocity at the top of the dense layer; α_0 = constant = $\rho_s$gd; d = d_r = d_{50} where d_r is the representative diameter for sediment mixture; c_m = 0.53 is the maximum concentration of the bed sediment; c_0 = 0.32 is the concentration of sediment at the upper limit of the dense layer; φ = 24.4° is the quasi-static angle of internal friction; Ψ= angle between the major principal stress and the horizontal axis:

$$\psi=\frac{\pi}{4}-\frac{\varphi}{2} \tag{3}$$

μ_2, μ_1 = functions of concentration, described (after Sayed and Savage 1983) as

$$\mu_1=\frac{0.03}{(c_m-c_g)^{1.5}}\rho_s d^2 \text{ and } \mu_2=\frac{0.02}{(c_m-c_g)^{1.75}}\rho_s d^2 \tag{4}$$

The stresses $\tau_{0r}(t)$ at the top of the dense layer are calculated by the integral model by Fredsøe (1984) using the results of a calculation procedure for maximum shear stress during the wave period describes by the Eq. (8-10).

The first component on the left-hand side of Eq. (1) describes the shear stress relation for plastic stresses, while the second component represents "viscous" stresses. Similarly, the first element on the left-hand side of Eq. (2) describes the normal stress relation for plastic stresses, while the second element describes normal "viscous" stresses. The combination of these stresses makes it possible to model both stresses related to the collision of grains, which disappear deeper into the dense mobile sublayer, and the residual part of stresses due to the tight inter-granular adherence, which increases deeper into the dense immobile sublayer as a rate-independent component.

Assuming that settling of sediment balances the vertical exchange and the momentum exchange balances the shear stress, following Deigaard (1993) and Kaczmarek et al. (2004) a set of two differential equations is proposed to determine the instantaneous concentration and velocity profiles for the i-th sediment fraction in the contact layer:

$$\left[\frac{3}{2}\left(\alpha_s \frac{d}{w_s}\frac{\partial u_i}{\partial z}\frac{3}{2}\frac{s+c_M}{c_D}+\beta_i\right)^2 d_i^2 c_i^2 (s+c_M)+l^2\right]\left(\frac{\partial u_c}{\partial z}\right)^2 = u'^2_{f*} \tag{5}$$

$$\left[3\left(\alpha_s \frac{d_i}{w_{si}}\frac{\partial u_i}{\partial z}\frac{2}{3}\frac{s+c_M}{c_D}+\beta_i\right)^2 d_i^2 \frac{\partial u_i}{\partial z} c_i + l^2 \frac{\partial u_i}{\partial z}\right]\frac{\partial c_i}{\partial z} = -w_{si} c_i \tag{6}$$

where w_{si} = settling velocity of the i-th fraction of sediment; c_M = added hydrodynamic mass coefficient; c_D = 1.0 is a drag coefficient; l = mixing length equal to κz; κ = von Karman's constant, which is around 0.40; s = ρ_s/ρ is the relative density; ρ_s is the density of sediments; $(s+c_m)$ = 3.0. Coefficients $\alpha_i = \beta_i$ are calculated by an iteration procedure, assuming the equality of the calculated sediment velocity $u_i(z,t)$ and the logarithmic flow velocity at the upper limit of the boundary layer at the time of the maximum skin shear stresses during the wave period.

To calculate the instantaneous sediment transport intensity, the instantaneous concentration and velocity profiles of the i-th fraction of the sediment are calculated in individual layers using the system of equations Eq. (1) and Eq. (2) for the dense layer and the system of equations Eq. (5) and Eq. (6) for the contact layer. Then, the instantaneous sediment transport rate for the i-th sediment fraction is calculated by integrating the instantaneous vertical streams throughout the entire flow region:

$$q_i(t) = \int_0^{\delta_g} \left|u_g(z',t)\right| c_g(z',t)dz' + \int_{\frac{k_{si}}{30}}^{\frac{k_{si}}{30}+\delta_c} |u_i(z,t)| c_i(z,t)dz + \int_{\frac{k_{si}}{30}+\delta_c}^{\frac{k_{si}}{30}+\delta'_{\frac{1}{2}}} |u_i(z,t)| c_i(z,t)dz = \int_0^{\delta_g} \left|u_g(z',t)\right| c_g(z',t)\mathrm{d}z' + \int_{\frac{k_{si}}{30}}^{\frac{k_{si}}{30}+\delta'_{\frac{1}{2}}} |u_i(z,t)| c_i(z,t)\mathrm{d}z \tag{7}$$

where $\delta'_{1/2}$, is the thickness of the wave boundary layer, δ_c and $\delta_{in}$are the thicknesses of the contact layer and the inner layer, respectively.

The instantaneous sediment transport is calculated only for the wave boundary layer. This is because it can be expected outside this layer (according to Kaczmarek et al. 2004), that transport of sediment depends only on the average velocity during the wave period (Fig. 1a), which is equal to zero in pure wave motion. The knowledge of the instantaneous sediment transport intensity for the *i*-th sediment fraction allows to calculate sediment transport for all sediment fractions.

It is worth noting that all sediment fractions in the dense layer move at a velocity equal to the velocity of the mixture. This assumption allows to take into account the hiding and exposure effects which can affect the transport rates of sediment grain fractions in the dense layer. Coarser sediments in the mixture are more exposed to the flow, whereas thinner sediments are hiding among the coarser ones.

Following the idea by Kaczmarek et al. (2019), the three mobile-bed effect parameters are introduced:

$$\gamma_0 = \sqrt{\frac{\tau_{0r}}{\tau'_{sr}}} = \frac{u_{f0r}}{u'_{fsr}} \tag{8}$$

In order to find the parameters γ_0 it is assumed that sediment transport in the dense and contact layers, calculated for maximum relative shear stresses during the wave period, can be compared to values calculated by the Meyer-Peter and Müller (1948) semi-empirical formula (MPM).

Then, the following equation is postulated (Kaczmarek et al. 2019):

$$q_g\left(\rho\gamma^2 u'^2_{fsr}\right) + q_c\left(\rho u'^2_{fsr}\right) = \Phi_{MPM}\sqrt{(s-1)gd_r^3} \tag{9}$$

The parameter $\gamma = \gamma_0$ in Eq. (9) is sought by the iterative method. The value q_g denotes sediment transport in the grain collision sublayer caused by the shear stresses τ_{0r}, whereas q_c denotes sediment transport in the contact layer caused by the shear stress τ'_r. The right-hand side of Eq. (9) expresses sediment transport described by the MPM formula:

$$\Phi_{MPM} = 8(\theta_r{}' - \theta_c)^{1.5} \text{ where } \theta'_r = \frac{u'^2_{fr}}{g(s-1)d} \tag{10}$$

The non-dimensional critical stresses θ_c are assumed to be constant over the contact layer thickness (Fig. 1b) and equal to 0.05.

4. Calculation results against measurements

The calculations of γ_0 (Fig. 2) were carried out for King's (1991) experiments, for both sine waves and asymmetrical waves, characteristic for waves described by Stokes' second approximation and for acceleration-skewed waves. King's (1991) experiments were performed for three grain diameters: d = 0.135 mm, 0.44 mm and 1.1 mm.

Comparison of the calculated γ_0 with the results of experiments by Rankin and Hires (2000) for d = 0.23 mm and by Jiang and Baldock (2015) for d = 0.22 mm and 2.83 mm shows that there are no major differences between the calculated and measured values, although there are clear differences between results for Stokes' approximations and results for skewed waves. The calculated values of γ_0 for skewed waves are smaller than those for the waves described by Stokes' first approximation (sine wave) and Stokes' second approximation (asymmetrical wave). This difference (of up to 0.75 γ_0 for d = 1.1 mm, 0.8 γ_0 for d = 0.44 mm and 0.65 γ_0 for d = 0.135 mm) occurs regardless of the grain diameter, although the calculated values of γ_0 are not smaller than the values measured by Jiang and Baldock (2015) for the diameter d = 2.83 mm (Fig. 2).

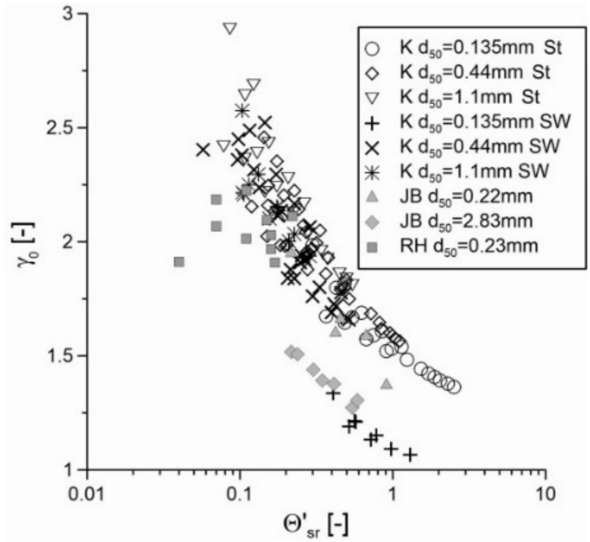

Fig. 2. Comparison of calculated γ_0 for sine waves and asymmetrical waves described by Stokes' approximations (St) and skewed waves (SW) from the experiment by King (1991) (K) with measurement data for γ_0 by Jiang and Baldock (2015) (JB) and Rankin and Hires (2000) (RH)

Fig. 3a compares calculated and measured values of the total sediment transport q_t. The data used for comparison come from measurements in full-scale oscillating tunnels with well-sorted semi-uniform sediments. Those measurements were carried out both for asymmetrical waves described by Stokes' second approximation (Ribberink & Al-Salem 1995, Hassan & Ribberink 2003) and for acceleration-skewed waves (van der A. et al. 2010).

The experimental data used for comparison (Fig. 3b) also come from full-scale oscillating tunnels (Cloin 1998, Hassan & Ribberink 2003), but with poorly sorted sediments. It can be seen that the present model reproduces the measured values of the total sediment transport q_t and q_{ti} within plus/minus a factor of two of measurements, regardless of the wave shape. The model also maps the values of the measured total transport q_t due to acceleration-skewed waves almost perfectly (Fig. 3a) when the bed is built of well-sorted, almost homogeneous sediment. It is worth noting that even great discrepancies in net sediment transport do not result in significant differences between calculated and measured values of total sediment transport q_t and q_{ti}. Agreement within plus/minus a factor of two of measurements is achieved.

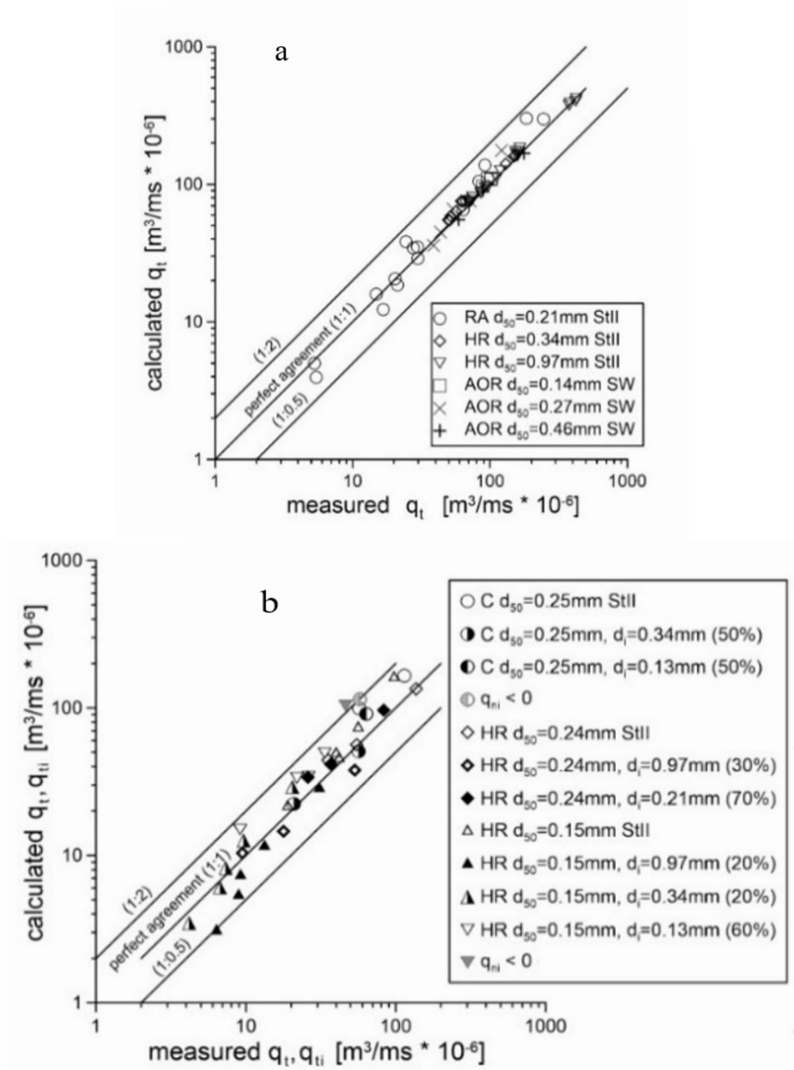

Fig. 3. Comparison of calculated and measured values of: a – total sediment transport q_t for well-sorted semi-uniform sediments; *b* – total sediment transport q_t and q_{ti} for poorly sorted sediments; RA: Ribberink and Al-Salem (1995), HR: Hassan and Ribberink (2003), AOR: van der A. et al. 2010), C: Cloin (1998), StII – Stokes second approximation, SW – Skewed waves

Fig. 4, also compares calculated and measured values of q_t. Here, the experimental data come from small-scale flumes (Kaczmarek 2004, Kaczmarek et al. 2015) and full-scale flumes (Schretlen 2012, Dohmen-Janssen & Hanes 2002), where both the effect due to the presence of bed forms (Kaczmarek 2004, Kaczmarek et al. 2015) and the streaming effect (Schretlen 2012, Dohmen-Janssen & Hanes 2002) on sediment transport are expected.

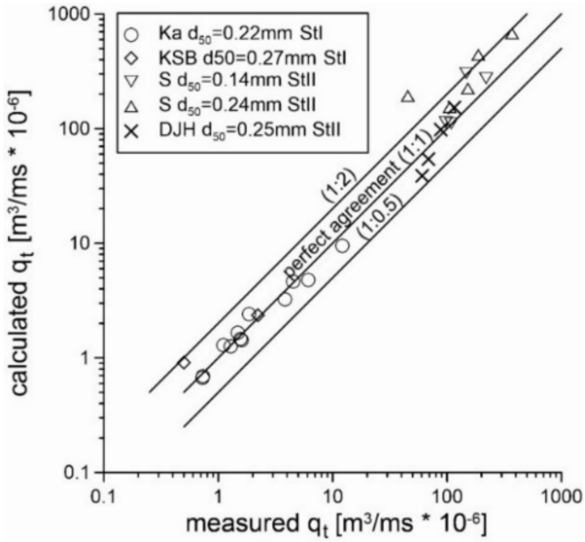

Fig. 4. Comparison of calculated and measured values of the total sediment transport q_t (Ka: Kaczmarek 2004, KSB: Kaczmarek et al. 2017, S: Schretlen 2012, DJH: Dohmen-Janssen & Hanes 2002). StI: Stokes' first approximation, StII: Stokes' second approximation

These effects can influence the modelled sediment transport mainly in the inner layer. They are not considered in the present model. This is the cause of the discrepancy between the experimental and modelled results. However, for the calculated total sediment transport, agreement within plus/minus a factor of two of measurements is achieved. The consistency of the results does not depend on the scale of experiments (full-scale or small-scale). The measurements analysed include those for symmetrical waves described by Stokes' first approximation (Kaczmarek 2004, Kaczmarek et al. 2015) and those for asymmetrical waves described by Stokes' second approximation (Schretlen 2012, Dohmen-Janssen & Hanes 2002).

5. Conclusions

The comparison of numerical calculations of total sediment transport with measurements indicates that the multi-layer model reproduces measured values within plus/minus a factor of two, regardless of the wave shape. The calculations were carried out for any grain size distribution of bed sediments, including well-sorted semi uniform and poorly sorted grains. Even great discrepancies in net sediment transport values for fine sediments do not result in significant differences between the calculated and measured values of total sediment transport. Then, the consistency of total sediment transport within plus/minus a factor of two of measurements is still achieved. The model also maps the values of the measured total transport almost perfectly when the bed is built of well-sorted, almost homogeneous sediment.

The comparison of numerical calculations with measurements shows that the multi-layer model can be applied to a very wide range of grain mobility conditions, including both non-intensive sediment transport and fully developed, intensive sediment transport under sheet flow conditions. To obtain a solution, only few measurable parameters are needed as input, and no additional calibration is needed. The above features make the model of potential engineering interest.

References

Berzi, D., & L. Fraccarollo. (2016). Intense sediment transport: Collisional to turbulent suspension. *Phys. Fluids, 28*(2): 023302. DOI: 10.1063/1.4941770.

Briganti, R., N. Dodd, G. Incelli, & G. Kikkert. (2018). Numerical modelling of the flow and bed evolution of a single bore-driven swash event on a coarse sand beach. *Coastal Eng., 142*, 62-76. DOI: 10.1016/j.coastaleng.2018.09.006.

Cheng, Z., T.-J. Hsu, & J. Calantoni. (2017). SedFoam: A multi-dimensional Eulerian two-phase model for sediment transport and its application to momentary bed failure. *Coastal Eng., 119,* 32-50. DOI: 10.1016/j.coastaleng.2016.08.007.

Cloin, B. (1998). Gradation effects on sediment transport in oscillatory sheet-flow. *Prog. Rep. H2305.* Delft, Netherlands: WL/Delft Hydraulics.

Deigaard, R. (1993). Modelling of sheet flow: Dispersion stresses versus the diffusion concept. *Prog. Rep. Lyngby, Denmark: ISVA.* Technical Univ. of Denmark.

Dohmen-Janssen, C. M., & D. M. Hanes. (2002). Sheet flow dynamics under monochromatic nonbreaking waves. *J. Geophys. Res., 107*(C10), 3149. DOI: 10.1029/2001JC001045.

Fredsøe, J. (1984). Turbulent boundary layer in combined wave-current motion. *J. Hydraul. Eng. 110*(8), 1103-1120.

Furbish, D. J., P. K. Haff, J. C. Roseberry, & M.W. Schmeeckle. (2012). A probabilistic description of the bed load sediment flux: 1. Theory. *J. Geo-Phys. Res. Earth Surf. 117*(F3): 3031. DOI: 10.1029/2012JF002352.

Hassan, W.N., & J.S. Ribberink. (2003). Transport processes of uniform and mixed sands in oscillatory sheet flow. *Coastal Eng. 52*, 745-770. DOI: 10.1016/j.coastaleng.2005.06.002.

Hsu, T., & J. T. Jenkins. (2004). On two-phase sediment transport: Sheet flow of massive particles. *Proc. R. Soc. Lond.* A 460 (2048), 2223-2250. DOI: 10.1098/rspa.2003.1273.

Jiang, Z., & T. E. Baldock. (2015). Direct bed shear measurements under loose bed swash flows. *Coastal Eng.,* 100, 67-76. DOI: 10.1016/j.coastaleng.2015.04.0010378-3839.

Kaczmarek, L. M., J. Biegowski, & R. Ostrowski. (2004). Modelling cross-shore intensive sand transport and changes of bed grain size distribution versus field data. *Coastal Eng., 51*(5-6), 501-529. DOI: 10.1016/j.coastaleng.2004.05.007.

Kaczmarek, L. M., S. Sawczyński, & J. Biegowski. (2015). Hydrodynamic equilibrium for sediment transport and bed response to wave motion. *Acta Geophys., 63*(2), 486-513. DOI: 10.1515/acgeo-2015-0008.

Kaczmarek, L. M., S. Sawczyński, & J. Biegowski. (2017) An equilibrium transport formula for modeling sedimentation of dredged channels. *Coastal Eng. J., 59*(3), 1750015-1750015-35. DOI: 10.1142/S0578563417500152.

Kaczmarek, L. M., J. Biegowski, & Ł. Sobczak. (2019). Modeling of Sediment Transport in Steady Flow over Mobile Granular Bed. *J. Hydraul. Eng., 145*(4), 04019009. DOI: 10.1061/(ASCE)HY.1943-7900.0001566.

King, D.B. (1991). *Studies in oscillatory flow bedload sediment transport.* PhD Thesis. USA, San Diego: Univ. of California.

Meyer-Peter, E., & R. Müller. (1948). Formulas for bed-load transport. In Proc., 2nd Meeting of the Int. Association for Hydraulic Structures Research. Delft, Netherlands: *International Association for Hydro-Environment Engineering and Research.*

O'Donoghue, T., & S. Wright. (2004a). Concentrations in oscillatory sheet flow for well sorted and graded sands. *Coastal Eng., 50*(3), 117-138. DOI: 10.1016/j.coastaleng. 2003.09.004.

Rankin, K. L., & R. I. Hires. (2000). Laboratory measurement of bottom shear stress on a movable bed. *J. Geo-Phys. Res. – Oceans., 105*(C7) 17011-17019. DOI: 10.1029/2000JC900059.

Ribberink, J. S., & A. Al-Salem. (1995). Sheet flow and suspension of sand in oscillatory boundary layers. *Coastal Eng., 25*(3-4), 205-225. DOI: 10.1016/0378-3839(95)00003-T.

Schretlen, J.L.M. (2012). *Sand transport under full-scale progressive surface waves.* PhD thesis. Enschede, Netherlands: Univeristy of Twente.

Silva, P. A., A. Temperville, & F. S. Santos. (2006). Sand transport under combined current and wave conditions: A semi-unsteady, practical model. *Coastal Eng., 53*(11), 897-913. DOI: 10.1016/j.coastaleng.2006.06.010.

Van der A, D. A., T. O'Donoghue, & J. S. Ribberink. (2010). Measurements of sheet flow transport in acceleration-skewed oscillatory flow and comparison with practical formulations. *Coastal Eng., 57*(3), 331-342. DOI: 10.1016/j.coastaleng.2009.11.006.

Van Rijn, L. C. (2007a). Unified view of sediment transport by currents and waves. I: Initiation of motion, bed roughness and bed-load transport. *J. Hydraul. Eng.*, *133*(6), 649-667.

Van Rijn, L. C. (2007b). Unified view of sediment transport by currents and waves. II: Suspended transport. *J. Hydraul. Eng.*, *ASCE, 133*(6), 668-689.

Van Rijn, L. C. (2007c). Unified view of sediment transport by currents and waves. III: Graded beds. *J. Hydraul. Eng., ASCE, 133*(7), 761-775.

Van Rijn, L. C., D.J.R. Walstra, & M van Ormondt. (2007d). Unified view of sediment transport by currents and waves. IV: Application of morphodynamic model. *J. Hydraul. Eng.*, *ASCE, 133(7)*, 776-793.

Vowinckel, B., V. Nikora, T. Kempe, & J. Fröhlich. (2017a). Momentum balance in flows over mobile granular beds: Application of double averaging methodology to DNS data. *J. Hydraul. Res., 55*(2), 1-18. DOI: 10.1080/00221686.2016.1260656.

Vowinckel, B., V. Nikora, T. Kempe, & J. Fröhlich. (2017b). Spatially averaged momentum fluxes and stresses in flows over mobile granular beds: A DNS-based study. *J. Hydraul. Res. 55*(2), 208-223. DOI: 10.1080/00221686.2016.1260658.

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Promoting Pro-ecological Behavior with Logistics Operators in Poland and Ukraine

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Abstract: Logistics operators are characterized by a high dynamics of an increase of incomes, and hence increased shipping. Owing to a rational policy in the area of the consolidation of production and distribution, they may boast of a better use of the means of transport. The aim of the article is to analyse the promoted behaviours of logistics operators in Poland and in Ukraine. The research methods used in the study include a literature analysis, a comparative analysis and a questionnaire survey of logistics operators' clients in Poland and in Ukraine. Selected items have been evaluated: eco-friendly programs, action for the environment, exhaust emission reports, CSR activities carried out locally, nationally and globally, sustainable development of logistics operators, professional development of employees, innovative technologies implemented by logistics operators and transport safety. The analysis conducted in relation to logistics operators will show similarities and differences in the promoted environmental activities and to what extent this is noticed by customers.

Keywords: logistics operators, pro-environmental, eco-logistics, green logistics, promoting, sustainable supply chain

1. Introduction

When transport systems and logistics systems are formed by logistics operators, finding a certain optimum between aiming at a cost reduction on the scale of these systems and aiming at an appropriate level of customer service while maintaining the rules of eco-logistics is of an essential significance. Both society and customers, suppliers and other participants of the supply chain are beginning to expect a higher level of environmental responsibility on the part of LSP (logistics – service – provider) companies.

Logistics as one of the directions of economic activity contributes to the deterioration of the environmental situation; therefore, logistics as a scientific and practical discipline within its activities must take into account environmental aspects in order to minimize the eco-destructive consequences of logistics operations. Sustainable development policy, while being understood on the highest levels of management with logistics operators and implemented as a key factor of long-term development and maintaining the value of the brand, is frequently defined as a green (sustainable) supply chain. A green (eco-friendly) sustainable supply chain is defined as a process of the use of environment friendly resources and their transformation in such a way that it could be possible to improve their side effects or to perform recycling in the existing environment without disturbing it (Brdulak & Michniewska 2009). In the Polish literature, there is a separation of the notion of eco-friendly logistics (eco-logistics) and green logistics.

Eco-logistics is defined as a formation of feedback flows conditioned with environmental requirements and under the influence of aiming at balancing the interests of the economy and environments, with the dominating decisions taken by the management concerning the environment. Eco-friendly logistics in Ukraine is a type of logistics, a scientific and practical activity which is aimed at taking into account environmental aspects at all stages of the flow of materials and other associated flows in order to optimize resource consumption and to minimize destructive environmental impacts (Mgebrishvili 2016). In the case of green logistics in Poland (Szołtysek & Sadowski 2013), it is defined as formation connected with the productivity of the processes of production, operation and development after the service life, and activities are related to the fundamental flow in the supply chain. A more adapted definition of green logistics is to be found in the foreign literature. Green logistics covers all the activities connected with the selection of the best means of transport, freights, carriers and transport routes in order to reduce pollution and the environmental impact of the whole supply chain (SC) (Murphy & Poist 2000, Abukhader & Jönson 2004).

The aim of the article is an analysis of pro-environmental behaviours promoted by logistics operators in Poland and in Ukraine. The research methods used cover a literature analysis, a comparative analysis and a diagnostic survey among the customers of logistics operators in Poland and in Ukraine. For this reason, the following hypotheses have been formulated:

H1. A sustainable supply chain is positively connected with the logistics operator's activities.

H2. There is a positive connection between internal environmental management practices and a quality improvement by logistics operators.

H3. Eco-friendly activities used by the selected logistics operators are taken notice of by their customers in Poland and in Ukraine.

2. Analysis and findings of the literature review

It is not only production companies but also companies from the LSP branch that put an emphasis on the ability of a rational management of natural resources.

The definitions presented herein highlight three key characteristics of SSC (sustainable supply chains). Firstly, more than one entity must be involved in the management of resources, information, and processes that may be beyond a particular company's control. Consequently, the decision-making process includes a number of decision-makers. Secondly, entities partaking in the chain might be working towards contradictory goals, i.e. profit maximization, carbon footprint reduction, or welfare improvement. The third characteristic aspect is the fact that the environmental impact must be considered in the decision-making process. The carbon footprint of the entire span of the chain must be considered, including suppliers, partners, and clients. Moreover, sustainable development requires adopting an interdisciplinary approach as it necessitates an integration of issues and solutions irrespective of functional divisions (Dowlatshahi 2000, Olkiewicz 2020).

The transformations that are taking place in the economy make logistics operators formulate the strategies of future activities taking into consideration among others processes connected with recycling. Reverse logistics was established as an important part of the consensus definition of Supply Chain Management – SCM (Stock & Boyer 2009). Too frequently research focusing on sustainable SCM has failed to explicitly include reverse logistics (Seuring & Müller 2008). Ignoring reverse logistics is inconsistent with the previously developed supply chain frameworks (Lambert et al. 2005). Early in the development of the theory, supporting benefits associated with reverse logistics, the environmental goals of reverse logistics were noted as complementary to economic outcomes (Dowlatshahi 2000). Moreover, a review of the existing sustainable supply chain literature determined that reverse logistics is a part of sustainability due to the aspects of recycling and green supply chain issues (Winter & Knemeyer 2013). Sustainable reverse logistics has also been investigated through a modelling approach where environmental concerns are balanced against other supply chain objectives (Ramos et al. 2014). This approach is known as CSR: Corporate Social Responsibility, where it is a tool that indicates the need to take into account elements connected with social responsibility and the aspects of natural environment protection at the stage of building company strategies (Wyszomirski & Olkiewicz 2020).

Operationalizing green logistics – Green Logistics (GL) is measured using a two-item scale based on Murphy and Poist (Murphy & Poist 2000) and McKinnon (McKinnon 2010), which covers two items: item one refers to choosing the location of the warehouse/distribution centre while accounting for emission reduction and renewable energy use in the centre (GL_1). This is related to the second item, i.e. using renewable energy/energy efficient lightning, such as sensor lamps and energy-saving lamps, solar power on the roofs, etc. in the warehouse distribution centre (GL_2). In this context, carbon dioxide emissions are frequently cited as a detrimental effect of logistical activities (Abukhader & Jönson 2004, Wong et al. 2015). While the first indicator is more strategic in nature and points to the impact of logistics on the environment, the second one is operational and it is related to day-to-day operations. Together, they allow a meaningful assessment of green logistics constructs. The results obtained from green supply chain management depend on the level of intellectual capital development of companies. A developed IT system, an effective knowledge diffusion inside and outside of the organization (Olkiewicz 2018), having certificates supporting supply chain management, a developed motivation system, long-term contracts with clients, a loyalty of suppliers and many more elements contributing to the intellectual capital, probably facilitate green supply management, and they simultaneously permit obtaining better results in this area (Maryniak 2017a). Therefore, the organizational objectives identified for the implementation of an individual firm's supply chain structure lead to an effective conduct that in turn leads to a potential achievement of operational and financial goals (Defee & Stank 2005). Applying the Supply Chain Planning – SCP paradigm to sustainable SCM, successful reverse logistics programs have been associated with positive performance measures, e.g. logistics performance (Morgan et al. 2016), economic performance and environmental performance (Huang & Yang 2014). We follow Zhu et al.'s (Zhu et al. 2008) approach to measure operational performance by assessing the amount of improvement an individual firm achieves on such logistics outcomes as delivery time, inventory levels, and capacity utilization as a result of implementing a sustainable supply chain strategy. Remanufacturing and recycling often provides cost-effective alternatives when compared to the sourcing of new raw materials for use in the supply chain.

For instance, third-party firms have begun to offer services to handle, package, and resell returned products. Exploring the impact of secondary market options as structures to manage these goods provides an opportunity for detailed strategic reverse logistics research (Rogers et al. 2012). These third-party providers can derive profits and reduce environmental costs (Douglas 2017). Future research may investigate how these third-party solutions work with sustainable supply chain strategies to achieve sustainability goals.

Research on the green chain and pro-environmental consumer behaviours has recently been undertaken in the following scope (Maryniak 2017): a general level of the implementation of pro-environmental activities differentiates enterprises in terms of the priority of competitive instruments; an implementation level of pro-environmental activities in each activity type (area) differentiates enterprises in terms of the priority of competitive instruments.

Therefore, an assumption was adopted that the current situation is connected with a low level of knowledge diffusion within the scope of Green Supply Chain Management – GSCM (Maryniak & Strąk 2017). In connection with the above, it seems justifiable to examine the level of knowledge diffusion within the area of these issues and to indicate any troublesome elements connected with it also for logistics operators.

3. Eco-friendly activities with selected logistics operators

In the processes realized by logistics operators, it is not only green logistics that is noticed, where the main problem is carbon dioxide emissions by logistics systems (Dyczkowska 2013) but also urban logistics (Chamier-Gliszczynski & Bohdal 2016, Chamier-Gliszczynski & Bohdal 2016a) and waste management connected with logistics activities. The main activities should focus on the eco-friendly service, the distribution network structure based on a comprehensive use of vehicles, minimization of the negative environment impact of packaging as well as other elements of the life cycle that have an influence on the selection of packaging, the use of the so-called green and renewable energy sources (green energy), energy-saving and passive construction of terminals and sorting plants to enable a reduction of carbon dioxide emissions. It can be noted on the example of logistics operators that many companies are more and more frequently becoming open to innovative solutions in the area of eco-logistics, ecology and whole supply chains. Many entities, which are directly and indirectly involved in the supply chain, derive benefits from this. Firstly, companies benefit from this, which reduce the costs of transport including carbon dioxide emissions while not lowering the level of customer service. What is more, the use of the solution described above also reduces the number of those vehicles that perform deliveries/distribution not only between terminals but also in the area of taking shipment back, thus contributing to a limitation of the traffic of heavy goods vehicles on roads and in cities. Owing to this, the average speed in road transport does not diminish, and logistic companies may perform deliveries within 24 hours. Therefore, it is to be noted that this approach offers an opportunity to companies to improve effectiveness both over a short and long time span. Therefore, this is an approach that is compliant with the conception of sustainable development. Table 1 presents the basic scope of activities in the area of the ecology of selected logistics operators in Europe.

Table 1. Eco-friendly activities realized by selected logistics operators in Europe

Eco-friendly activities	GLS	DPD	FedEx	DHL	DB Schenker
sustainable development (eco-friendly, warehouses, vehicles and e-documents)	V	V	V	V	V
responsible supply chains (including the security of shipments and information)	V	V	V	V	V
neutral to the environment, for example: reduction of emissions CO_2)	V	V	V	V	V
social responsibility (including taking care of health and development of employees)	V	V	V	V	V
activities for the benefit of the local community	V	V	V	V	V
Summary	5	5	5	5	5

Source: Author's own study based on the websites of logistics operators

All the selected logistics operators provide information on their websites about their eco-friendly activities in a basic scope. Activities in the CSR area are a standard in relation to employees so that the present employees should not change their employer and recruit the best personnel to work.

Their Environmental Policy focuses on finding solutions that reduce their own footprint and inspire action in others. Their enterprise-wide Environmental Management System (EMS) is based on the key elements of ISO 14001 (Olkiewicz et al. 2019). The company provides the project leaders with funds necessary for the implementation of their ideas. An interesting idea, teamwork, including the involvement of customers and suppliers as well as partnership with a local social organization or a public institution are the key factors in order to achieve support. What is special about this programme is the fact that the employees themselves as the members of the local communities in which they live and work decide locally who they want to help in their community, and on this basis they submit their ideas. Examples of eco-friendly activities include only some of those selected that are realized by logistics operators in Europe and Ukraine.

4. Methodology and research limitations/implications

Research using the method of indirect measurements (a direct survey with a computer and Internet access) was carried out to analyse the eco-friendly activities of logistics operators. The research was carried out in Poland (Koszalin, Bydgoszcz) and in Ukraine (Poltava) in the period from February 2019 to March 2020 using a quantitative method based on non-random snowball sampling taking into account opinions expressed by people connected with the TSL branch, logistics and having contact with management and marketing. In Poland, 77 persons participated in the research. Three questionnaires were rejected due to the shortage of some data. In Ukraine, 32 people participated and 4 questionnaires were rejected.

In Poland, the women surveyed constituted 51.35% and men accounted for 48.65%. 36.49% of the respondents live in places with up to 10 thousand of residents, 27.02% in places with up to 50 thousand of residents, 9.46% in places with up to 100 thousand of residents and 27.03% in places with over 100 thousand of residents. 46.67% work in service companies and 53.33% in production companies. In Ukraine, women constituted 64.29% and men 35.71%. All of them are the residents of places with over 100 thousand of residents. They hold managerial positions and work in large and very large service companies connected with the LSP branch.

In Poland, 64.86% of people notice eco-friendly activities in connection with logistics operators; in Ukraine, this is only 28.57% of people. This relation is opposite in the case of the lack of eco-friendly activities in Poland. Responsible supply chains were determined (Table 2) as the most important activities which logistics operators should take into account in the area of social responsibility policy in Poland and in Ukraine.

In Poland, activities connected with carbon dioxide emissions were placed on the second position in the ranking, and active work to the benefit of employees on the third position, while in Ukraine, this was placed on the second position and sustainable development in the form of ecological warehouses, vehicles or e-documents on the third position; in Poland, this was placed on the fourth position as this is considered to be a standard within the implemented savings and applicable regulations related to environmental protection. In both countries, activities to the benefit of local communities were placed on the fifth position only. This could because these are not perceived by companies that cooperate with logistics operators and it is not only them that pursue such campaigns.

Table 2. The most important activities connected with corporate social responsibility policy (CSR) which need to be undertaken by logistics operators in Poland and Ukraine

Eco-friendly activities	Poland	Ukraine
neutral to the environment, for example reduction of CO_2 emissions	II position	IV position
activities to the benefit of the local community	V position	V position
responsible supply chains (including the security of shipments and information)	I position	I position
social responsibility (including taking care of health and the development of employees)	III position	II position
sustainable development (eco-friendly, warehouses, vehicles and e-documents)	IV position	III position

Source: author's own study on the grounds of the research.

In Poland, activities connected with carbon dioxide emissions were placed on the second position in the ranking, and active work to the benefit of employees on the third position, while in Ukraine, this was placed on the second position and sustainable development in the form of ecological warehouses, vehicles or e-documents on the third position; in Poland, this was placed on the fourth position as this is considered to be a standard within the implemented savings and applicable regulations related to environmental protection. In both countries, activities to the benefit of local communities were placed on the fifth position only. This could because these are not perceived by companies that cooperate with logistics operators and it is not only them that pursue such campaigns.

In Poland, the respondents notice promotion related natural environment with as many as 14 companies from the TSL branch including 62.16% in DP DHL; 36.49% in DPD; 33.78% in UPS and 24.32% in InPost and GLS. In the case of the respondents, only three companies were distinguished: DP DHL (the leader of the promotion of environment friendly activities), FM Logistic as well as Nova Poszta, UVK and Intime.

The activities pursued by DHL, which is the leader on the global market, are mainly promoted. The Citylogin project offered by FM Logistic, which was noted by 16.22% of the Polish respondents and 10.72% of Ukrainian respondents, is worth noticing. Such activities as the Citylogin project have been taken up in FM Logistic Group for many years now, and the protection of natural environment is their purpose. Initiatives aimed at supporting sustainable development policy constitute an element of strategies practically in each of those countries where the operator runs its business. The latest Citylogin project is an example of the involvement of the company in environment friendly logistics. Within the framework of this project, the operator invests in the purchase of cars with hybrid and electric drives. The system of a modern and environment friendly fleet is operated with the use of specialist software, which enables the management of the whole supply chain starting from loading of the car to an optimization of the delivery route, thus enabling a real time control of the vehicles. The satisfactory results of the pilot Citylogin stage encouraged the Management Board of FM Logistic to implement the project in other large European cities. Paris, Madrid, Milan, Cracow, Warsaw, Poznan, Kiev and Moscow were selected in the first stage. By the end of the year 2019, this modern solution is to be also available for customers in Lisbon, London and Amsterdam, Wroclaw and Lviv.

Activities aimed at environmental protection which are implemented by logistics operators, and which are not promoted in Poland but noticed by the respondents include the following: electronic flow of documents (EDI, e-documents); reduction of fumes emissions (a modern transport fleet, organization of the consolidation of freights and optimization of routes); eco-friendly packaging and point collection (e.g. parcel stations, increased shipment safety); supply chain management including reverse logistics and waste management; modern and energy-saving terminals, sorting plants and warehouses; logistics operator as the first choice employer; organization of charity events and cooperation with foundations (e.g. We notice other people), aid offered to casualties in cataclysms.

Those activities that address natural environment protection which, according to the respondents, receive too little attention on the part of logistics operators in Ukraine are as follows: optimization and management of material, financial and information flow; promptness, comfort and cost-effectiveness based on environmental protection rules improvement of supplier-consumer relations, provision of the required services, economic and eco-friendly transport; the tool of a rational organization of streaming processes with minimal expenses, management of material, information and human flows on the basis of their optimization, the right product of the right quality of the right collie at the right time in the right place at the lowest cost; find a shortcut, optimal solution, automate decision making.

Additionally, the “GOGreen” action conducted by DP DHL capital group is worth noting; 18.92% of the Polish respondents and 35.72% of the Ukrainian respondents knew about this action.

5. Conclusions and future research

The world and in the Polish literature includes many references that discuss the sustainable supply chain, green logistics or eco-logistics. In spite of similarities, these notions differ, yet all of them are connected with environmental protection realized by logistics operators. Research has been undertaken concerning the green chain of supplies and corporate social responsibility (CSR) conducted by logistics operators in Poland and Ukraine. It is to be noted that the sustainable supply chain is positively connected with the activities of the logistics operator; in both countries, the following programmes are given as an example: GoGreen – DP DHL and Citylogin – FM Logistic. The respondents observe a positive connection between the internal practices of environmental management and an improvement of the quality of services through such activities as a reduction of carbon dioxide emissions and publishing of the reports on fume emissions (neutral to environment), where the respondents in Poland ranked as second in terms of importance. Responsible supply chains related the safety of shipments and information were determined as the most important activities which logistics operators should take in the scope of the social responsibility policy in Poland and in Ukraine. In both countries, activities to the benefit of local communities ranked on the fifth position only. This could be because they are not visible to those companies that cooperate with logistics operators and it is not only them that pursue such campaigns. In Poland, 64.86% of the respondents observe environmentally oriented activities among logistics operators; in Ukraine; this is merely 28.57%. In spite of the implementation of many programmes connected with environmental protection by logistics operators, there is no promotion. This can only be seen only on the websites of logistics operators and in trade press. This causes customers to be unfamiliar with them. Due to the regulations, TSL companies in Poland implement environmentally oriented behaviours considerably faster than in Ukraine, such as e-documents or parcel stations. Without an introduction and later promotion of CSR among customers, in spite of the expenditures and efforts incurred, logistics operators will be perceived as companies that pollute air, which can especially be observed in Ukraine. In the future, the research needs to be repeated to see whether there has been an improvement in the promotion of environmentally oriented activities by logistics operators in Poland and especially in Ukraine; these activities will have to be compared with those in West European states. Additionally, it should be determined what new environment friendly elements have been introduced by logistics operators and whether they have an impact on the quality of services provided by them. In the future, Green Logistic will contribute to the solution of many local problems connected with urban traffic. At this moment, this is on the last position in the ranking. The environment friendly policy will have an impact on the profitability of management processes (a better use of vehicles, an optimization of routes), which will constitute a new quality in the modelling customer service processes and the sustainable supply chain management. Logistics operators should promote their investments in the scope of environmental protection using such tools as public relations and sponsorship of local activities aimed at an improvement of the company's image. The effectiveness of the investments realized cannot be directly assessed considering the unavailability of data. An introduction of the ISO 14001 Standard in their corporations brought about procedural transformations, and those subcontractors that provide transport services in a logistic chain have to replace their means of transport with more environment friendly ones.

References

Abukhader, S.M., Jönson, G. (2004). Logistics and the environment: is it an established subject? *International Journal of Logistics Research and Applications, 7*(2), 137-149.

Brdulak, H., Michniewska, K. (2009). Zielona logistyka, ekologistyka, zrównoważony rozwój w logistyce. *Logistyka*, *4*, 9 (in Polish).

Chamier-Gliszczynski, N., Bohdal, T. (2016). Mobility in Urban Areas in Environment Protection. *Rocznik Ochrona Środowiska, 18*(1), 387-399.

Chamier-Gliszczynski, N., Bohdal, T. (2016a). Urban Mobility Assessment Indicators in the Perspective of the Environment Protection. *Rocznik Ochrona Środowiska*, *18*(1), 670-681.

Defee, C.C., Stank, T.P. (2005). Applying the strategy-structure-performance paradigm to the supply chain environment. *The International Journal of Logistics Management*, *16*(1), 28-50.

Douglas, D. (2017). Maryland Startup Redirects River of Rejected Gifts, NPR National Public Radio, available at: www.npr.org/2016/01/01/461615668/maryland-startup-redirects-river-of-rejectedgifts (accessed on 31 January, 2017).

Dowlatshahi, S. (2000) Developing a theory of reverse logistics. *Interfaces*, *30*(3), 143-155.

Dyczkowska, J. (2013). Eco-logistics In the Transport, Shipping and Logistics Branch: an Analysis. *Rocznik Ochrona Środowiska*, *15*(1), 649-658.

Huang, Y.C., Yang, M.L. (2014). Reverse logistics innovation, institutional pressures and performance. *Management Research Review*, *37*(7), 615-641.

Kozłowski, S. (2000). *Ekorozwój. Wyzwanie XXI wieku.* Warszawa: PWN, 81 (in Polish).

Lambert, D.M., Garcia-Dastugue, S.J., Croxton, K.L. (2005). An evaluation of process-oriented supply chain management frameworks. *Journal of Business Logistics*, *26*(1), 25-51.

Maryniak, A. (2017). Economic, environmental, marketing and logistic effects of intellectual capital resulting from the implementation of green supply chains, *Вісник Національного університету,* Львівська політехніка, Логістика, 863, 285-294.

Maryniak, A. (2017). Competitive, instruments preferred by customers versus the level of pro-environmental activities supply chain. *LogForum*, *13*(2), 159-169.

Maryniak, A., Strąk, Ł. (2017). Analyses of Aspects of Knowledge Diffusion Based on the Example of the Green Supply Chain, In Nguyen, N.T., Tojo, S., Nguyen, L.M., Trawiński, B. (eds.), *Intelligent Information and Database Systems, 9th Asian Conference*, ACIIDS 2017, Kanazawa, Japan, April 3-5, Proceedings, eBook, Part I, 335-344.

McKinnon, A. (2010). Environmental sustainability: a new priority for logistics managers, In McKinnon, A., Cullinae, S., Browne, M., Whiteing, A. (Eds), *Green logistics: improving the environmental sustainability of logistics*. London: Kogan Page Limited, United Kingdom, 3-30.

Mgebrishvili, Kh.A. (2016). Ecological aspects in logistics. *Modern technologies in engineering and transport*, *2*, 105-109.

Morgan, T.R., Richey, R.G., Autry, C.W. (2016). Developing a reverse logistics competency the influence of collaboration and information technology. *International Journal of Physical Distribution & Logistics Management*, *46*(3), 293-315.

Murphy, P.R., Poist, R.F. (2000). Green logistics strategies: an analysis of usage patterns. *Transportation Journal*, *40*(2), 5-16.

Olkiewicz, M. (2018). Quality improvement through foresight methodology as a direction to increase the effectiveness of an organization. *Contemporary Economics*, *12*(1), 69-80.

Olkiewicz, M. (2020). The role of a stakeholder in the quality improvement of an organization. *Scientific Papers of Silesian University of Technology. Organization and Management Series*, *143*, 235-245.

Olkiewicz, M., Bober, B., Majchrzak-Lepczyk, J. (2015). Instruments of environmental protection management, *Rocznik Ochrona Środowiska*, *17*(1), 710-725.

Olkiewicz, M., Wolniak, R., Skotnicka-Zasadzień, B. (2019). Implementation of ISO 14001 standard in the European Union countries. *Rocznik Ochrona Środowiska*, *21*(2), 868-880.

Ramos, T.R.P., Gomes, M.I., Barbosa-Povoa, A.P. (2014). Planning a sustainable reverse logistics system: balancing costs with environmental and social concerns. *Omega*, *48*(1), 60-74.

Rogers, D.S., Melamed, B., Lembke, R.S. (2012). Modeling and analysis of reverse logistics. *Journal of Business Logistics*, *33*(2), 107-117.

Seuring, S., Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, *16*(15), 699-710.

Stock, J.R., Boyer, S.L. (2009). Developing a consensus definition of supply chain management: a qualitative study. *International Journal of Physical Distribution & Logistics Management*, *39*(8), 690-711.

Szołtysek, J., Sadowski, A. (2013). Logistyka zwrotna – dylematy związane z celami. *Logistyka*, *6*, 8-10.

Winter, M., Knemeyer, A.M. (2013). Exploring the integration of sustainability and supply chain management: current state and opportunities for future inquiry. *International Journal of Physical Distribution & Logistics Management*, *43*(1), 18-38.

Wong, C.Y., Wong, C.W.Y., Boon-itt, S. (2015). Integrating environmental management into supply chains. *International Journal of Physical Distribution & Logistics Management*, *45*(1/2), 43-68.

Wyszomirski, A., Olkiewicz, M. (2020). Environmental Corporate Social Responsibility as a tool for creating the future of environmental protection. *Rocznik Ochrona Środowiska, 22*(2), 1145-1161.

Zhu, Q., Sarkis, J., Lai, K.H., Geng, Y. (2008). The role of organizational size in the adoption of green supply chain management practice in china. *Corporate Social Responsibility and Environmental Management*, *15*(6), 322-337.

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Evaluation of Technical Measures Implemented in the Field of Flood Protection and Water Retention in Poland During the Period of 2003-2018

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Abstract: Flood prevention has become one of the most important priorities of public safety and risk mitigation in Poland. The study presents an evaluation of the actions implemented in 16 voivodships of Poland in the field of flood prevention and water retention. Voivodships correspond to individual regions of the country. The analysis covering the period of 2003-2018 was carried out on the basis of data obtained mainly from Local Data Bank. A set of indicators, divided into infrastructural and economic ones were applied. The assessment of technical measures covered two basic types of hydro engineering facilities: flood embankments and retention reservoirs. The economic indicators illustrate the expenditures incurred on the implementation of technical means of flood prevention. The obtained results provide means to categorise the voivodships into subsets. Units similar in terms of the carried out water management were assigned to 4 types. Voividships similar in terms of the expenditures designated to the implementation of water management tasks were divided into 4 groups. Taking into account the dynamics of the investments and financial outlays on water management measures related to the existing flood risk assessment, the situation is satisfactory in 4 voivodships, but insufficient or unsatisfactory in 7 of them. The obtained results show that in order to achieve the flood prevention levels required in the studied regions additional actions are necessary, including but not limited to technical measures.

Keywords: water management, flood protection, retention, regional differentiation, multi-indicator analysis

1. Introduction

Flooding is listed as one of the most frequent weather-related disasters (EC 2015). Changes in the pattern of this phenomenon are difficult to observe. Even though no robust and widespread increase in the amplitude and frequency of high river flows throughout Europe could be detected, there have been an increasing trend in the number of floods with large magnitude and severity (Kundzewicz et al. 2018). The magnitude and frequency of floods varies inter alia with human pressure and climate change, including global warming (Blöschl et al. 2019). Increasing temperatures and changes in precipitation significantly affect hydrological systems, water resources and properties that are essential for water management such as mean and extreme values of river flows, river and lake water levels and groundwater levels, i.e. (Staśko et al. 2017, Piniewski et al. 2020). Observing the current rate of global warming, the target of limiting it within 2 degrees by the end of the century seems more and more unrealistic. At 4 C global warming and climate change could increase the flood risk in Europe by 220% by 2080 (Alfieri at al. 2015). This threat has an important social and economic dimension. There is no doubt that costs of flood-related damages have been rising, partly due to the increasing exposure of people and assets (Kundzewicz et al. 2014, Alfieri et al. 2015).

The occurrence of floods in Europe and Poland is diversified in temporal and spatial terms. Short-term floods lasting less than 24 h (56%) prevail, of which 39% are river floods, 4% are coastal floods and the remaining 1.5% are compound events, i.e., floods caused by a co-occurrence of storm surge and high river flows (Paprotny et al. 2018). In southern Europe there are mostly flash floods that occur between September and November, in western and central Europe there are mostly river foods that take place between June and Augusts. Snowmelt floods dominate in northern European countries, while coastal floods are typical in areas of the North and the Baltic seas.

Poland is located in a temperate-transitional climate zone, therefore it is exposed to the clash of oceanic and continental air masses. These factors, together with much varied topography create the high risk of various natural hazards. Floods are considered to be one of the most important of them. In Poland, in case of natural phenomena there are four basic types of floods: flash floods, snowmelt floods, ice-jam floods and coastal floods. The areas of flash floods risk are located:

- in the Oder basin – the upper and middle Oder basin with the basins of the mountain tributaries (the Olza, Osobłoga, Mała Panew, Nysa Kłodzka, Ślęza, Bystrzyca, Kaczawa, Bóbr, Nysa Łużycka);

- in the Vistula's basin – the basin of the upper and middle Vistula (to the estuary of the Wieprz River) including the basins of the mountain and foothill tributaries (Przemsza, Soła, Skawa, Raba, Dunajec).

Administratively, they belong to the southern voivodships, i.e.: Małopolskie, Podkarpackie, Śląskie, Opolskie, Świętokrzyskie and Dolnośląskie. The threat of snowmelt floods occurs mainly in the central lowland part of the country, i.e. the areas of the middle and lower Odra and Vistula rivers, in the lowland tributaries of the Odra (Barycz, Warta, Noteć), in the lowland tributaries of the Vistula (Bug, Narew, Bzura, Drwęca) and rivers which run directly into the Baltic Sea. This kind of threats occur mainly in the voivodships: Wielkopolskie, Zachodniopomorskie, Mazowieckie, Warmińsko-Mazurskie and Podlaskie. Ice-jam floods occur in larger lowland rivers, mainly in the middle and lower Vistula and Oder rivers and in their larger tributaries. It concerns mainly the voivodships: Mazowieckie, Zachodniopomorskie and Pomorskie. Coastal flooding take place in the north of the country, including areas of Żóławy, the Vistula Lagoon, the Szczecin Lagoon and the lower sections of rivers running directly into the Baltic sea. It concerns mainly the Pomorskie and Zachodnio-Pomorskie Voivodships (Bednarczyk et al. 2006, Kowalewski 2006, KPZK 2020).

According to the assessment of flood risk for voivodships developed by Gołąb (2018):

- high risk exists in eight voivodships: Dolnoślaskie, Lubuskie, Małopolskie, Opolskie, Podkarpackie, Śląskie, Pomorskie, Zachodnopomorskie;
- medium risk exists in five voivodships: Kujawsko-pomorskie, Łódzkie, Mazowieckie, Podlaskie, Wamińsko-mazurske, Wielkopolskie;
- low risk covers two voivodships: Lubelskie, Świętokszyskie.

Until the end of 2020, The Concept of the National Spatial Planning 2030 (KPZK 2011) was the main document concerning spatial development and spatial planning of national importance. According to this concept, flood and drought counteractions were indicated as one of the most important strategic objectives. Two so-called functional areas (FA)were designates: FA exposed to flood hazard at the level of river basins, FA of water resources conservation and management. Objectives established for functional areas should be taken into account in planning activities carried out by administrative units. The complexity of the issue and the considerable spatial distribution of existing threats require an integrated territorial approach to development. Integrated management for functional areas related to water management requires cooperation within basin districts and water regions as well as administrative units of various levels. Protection against flooding and drought is a matter of State Water Holding Polish Waters as well as central, regional and local administration bodies. These authorities develop and implement policy concerning technical and non-technical measures to minimize risks at regional level, i.e. functional areas, voivodships as well as local (municipal) levels. The authorities are also involved in decision making process regarding water, building, settlement and infrastructure investments allocated in flood risk areas. The activities are based on water management planning documents, including: flood hazard maps, flood risk maps, flood risk management plans. According to the National Flood Hazard Management Plan (KPZK 2020) the areas at risk of flooding were determined for 981 river sections having total length of 29 301.7 km. Moreover, a significant flood risk was determined for rivers sections having total length of 1 394.4 km.

According to the provisions of Art. 165.1. of the Water Law Act (Dz. U. 2017, item 1566, as amended), flood protection shall be implemented by:
- spatial management of river valleys and floodplains areas,
- rational water retention, rational use of flood-control structures, water flow control,
- ensuring the proper functioning of early warning and response system for hazards in the atmosphere and hydrosphere and forecasting floods,
- preservation, creation and restoration of water retention systems,
- construction, reconstruction and maintenance of flood control structures,
- carrying out ice-breaking activities,
- conducting information policy in the field of flood prevention, protection and mitigation.

Due to the existing legal, natural and socio-economic conditions most of the existing spatial development plans for voivodships required designation of functional areas related to flood risk and then the revision and adjustments of planned activities in their respective areas.

The literature regarding cross-sectional or comparative assessment of actions undertaken by administrative units for flood protection and the state of flood protection is limited. An example of a study using various indicators (mainly socio-economic) covering the whole country is the one conducted by Dumieniecki, Pasiecznik-Dominiak and Tiukało (2015) for municipalities. The authors indicated the quantitative and spatial differentiation of the municipalities depending on the exposure of the inhabitants to the flood risk with probability of Q1% and differentiation of municipalities due to the potential losses caused by flooding. The survey shows that that flooding with medium probability (Q1%) covers more than 50% of municipalities (1301 units). The largest number of them is located in the southern voivodships, i.e.: Lubuskie, Dolnośląskie, Opolskie and Podkarpackie. Similar conclusions apply to potential flood losses. In this case, apart from municipalities located in mountain regions in the south of the country, significant threat was indicated in several units of Mazowieckie Voivodship. Dubiel (2015) conducted questionnaire and empirical surveys on flood prevention, protection and mitigation in the Śląskie Voivodship. The Oder and Vistula (Poland's two largest rivers) and their numerous tributaries in the voivodship are mostly unregulated, embanked only at small sections. The preparation of flood protection facilities in 17% of the surveyed municipalities has been considered to be good. However, similar number of municipalities indicated poor preparation, poor technical condition and insufficient number of hydrotechnical structures, flood banks, polders and retention reservoirs. An assessment of flood protection measures implemented between 2007 and 2016 was prepared by Gołąb (2018). The evaluation was based on flood protection programmes for individual river basins and the incurred costs of their implementation. The basic scope of investment activities of such programmes included, among others: construction, reconstruction and modernisation of flood protection embankments, protection of banks and stream bottoms, reconstruction of watercourse channels, construction of flood control reservoirs. The results were related to the current degree of flood risk in the voivodeships. The research shows that none of the flood programmes have delivered the expected results. There were significant delays in implementation, some of the programmes were even cancelled before the deadline. In the author's opinion, considerable financial outlays have not been translated into improved flood safety.

The main objective of the presented study was to evaluate the actions implemented in the years 2003-2018 in voivodships in the field of flood protection and water retention. The assessment was carried out using a set of infrastructural and economic indicators. The obtained results show diversification of the voivodships in terms of the amount of investments carried out and financial expenses incurred for water management

2. Methods

The assessment of the existing flood risk indicates the need to monitor the situation with respect to river basins as well as administrative units. In this study, the analysis concerns technical flood protection measures, i.e. those related to the construction of flood control structures and water retention facilities in 16 voivodships. A set of indicators, divided into infrastructural (4 indicators) and economic ones (3 indicators) were applied.

2.1. Infrastructural indicators

The assessment of technical measures covered two basic types of hydroengineering facilities: flood embankments and retention reservoirs. In the first case, a flood banks density index W1 was calculated according to Equation:

$$W_1 = \left[\frac{X_1}{X_{11}}\right] x1000 \text{ [-]}, \tag{1}$$

where:
X_1 – the total length of flood banks constructed in the years 2003-2018 [km],
X_{11} – the length of rivers [km].

One of the flood protection measures and drought prevention is surface water retention. The proposed indicator refers water retention in surface water reservoirs to urban areas. The surface water storage capacity index W2 was calculated by means of the following Equation:

$$W_2 = \left[\frac{X_2}{X_5}\right] x100 \text{ [m}^3\text{/10 ha]}, \tag{2}$$

where:
X_2 – the capacity of surface water reservoirs built in the years 2003-2018 [m^3],
X_5 – the mean area of urbanized and built-up land in the years 2003-2018 [ha].

Apart from the capacity of water reservoirs, the number of reservoirs was taken into account. It is implicated by the fact that a higher number of smaller capacity reservoirs can be more spatially and functionally favorable than one very large reservoir. Therefore, the surface density index of constructed artificial reservoirs W3 was determined by the following Equation:

$$W_3 = \left[\frac{X_3}{X_5}\right] \text{ [pcs./km}^2\text{]}, \tag{3}$$

where:
X_3 – number of water reservoirs built in the years 2003-2018 [pcs],
X_5 – the mean area of urbanized and built-up land in the years 2003-2018 [km^2].

In addition to technical means for flood protection, drought-related measures were analyzed. The irrigation surface density index was calculated from Equation:

$$W_4 = \left[\frac{X_8}{X_6}\right] \text{ [-]}, \tag{4}$$

where:
X_8 – the area of irrigated land in the years 2013-2018 [km^2],
X_6 – the area of the voivodship in 2018 [km^2].

2.2. Economic indicators

Apart from the indicators that allow to assess technical flood prevention measures of voivodships in terms of quantity, two indicators related to economic issues were proposed. The first indicator illustrates the expenditures incurred on the implementation of flood-banks in relation to 1 km of the river network. It was calculated according to Equation:

$$W_5 = \left[\frac{X_4}{X_{11}}\right] \text{[PLN/km]}, \tag{5}$$

where:
X_4 – expenditures on flood-banks in the years 2013-2018 [PLN],
X_{11} – the length of river network [km].

The indicator that describes the expenditure incurred on the implementation of small water retention facilities in relation to the impermeable surfaces, is calculated by the following Equation:

$$W_6 = \left[\frac{X_9}{X_5}\right] \text{[PLN/km}^2\text{]}, \tag{6}$$

where:
X_9 – financial expenditure on the implementation of small water retention facilities in the years 2013-2018 [PLN],
X_5 – the mean area of urbanized and built-up land in 2003-2018 [km^2].

The indicator regarding expenditure incurred on water management in general, related to the number of inhabitants, was calculated by means of the following Equation:

$$W_7 = \left[\frac{X_{10}}{X_7}\right] \text{[PLN/person]}, \tag{7}$$

where:
X_{10} – water management expenditures in the years 2013-2018 [PLN],
X_7 – average population in the province in the years 2003-2018 [person].

2.3. Standardized indictors and similarity intervals

In order to transform previously calculated indicators into comparable form, the values obtained for each voivodships were normalized according to Equation:

$$Z_{1.....7} = \frac{W_{1....7}}{W_{1...7\,\max}} \text{ [-]}, \tag{8}$$

Aggregate assessment for water management in individual voivodships was conducted by means of the synthetic Perkel index [Runge 2007] according to Eqution:

$$W_{IT(E)} = \frac{1}{n}\sum_{1}^{n} Z_{ij} \quad [-], \tag{9}$$

where:
$W_{IT(E)}$ – infrastructural (IT) or economic (E) synthetic indicator of water management in a voivodship,
j – 1,2, ..., n,
Zij – normalized value of indicators Wij,
n – the number of attributes.

The synthetic indicator was calculated separately for infrastructural and economic indicators. The higher value of the infrastructural synthetic indicator means the higher investment activity of the voivodship related to the implementation of tasks in the field of water management. The higher values of the economic synthetic indicator the higher financial expenses designated for this purpose in the years 2003-2018.The next step was to develop classes of the voivodships with similar characteristics. The number of classes was determined using basic formulas for the frequency distribution of grouped data (Tarka & Olszewska 2018), taking into account that the analysis concerns 16 voivodships:

- $k = \sqrt{N} = \sqrt{10} = 3{,}16$
- $k \leq 1 + 3{,}222\ logN \leq 4{,}222$
- $k \leq 5\ logN \leq 5$

The number of classes was set at 4 (k = 4), and the range of intervals was established by the mean of Equation:

$$h = \frac{Z_{1-7(\max)} - Z_{1-7(\min)}}{k} \tag{10}$$

where:
N – number of the voivodeships,
h – the range of intervals.

Input data for the variables X_1-X_{10} were taken from the Local Data Bank (LDB). The variable X_{11} was calculated on the basis of the Map of Hydrographic Division of Poland (2013) in shp. format. The obtained values of the indicators X_1-X_{11} are presented in Tables 1-2. Spatial analyses were performed and the individual maps prepared by means of the ArcMap application being part of the ArcGIS software.

Table 1. The variables X_1-X_6 concerning water management in the analyzed voivodeships for the years 2003-2018 (Own study based on LDB)

No.	Voivodship	X_1 [km]	X_2 [m^3]	X_3 [pcs.]	X_4 [kPLN]	X_5 [ha]	X_6 [km^2]
1.	Dolnośląskie	158.1	27 783 691	7	823 952.1	135254.8	19 947
2.	Kujawsko-Pomorskie	82.2	26 000	1	164 795.3	84166.94	17 971
3.	Lubelskie	87.0	1 090 400	15	267 289.8	91586.38	25 123
4.	Lubuskie	95.6	3 380 321	4	227 287.6	62261.75	13 988
5.	Łódzkie	37.3	21 052 288	10	34 165.9	95183.44	18 219
6.	Małopolskie	556.0	759 250	2	522 056.9	86065.31	15 183
7.	Mazowieckie	154.4	3 493 676	14	268 012.2	185104.9	35 559
8.	Opolskie	73.5	5 679 700	3	180 134.5	55545.44	9 412
9.	Podkarpackie	208.1	625 214	12	468 087.3	78307.94	17 846
10.	Podlaskie	2.1	773 170	14	9 152.1	74762.75	20 187
11.	Pomorskie	265.3	289 519	12	476 904.2	91191.63	18 323
12.	Śląskie	102.7	51 721 963	10	147 934.5	140967.6	12 333
13.	Świętokrzyskie	109.6	38 273 794	13	301 707.0	51829.63	11 710
14.	Warmińsko- Mazurskie	174.5	15 759	6	77 811.4	88168.69	24 173
15.	Wielkopolskie	255.2	9 781 538	11	128 933.4	151594.4	29 826
16.	Zachodniopomorskie	173.2	694 028	10	278 557.5	97922.44	22 905

Table 2. The variables X_7-X_{11} concerning water management in the analyzed voivodeships for the years 2003-2018 (Own study based on LDB)

No.	Voivodship	X_7 [person]	X_8 [km^2]	X_9 [kPLN]	X_{10} [kPLN]	X_{11} [km]
1.	Dolnośląskie	2 898 271	10170.16	96 044.1	5 632 854.6	12378.790511
2.	Kujawsko-Pomorskie	2 080 066	84.836	28 649.3	1 873 086.9	6061.399851
3.	Lubelskie	2 159 436	167.346	73 081.7	1 487 635.8	9884.609199
4.	Lubuskie	1 015 091	73.946	27 587.0	1 194 308.8	5084.137697
5.	Łódzkie	2 532 163	1512.158	56 642.1	1 430 567.1	7073.719764
6.	Małopolskie	3 326 769	932.16	25 617.6	5 309 226.0	9354.699512
7.	Mazowieckie	5 264 696	0.912	140 253.8	5 305 643.5	15414.414958
8.	Opolskie	1 019 379	1786.858	36 590.0	1 573 938.6	5220.06819
9.	Podkarpackie	2 115 509	30.92	34 547.2	1 968 417.0	10208.140796
10.	Podlaskie	1 194 294	9.64	70 897.8	940 532.6	7660.01446
11.	Pomorskie	2 260 886	131.162	11 159.6	2 235 003.4	6463.231316
12.	Śląskie	4 624 091	57.456	34 494.7	4 625 456.9	6583.006154
13.	Świętokrzyskie	1 270 564	3.015	58 670.1	1 172 792.5	4814.042811
14.	Warmińsko- Mazurskie	1 436 272	18.3	30 196.1	1 237 677.0	10197.969557
15.	Wielkopolskie	3 432 066	624.004	274 753.6	2 733 735.4	10478.150434
16.	Zachodniopomorskie	1 705 236	3316.43	45 404.1	1 867 432.3	8407.824052

3. Characteristics of voivodships in terms of investment measures in water management

The results of the individual indicators for the voivodships according to annual reporting periods from 2003 to 2018 are presented in Figures 1-2 and Tables 3-4.

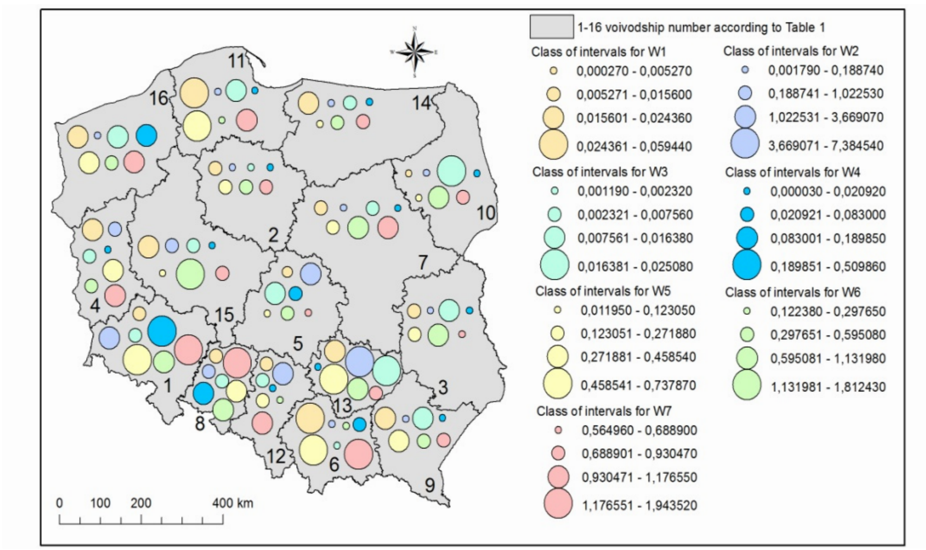

Fig. 1. Diversity of voivodships according to infrastructural and economic indicators W1-W7 (Own study)

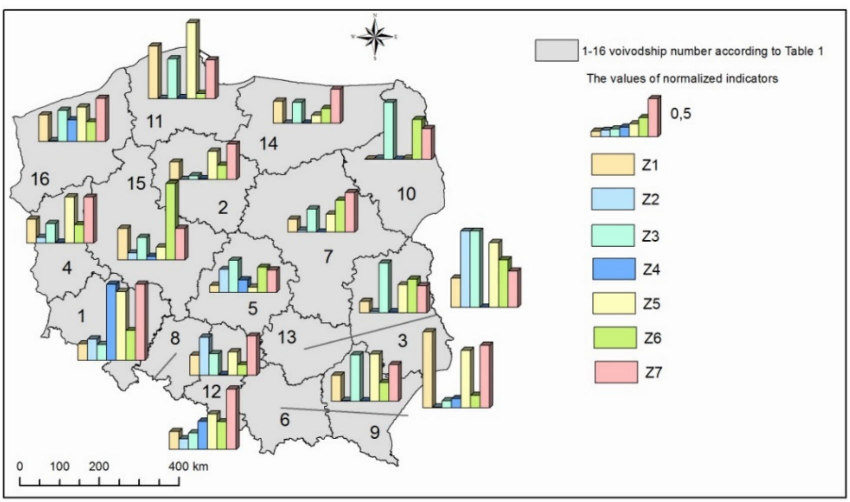

Fig. 2. Diversity of voivodships according to the normalized indicators Z1-Z7 (Own study)

Table 3. Values of the infrastructural and economic indicators for the voivodeships in the years 2003-2018 (Own study)

No.	Voivodship	W_1 [-]	W_2 [m^3 /10ha]	W_3 [pcs. /km^2]	W_4 [-]	W_5 [kPLN /m]	W_6 [kPLN /ha]	W_7 [kPLN /person]
1.	Dolnośląskie	0.01277	2.05417	0.00518	0.50986	0.66562	0.71010	1.94352
2.	Kujawsko-Pomorskie	0.01356	0.00309	0.00119	0.00472	0.27188	0.34039	0.90049
3.	Lubelskie	0.00880	0.11906	0.01638	0.00666	0.27041	0.79795	0.68890
4.	Lubuskie	0.01880	0.54292	0.00642	0.00529	0.44705	0.44308	1.17655
5.	Łódzkie	0.00527	2.21176	0.01051	0.08300	0.04830	0.59508	0.56496
6.	Małopolskie	0.05944	0.08822	0.00232	0.06139	0.55807	0.29765	1.59591
7.	Mazowieckie	0.01002	0.18874	0.00756	0.00003	0.17387	0.75770	1.00778
8.	Opolskie	0.01408	1.02253	0.00540	0.18985	0.34508	0.65874	1.54402
9.	Podkarpackie	0.02039	0.07984	0.01532	0.00173	0.45854	0.44117	0.93047
10.	Podlaskie	0.00027	0.10342	0.01873	0.00048	0.01195	0.94830	0.78752
11.	Pomorskie	0.04105	0.03175	0.01316	0.00716	0.73787	0.12238	0.98855
12.	Śląskie	0.01560	3.66907	0.00709	0.00466	0.22472	0.24470	1.00030
13.	Świętokrzyskie	0.02277	7.38454	0.02508	0.00026	0.62672	1.13198	0.92305
14.	Warmińsko-Mazurskie	0.01711	0.00179	0.00681	0.00076	0.07630	0.34248	0.86173
15.	Wielkopolskie	0.02436	0.64524	0.00726	0.02092	0.12305	1.81243	0.79653
16.	Zachodniopomorskie	0.02060	0.07088	0.01021	0.14479	0.33131	0.46367	1.09512

Table 4. Values of the normalised indicators for the voivodeships in the years 2003-2018 (Own study)

No.	Voivodship	Z1	Z2	Z3	Z4	W_{IT}	Z5	Z6	Z7	W_E
1.	Dolnośląskie	0.21489	0.27817	0.20634	1.00000	**0.42485**	0.90207	0.39179	1.00000	**0.76462**
2.	Kujawsko-Pomorskie	0.22817	0.00042	0.04737	0.00926	**0.07131**	0.36846	0.18781	0.46333	**0.33987**
3.	Lubelskie	0.14809	0.01612	0.65297	0.01306	**0.20756**	0.36647	0.44027	0.35446	**0.38707**
4.	Lubuskie	0.31637	0.07352	0.25614	0.01037	**0.16410**	0.60587	0.24447	0.60537	**0.48524**
5.	Łódzkie	0.08872	0.29951	0.41886	0.16279	**0.24247**	0.06546	0.32834	0.29069	**0.22816**
6.	Małopolskie	1.00000	0.01195	0.09265	0.12042	**0.30626**	0.75632	0.16423	0.82114	**0.58056**
7.	Mazowieckie	0.16853	0.02556	0.30154	0.00005	**0.12392**	0.23564	0.41806	0.51853	**0.39074**
8.	Opolskie	0.23690	0.13847	0.21533	0.37236	**0.24077**	0.46767	0.36346	0.79444	**0.54186**
9.	Podkarpackie	0.34299	0.01081	0.61096	0.00340	**0.24204**	0.62144	0.24341	0.47875	**0.44787**
10.	Podlaskie	0.00461	0.01400	0.74658	0.00094	**0.19153**	0.01619	0.52322	0.40520	**0.31487**
11.	Pomorskie	0.69063	0.00430	0.52464	0.01404	**0.30840**	1.00000	0.06752	0.50864	**0.52539**
12.	Śląskie	0.26248	0.49686	0.28282	0.00914	**0.26283**	0.30455	0.13501	0.51468	**0.31808**
13.	Świętokrzyskie	0.38305	1.00000	1.00000	0.00050	**0.59589**	0.84936	0.62457	0.47494	**0.64962**
14.	Warmińsko-Mazurskie	0.28790	0.00024	0.27131	0.00148	**0.14023**	0.10341	0.18896	0.44339	**0.24525**
15.	Wielkopolskie	0.40978	0.08738	0.28930	0.04103	**0.20687**	0.16676	1.00000	0.40984	**0.52553**
16.	Zachodniopo-morskie	0.34659	0.00960	0.40715	0.28398	**0.26183**	0.44900	0.25583	0.56347	**0.42277**

4. Discussion

In accordance with the methodological assumptions the voivodships were divided into 4 types in terms of water management activities that were carried out and 4 groups in terms of the expenditures devoted to the implementation of water management tasks (Fig. 3, Table 5).

Types of the voivodships are the following:

- type A – voivodships at very high level of water management investments,
- type B – voivodships at high level of water management investments,
- type C – voivodships at medium level of water management investments,
- type D –voivodships at low level of water management investments.

Groups of the voivodships are the following:

- group 1 – the voivodships with very high expenditure,
- group 2 – the voivodships with high expenditure,
- group 3 – the voivodships with medium expenditure,
- group 4 – the voivodships with low expenditure.

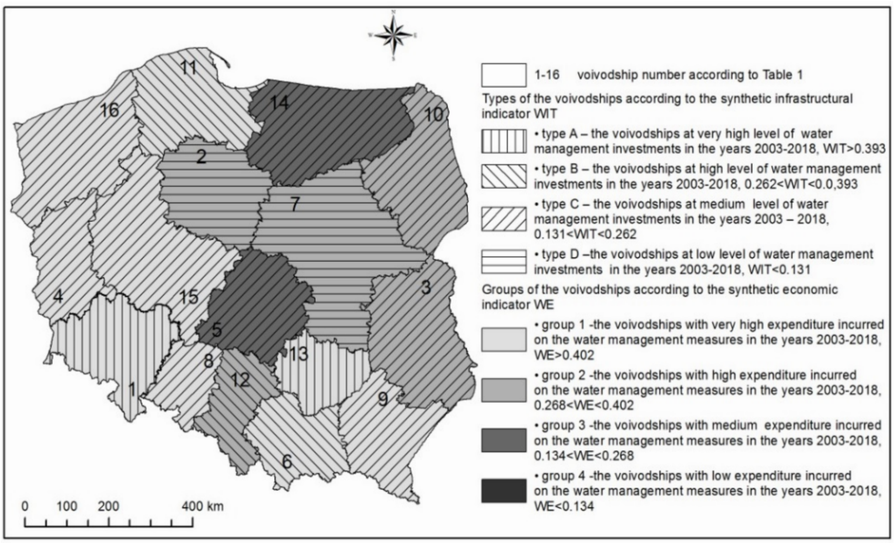

Fig. 3. Types and groups of the voivodships according to the implementation level and expenditures incurred on water management in the years 2003-2018 (Own study)

Table 5. Typology of voivodships according to implementation level and expenditures incurred on water management in the years 2003-2018 (Own study)

	Type A		Type B		Type C		Type D	
Group 1	Dolnośląskie Świętokrzyskie	2*	Małopolskie Pomorskie	2	Lubuskie, Opolskie, Podkarpackie, Wielkopolskie, Zachodniopomorskie	5		0
Group 2		0	Śląskie	1	Lubelskie. Podlaskie	2	Kujawsko-Pomorskie Mazowieckie	2
Group 3		0		0	Łódzkie. Warmińsko-Mazurskie	2		0
Group 4		0		0		0		0

* no. of the voivodships

According to the results presented above, there is a diversification of the voivodships with regard to technical flood protection measures undertaken in the analysed period. The obtained picture of the situation was compared with the results of the study made by Gołąb (2018) that concerns the issue of flood protection of Poland in 2007-2016. The abovementioned work contains the flood risk assessment of the voivodeships that was developed using the RCB method (2010, pp. 14-18) and flood risk maps (ISOK 2018). The results of the assessment are presented in Fig. 4.

The analysis of relation between the existing flood risk in the voivodships with the infrastructural and economic activities undertaken by the authorities in the analyzed period to prevent, reduce and counteract floods shows that in the group of the voivodships with a high flood risk, the best results were achieved in the Dolnośląskie Voivodship. Lower but still satisfactory effects were noted in the Pomorskie and Małopolskie Voivodships. In the remaining voivodeships of this group (Lubuskie, Opolskie, Podkarpackie, Zachodniopomorskie) the level of implementation of technical measures to minimize risks is medium, in spite of the very high financial expenditure. The Śląskie Voivodship is the only region with a high flood risk, slightly lower expenditure incurred on water management and high level of implemented technical investments.

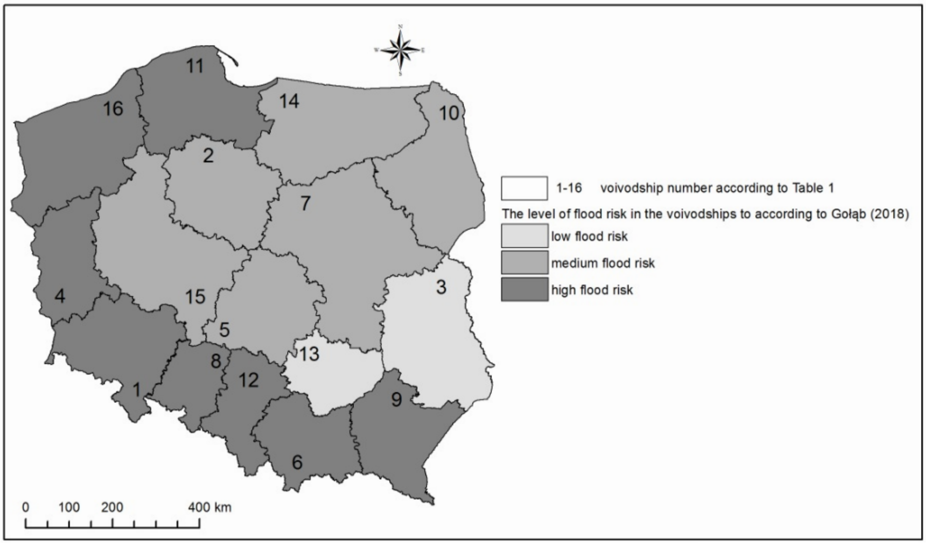

Fig. 4. The flood risk assessment in voivodships using RCB method (Own study based on Gołąb, 2018)

Quite large variation was observed in the case of regions assigned to a group of low flood risk. In Świętokrzyskie Voivodship the tasks were implemented at a high level and with very high expenditure. Whereas, in the Lubelskie Voivodship the achievements are medium despite high expenditure. The unfavorable situation occurs in the voivodeships of medium flood risk. This is particularly evident in case of the Kujawsko-Pomorskie and Mazowieckie Voivodeships, where significant financial expenditures were not reflected in investment activities in water management, especially compared to other voivodeships. The situation is slightly better in the Wielkopolskie Voivodship. Łódzkie, Warmińsko-Mazurskie and Podlaskie Voivodships were assessed at the medium level.

5. Summary

Flood protection has become one of the most important priorities of public safety and risk prevention in Poland. In accordance with the overall objective of the European Directive (Directive 2000) there is a strong need to limit flood losses which involves appropriate land-use management of flood risk areas. Taking into account the progressing climate change, and consequently the increasing number of extreme weather events, it is fair to assume that the endangered areas will grow larger.

Spatial development plans for each of the 16 voivodships place a strong emphasis on enhancement of security in the flood risk areas as well as on drought mitigation. These tasks are implemented mainly using technical methods, including e.g. the establishment and modernisation of flood prevention embankments or construction of retention reservoirs. Taking into account the dynamics of the investments and financial outlays on water management measures, the situation is satisfactory in 4 voivodships i.e. Dolnośląskie, Świętokrzyskie, Małopolskie and Pomorskie. The study also indicated voivodships where implementation of flood protection measures appears to be insufficient (Kujawsko-Pomorskie and Mazowieckie voivodships) or unsatisfactory (Lubelskie, Opolskie, Podkarpackie, Wielkopolskie, Zachodniopomorskie). Development plans for voivodships define three main measures applicable in flood loss mitigation: restriction of settlement development in high flood risk areas, enhancement of water retention and implementation of the broadly defined green-and-blue infrastructure. These goals are directly linked to the coordination of activities undertaken by various entities responsible for water management, flood prevention and spatial planning. These are State Water Holding Polish Waters as well as regional, sub regional and local administration authorities. Apart from flood risk mitigation implemented at the regional level, local spatial planning also plays a very important role, especially in terms of rational conversion of arable land into urbanized and built-up land (Mrozik & Przybyła 2013, Pawłat-Zawrzykraj & Podawca 2019, Podawca & Pawłat-Zawrzykraj 2019). Unfortunately, adverse situation associated with uncontrolled urbanisation, especially due to administrative decisions that allow to place new investments (particularly new settlements) in flood-risk areas and rising urban pressure on river valleys, do not correspond to the flood prevention objectives listed above. These particular problems were highlighted in the report of the Supreme Audit Office (Kowalewski 2018). The report pointed them out as symptoms of defective spatial planning system and inadequate spatial management. In Poland, the demand for residential areas is overestimated. In the country populated by 38.162 million people, the capacity of areas designated for settlements is about 60 million. Some of these areas are also designated in flood-risk areas (Kowalewski 2018). All of these factors demonstrate the need for stronger coordination of activities undertaken at various administrative levels, starting from national, through regional to local ones.

References

Alfieri, L., Feyen, L., Dottori, F. & Bianchi, A. (2015). Ensemble flood risk assessment in Europe under high end climate scenarios. *Global Environmental Change, 35*, 199-212. Retrieved from: https://doi.org/10.1016/j.gloenvcha.2015.09.004. (12.02.2021)

Bednarczyk, S., Jarzębińska, T., Mackiewicz, S. & Wołoszyn, E. (2006). *The vademecum of flood protection*. KZGW, Gdańsk. Retrieved from: https://docplayer.pl/4135934-Vademecum-ochrony-przeciwpowodziowej.html.(10.02.2021) (in Polish).

Blöschl, G., Hall, J., Viglione, A., Perdigão, R.A., Parajka, J., Merz, B. & Boháč, M. (2019). Changing climate both increases and decreases European river floods. *Nature, 573*(7772), 108-111.

Dubiel, B. (2015). Prevention and compensation the results of flood risk in the silesian municipalities. *Studia Ekonomiczne. Zeszyty Naukowe Uniwersytetu Ekonomicznego w Katowicach, 232*, 23-38 (in Polish).

Dumieński, G., Pasiecznik-Dominiak, A. & Tiukało, A. (2015). Social-economical assessment of polish communities to flood threat w: Kotowski, A., Piekarska K., Kaźmierczak B. (red). *Interdyscyplinarne Zagadnienia w Inżynierii i Ochronie Środowiska*. 100-125. Wrocław. Oficyna Wydawnicza Politechniki Wrocławskiej, Tom 6 (in Polish).

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy Retrieved from: https://eur-lex.europa.eu/eli/dir/2000/60/oj. (08.02.2021)

Dz. U. 2017. item 1566 as amended; The Act of 20 July 2017 - Water Law.

EC – European Commission 2015. Communication from the Commission to the European Parliament and the Council - The Water Framework Directive and the Floods Directive: Actions towards the ‘good status’ of EU water and to reduce flood risks, COM(2015) 120 final, European Commission, Brussels.

Gołąb, N., (2018). Flood Protection of Poland in the Years 2007-2016. Bezpieczeństwo i zagrożenia kryzysowe. Źródła i rodzaje zagrożeń bezpieczeństwa publicznego. *Przedsiębiorczość i Zarządzanie, 19,8*(2), 87-100 (in Polish).

ISOK, (2018). Flood hazard maps and flood risk maps. Retrieved from: https://wody.isok.gov.pl/imap_kzgw/ (01.02.2021).

Kowalewski, Z., (2006). Floods in Poland – types, occurence and flood control system. *Water-Environment-Rural Areas, 6,1*(16), Instytut Melioracji i Użytków Zielonych w Falentach, 207-220 (in Polish).

Kowalewski, A., Markowski, T. & Śleszyński, P. (2018). Studies on spatial chaos. *Studia KPZK PAN, 182*, Warszawa. Retrieved from: https://journals.pan.pl/skpzk/125267 (01.02.2021) (in Polish).

KPZK, (2011). *The National Spatial Development Concept 2030*. Retrieved from: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=wmp20120000252(08.02.2021)

KPZK, (2020). *The national crisis management plan*. Retrieved from: https://rcb.gov.pl/krajowy-plan-zarzadzania-kryzysowego (08.02.2021).

Kundzewicz, Z.W., Kanae, S., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L.M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R., Kron, W., Benito, G., Honda, Y., Takahashi, K. & Sherstyukov, B. (2014). Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal, 59*(1), 1-28.

Kundzewicz, Z.W., Pińskwar, I. & Brakenridge, G.R. (2018). Changes in river flood hazard in Europe: a review. *Hydrology Research 49*(2), 294-302. DOI: https://doi.org/10.2166/nh.2017.016. (12.02.2021)

LDB. Local Data Bank of Statistics in Poland. [online] https://bdl.stat.gov.pl/BDL/start (01.02.2021).

Map of Hydrographic Division of Poland (2013) prepared by the Department of Hydrography and Morphology of River Channels of the Institute of Meteorology and Water Management commissioned by the Minister of Environment and financed by the National Fund for Environmental Protection and Water Management – shp.

Mrozik, K., Przybyła, Cz. (2013). *Mała retencja w planowaniu przestrzennym*. Poznań: PRODRUK, 1-216.

Pawłat-Zawrzykraj, A., Podawca, K. (2019). Voivodeship classification in accordance with the directions of agricultural and forest lands repurposement, *Journal of Ecological Engineering. 20*(11), 100-108.

Piniewski, M., Okruszko, T. & Kundzewicz, Z.W. (2020). Impact of the climate change on the water resources of Poland. *Gospodarka Wodna. 3*, 19-25 (in Polish).

Podawca, K, Pawłat-Zawrzykraj, A. (2019). The agriculture and forestry lands level of changes in planning process as a sustainable development measure of municipalities located within national parks impact areas. *Journal of Ecological Engineering, 20*(8),153-164.

RCB (2010). Procedure of elaboration of sub-reports for the Report on the National Security. Retrieved from: http://rcb.gov.pl/wp-content/uploads/procedura.pdf (01.02.2021).

Staśko, S., Tarka, R. & Buczyński, S. (2017). Extreme weather events and their effect on the groundwater level (Examples from Lower Silesia). *Przegląd Geologiczny. 65,* 11(2), 1244-1248 (in Polish).

Suttie, D., Hussein, K. (2015). *Territorial approaches to Regional Development*. IFAD. p.5. Retrieved from: https://aer.eu/territorial-approaches/(10.02.2021).

Tarka, D., Olszewska, A.M. (2018). *Elements of Statics. Statistical description*. Białystok: Publishing House of the Białystok University of Technology, 1-213 (in Polish).

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Evaluation of Environmental Effects by LCA Method of Recycling of Depleted Electrical Insulators by Their Reuse for Cementitious Composites

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Abstract: This paper is devoted to the evaluation of the environmental effects by the LCA method of recycling electrical insulators through their secondary use in the production of cementitious composites as replacements for traditional mineral aggregates. For the proposed waste recycling system, using the life cycle assessment (LCA) method, the environmental impact of product manufacturing was evaluated at the level of several key factors. A cubic meter of concrete composite was used as the functional unit. The environmental impact assessment was carried out for recycled and traditional composite products. The work was carried out using the openLCA computer program. The obtained results confirmed that the replacement of traditional aggregate with recycled aggregate after its prior deposition and grinding at the concrete producer brings positive effect. Compared to the production of traditional composite, the production of composites with recycled aggregate showed a favorable parameter: the amount of depletion of natural resources. Other studied parameters such as climate change, air pollution and process toxicity ware almost the same for both types of composites. Taking into account the results obtained, it was concluded that this type of waste trading system can be implemented in industrial activities with a positive effect on the environment.

Keywords: recycling aggregates, aggregate substitutes,
life cycle assessment method, municipal mines, ceramic waste

1. Introduction

Electrical insulators are ceramic elements used for insulating overhead power lines. Due to the structure, insulators can be divided into insulators with solid structure – then they are called solid insulators and having empty space inside – so called hollow insulators. Insulators due to the place of application can be divided into linear, standing, cantilever, cap, lashing, etc. (Zegardło et al. 2016). The main part of the insulator is made of fine ceramic produced from white clays. Some insulators have an integral steel element connected to the ceramic part. Fig. 1 shows the used electrical insulators recovered during power line rehabilitation.

Electrical insulators, although their main function is to insulate electrical conductors installed in power systems, they also carry their weight and the weight of electrical cables. For this reason, they are made from high quality materials that are both durable and resistant to environmental factors. Insensitivity to high temperature, repeated freezing and thawing processes and high strength parameters are provided by high quality ceramics. However, surveys conducted among entrepreneurs have shown that despite the longevity of ceramic elements themselves, the service life of electrical insulators is about 30 years. After this period, with the comprehensive replacement of overhead power lines, electrical insulators are replaced with new ones and at this point they become waste (Zegardło 2020). Surveys carried out in companies carrying out repair works have proved that insulators obtained in this way end up in landfills of electrical companies. They are collected from these places by specialized recycling companies, which charge the depositor for their service.

Fig. 1. Exhausted electrical insulators obtained during power line repair

Surveys conducted among entrepreneurs indicate that it would be much more beneficial to dispose of waste free of charge in places designated for that purpose. In such places, producers of recycled materials, for whom waste would be a substrate in production, would have a chance to acquire and reuse it free of charge. However, the current state of trade in such materials is very poor. The statements of the representatives of local municipal enterprises prove that currently all kinds of ceramic materials are mixed with construction debris and used only as spacers to strengthen heaps on landfills. In the opinion of the author of this study, this method is extremely inefficient. When considering the possibilities of recycling ceramic materials, several criteria should be taken into account. Depositing such waste on landfills is not only a devastation of natural mineral resources, from which ceramic products were created, but also a waste of energy, which was used to fire them. This energy gave the plastic clay its compact, weather-resistant and durable structure. Summarizing the above, it was concluded that the current system of used electrical insulators is not correct. This view is unambiguously confirmed by analyses of the possibilities of secondary use of technical ceramics presented in numerous research works.

As evidenced by published studies, fine ceramic waste has a wide range of applications, including in the construction industry. They can be used both for mundane road base construction (Ogrodnik & Zegardło 2016) and for sophisticated applications as aggregates for special concretes.

For example, the paper (Halicka et al. 2013) presents the possibility of using noble ceramic waste from sanitary material waste to produce special concretes resistant to abrasion and high temperature resistance. In the work (Zegardło et al. 2016) the possibility of using the same waste in ultra-high strength cement concretes was presented. The work (Ogrodnik et al. 2017) presents research results that prove that waste sanitary ceramics are excellent for composing composites with their participation with high resistance to chemically aggressive environments. In the works (Zegardło et al. 2018) and (Ogrodnik et al. 2017) the authors proved that composites containing cullet can be used to work in fire conditions, and their ability to accumulate heat in their interior can make them useful as accumulators of thermal energy.

As for the electrical insulators themselves, there are also scientific papers confirming their use in cement composites

In (Senthamarai & Devadas 2005), the authors present a study in which they used crushed electrical ceramic insulators as a substitute for natural stone ballast. Portland cement, traditional stone aggregate, aggregate obtained from crushed electrical insulators and water were used to prepare concrete. Based on the study, the authors concluded that the properties of concretes prepared using aggregate from crushed electrical insulators did not differ by more than a few percent from those of concretes prepared using traditional aggregates. In (Senthamarai et al. 2011), the authors compared concretes prepared using crushed ceramic insulator aggregate with traditional concretes in terms of water absorption, pore volume and chloride diffusion with varying *w/c* ratio. The results of the density and strength of the concretes showed that there are no clear differences between the compared recycled and traditional composites, and the mentioned characteristics differ more due to the water-cement ratio than due to the type of aggregate used.

The author of the present paper presents in (Zegardło et al. 2016) the results of the study of concretes, in which the only aggregate used in the composites were crushed electrical insulators. In this research, for the preparation of concrete composites of high classes, high value cement CEM I 42.5N – SR 3/NA and admixture – superplasticizer ISOFLEX 7130 were used. The results showed that the composite containing waste insulators had a very high average compressive strength of 86.40 MPa and can be a substitute for high value aggregate such as basalt, for which the tested average compressive strength using the same other components of concrete was 76.50MPa.

In (Xu, Nana et al. 2015), the authors presented the preparation and properties of porous ceramic aggregates produced using electrical insulating waste. The effects of sintering temperature and waste content on aggregate properties such as bulk density, apparent porosity, total porosity and cold crushing strength were investigated. The main conclusion of this work was that insulator waste can also be used for this type of application.

Another application of these wastes was proposed by the authors of (Liu, Zang et al. 2015) who produced glass-ceramic foams with high porosity and high strength using electroinsulator waste and red slurry waste as raw materials. The results showed that as the content of electroinsulator waste increased, various chemical components of the waste promoted the formation of a liquid phase whose composition transformed from a Ca-Al-Si-O system to an Al-Si-O glass system, and thus caused changes in the pore structure of glass-ceramic foams.

Paper (Higashiyama, Hiroshi et al. 2012) presents the results of an experimental study: compressive strength and resistance to chloride ion ingress of mortars made from fine aggregates of ceramic waste. In this study, ceramic waste from electrical insulators supplied by a Japanese power company was crushed and ground to produce fine aggregate for mortars. It was confirmed that partial replacement of cement with waste ceramic powder up to 20% was effective in terms of compressive strength and resistance to chloride ion ingress.

The following work (Sabarinathan, Annamalai et al. 2019) discusses the effect of waste fillers – inorganic electrical insulators on the properties of glass fiber reinforced epoxy composite. The waste fillers of electrical insulators were uniformly mixed with the resin using ultrasonic technique. Composites with different filler contents (0, 5, 10, 20%) and 20% glass fiber were produced by hand lay-up method. The physical, mechanical, absorption, thermal and dynamic properties of the composites were studied. At the end of the experimental work, the possibility of reprocessing used electrical insulators as cheap reinforcement in polymer composites was indicated.

The author of the paper (Salam 2018) also notes that electrical porcelain insulators made from refractory materials have to undergo rigorous testing before final verification of acceptance into service. This also results in a large amount of waste available in manufacturing plants. In the present study, porcelain waste was crushed and ground and then used as a partial substitute for sand in cement mortar for paving. The results showed that this substitution had only a moderate effect on most of the properties studied, while it contributed to the mechanical strength of the samples.

The aim of the work presented in (Geraldo, Souza et al. 2018) was to study some characteristics of building elements made of waste red ceramics and porcelain, which in the case of this work came from decommissioned electrical insulators. The compressive and flexural strength, porosity and microstructure of the recycled masonry materials were evaluated. Compressive strength results ranged from 12.3 to 33.9 MPa, which is above the minimum required by Brazilian standards for building elements (≥ 2.5 MPa). The low water-to-solid ratio and the uniaxial loading pressure before the setting time contributed to the reduction of porosity, which was evident in the dense microstructure. The results obtained indicate that the aforementioned wastes can be successfully used as filler in the production of masonry elements.

The results of all the studies described above led the author of this paper to propose a new system of electro-insulation waste circulation. The system allocation was carried out for a medium size town located in the eastern part of Poland with 70 000 inhabitants. The proposal of the system was based on field inspections, questionnaires to entrepreneurs acquiring waste, representatives of municipal plants and producers of concrete composites. The field inspections and materials in the form of spatial development plans of the cities have shown that both electric companies acquiring waste and companies producing concrete composites are in close vicinity due to the fact that they are located in the same industrial districts of the cities. Due to the fact that landfills and selective waste collection points are often located outside cities, it was decided that waste deposition should take place directly at the producer of concrete composites. Such a procedure not only reduced the transport of waste by the depositor to the landfill but also the costs of waste deposition. This type of solution was also beneficial for the composite producer. Despite the necessity of adjusting the waste in the crushing process, he obtained a substrate for his production free of charge, omitting the necessity of transporting the aggregate from the mine located about 30 km away, as was the case with traditional aggregates.

For the proposed system, the assessment of the influence of the adopted solutions on the environment was made with the use of the LCA (Life Cycle Assessment) method. The functional unit was assumed to be 1 m^3 of concrete composite. The assessment of the influence on the environment has been carried out in relation to the products with recycled and traditional composite. The study was carried out using the openLCA computer program.

2. Research methodology

The Life Cycle Assessment (LCA) method (Kowalski et al. 2007) is a technique in the field of research systems, whose aim is, among others, to assess the impact of various processes on the environment, and in particular to evaluate potential threats that may occur.

The main idea of this method is not only to determine the final result for the tested process, but also to estimate and evaluate the effects of the whole process for many environmental hazard criteria. The test method is defined in several standards (PN-EN ISO 14040, PN-EN ISO 14041, PN-EN ISO 14042, PN-EN ISO 14043). ISO 14040 defines the environmental impact assessment methodology, indicating four different phases of the study. The first phase is the aim and scope phase, which sets the context for the study. The second phase is the data set analysis (LCI), which determines the raw materials entering the system and identifies the emissions and wastes entering the environment. The third phase is the impact assessment phase, in which potential environmental impacts are identified. The fourth and final phase is the interpretation phase where the information from the results is evaluated (ISO 14040: 2006).

For the research and analysis presented in this paper, the computer software OpenLCA 1.10.3 was used. OpenLCA is a free open source software whose main purpose is to support sustainable development. It allows performing calculations as well as detailed analysis with identification of all factors.

Following the guidelines of the standards in the first stage of the research work described in this paper in the purpose and scope phase, which sets the context for the study, it was determined that the environmental implications would be carried out for the city for which the waste trading system presented above was developed. The system allocation was conducted for a medium-sized city located in the eastern part of Poland with a population of 70,000. In this city, composite manufacturing plants and electrical repair companies are located in close proximity to each other. In suburban areas within 30 km, there are deposits of sand and gravel from where concrete composite producers supply aggregates. It was established that the aim of the analysis would be to compare the environmental impact of the production system of two composites: a traditional sand and gravel one and a recycling one containing only ceramic waste from crushed electrical insulators. The functional unit was the production of one cubic meter of each composite. The time range of the study was from the production of the substrates to the production of the composite without building the composite into the structure and demolishing the objects that were made of it. In modeling the data, it was assumed that the properties of the composites produced would be the same. Both composites would have a compressive strength of 25MPa and this would correspond to composites that are most commonly produced in concrete batching plants. It was also assumed that all the components of the composites would be the same except for the aggregate itself. Fig. 1 and Fig. 2 show the system boundaries, processes and materials for the conventional and recycled concrete production system. Table 1 shows the composition of the concrete mixtures.

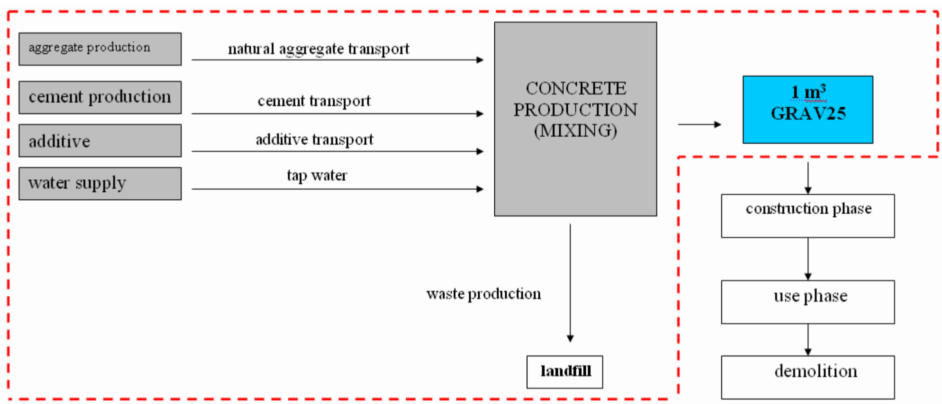

Fig. 2. System boundaries, processes and materials for conventional concrete production system

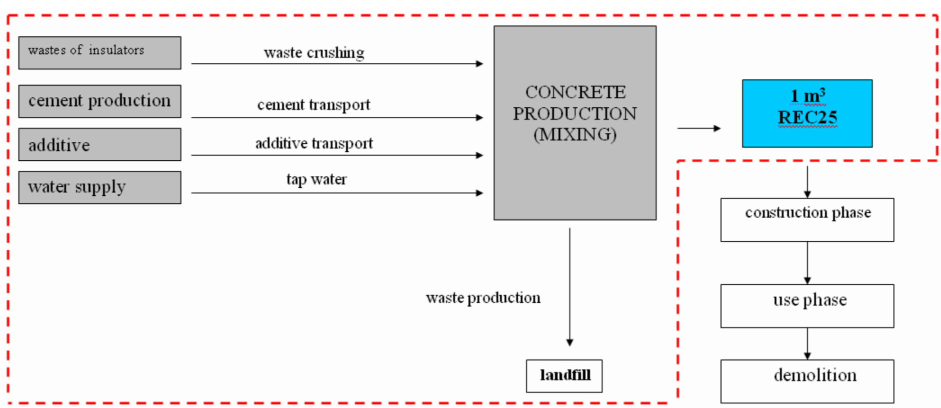

Fig. 3. System boundaries, processes and materials for recycled concrete production system

The second phase of the project was to analyze the dataset to determine the raw materials going into the system and identify the emissions and waste going into the environment. This phase of the research used the publicly available OzLCI_2019 database to determine all the raw materials needed to produce the traditional composite, designated GRAV25, and the process output. All the basic raw materials that are also used in the production of concrete elements, such as the minerals from which cement is made, the energy resources required for its production and consumption by the machines of the concrete batching plants, the fuels used in transportation, etc., were considered for the calculation.

Table 1. Composition of concrete mixes

Lp.	Substrates in 1dm^3 of concrete	GRAV25	REC25
1	Portland cement	240 kg	240 kg
2	Microsilica	24 kg	24 kg
3	Sand 0-2 mm	790 kg	–
4	Gravel 2-16 mm	1102 kg	–
5	Ceramic wastes 0-2 mm	–	790 kg
6	Ceramic wastes 2-16 mm	–	1102 kg
7	Superplasticizer	4.8 kg	4.8 kg
8	Water	198 kg	198 kg

Modelling the input and output data set for the recycled composite, named REC25, in the first step an amendment was made to the process used in the production of the traditional composite to account for the reduction in the use of natural aggregates at the expense of the use of waste. Similar changes were made to account for the reduction in factors caused by the transport of natural aggregates. The NEEDS_2018 database was used for this purpose. It also takes into account the need to adapt the recycling aggregate consisting of crushing and separation of steel elements from waste.

The LCI datasets available in databases are intended for use in long-term environmental technology assessment. The data in the databases have been developed for a number of different time scenarios. The 2020 scenario, assuming the Polish system allocation, was used in this study.

In the third stage of research work, an impact assessment was carried out to identify potential environmental impacts. For this purpose, two methods were applied depending on the examined parameter. The first was the method of the Leiden University Institute of Environmental Engineering (CML). This method assessed the impact of composites production on climate change, which was expressed in kilograms of CO_2 equivalent released into the environment. Another parameter assessed by this method was the amount of energy resource depletion expressed in MJ units. The last parameter examined by this method was human toxicity expressed in units of kg of 1,4-dichlorobenzene equivalent. The second method of environmental impact assessment was the Ecological Scarcity Method (ESM). This method assessed the impact on the depletion of natural resources, which was expressed in units of UBP, i.e. units of ecological scarcity. The total air pollutant emissions were assessed using the same method.

The fourth and final phase of the research paper was the interpretation phase, in which the information obtained from the results was evaluated.

3. Findings and its analysis

A summary of the results of the conducted tests is included in Table 2.

Table 2. Summary of test results

Test method	Test value	Unit	The result obtained for production GRAV 25	The result obtained for production REC 25	Ddifference [%]
CML	Climate change GWP 100	kg CO_2 eq.	507.26	507.15	0.2
CML	Depletion of resources	MJ	1519.84	1487.15	2.15
CML	Human toxicity	kg 1,4-dichloro-benzene eq.	8.095	8.095	0
ESM	Natural resources	UBP	84.82	58.00	31
ESM	Emission to air	UBP	2.528	2.527	0.04

The analysis of the results presented above proves that the parameters evaluated for the recycled REC 25 composite were in most cases more beneficial than those calculated for the traditional GRAV 25 composite. The impact of the composite production on the climate change, expressed in kilograms of CO_2 equivalent introduced to the environment, was only slightly lower for the recycled REC 25 composite than for the traditional GRAV 25 composite. The difference was only 0.2%. The next parameter assessed, the amount of energy loss expressed in MJ units, was also more favorable for the recycled composite. This time the value difference was slightly higher and amounted to 2.15%. In the case of the calculated values in the aspect of toxicity to man expressed in units of kg of 1,4-dichlorobenzene equivalent, no differences were found between the production of the traditional GRAV 25 composite and the recycled REC 25 composite. The biggest difference in the calculated results was observed in the aspect of depletion of natural resources, which was expressed in UBP units, i.e.

units of ecological deficit. In this case, the value assessed for the production of REC 25 recycling composite was 58.00 UBP and was as much as 31% lower than for the traditional GRAV 25 composite, for which the value was 84.82 UBP. Similarly, the total air emissions also expressed in UBP units were lower for the REC 25 recycling composite, but this value was only 0.04% lower.

Analyzing the above values, it is noted that the greatest environmental benefit was recorded for the depletion of natural resources. Aggregate in the concrete space occupies the largest volume, which is 60% for some composites. By reducing the proportion of natural aggregate in the production of composites in favor of recyclate, the natural resources of minerals drawn from natural deposits are conserved. This is in line with the policy of sustainable development, which consists in leaving raw materials in deposits also for future generations. Especially since in many areas natural aggregate resources have already been depleted or are shrinking rapidly.

The other volumes evaluated are not significantly different. Material and energy resources for the transportation of traditional aggregates are similar to those involved in the processes of adaptation of recyclates. This is due to the negative environmental impact of the waste adaptation process for the production of composites. Their crushing takes place in combustion crushers, whose crushing elements are temporarily replaced. The comminuting process reduces energy resources, releases unfavorable toxic compounds into the atmosphere along with the exhaust gases, and reduces natural resources through the necessary replacement of crushing machine elements. In the results of the analyses carried out, it was noted that the parameters of the adverse environmental impact of the use of mineral aggregates, apart from the depletion of resources, are similar to those caused by the process of adaptation and use of recyclates. In the case of waste trading, in which it would be additionally transported from landfills to composite producers, the environmental impact of the use of recyclates would be more adverse than the extraction of natural aggregates. On this basis, it can be concluded that the only valid approach is to deposit aggregates at the composites production site.

4. Conclusions

Taking into account the positive factor of using recyclates in the proposed system – reduction of natural resources, it should be remembered that this parameter positively influences the environment on several levels. Apart from saving the minerals in the deposits, the amount of post-mining excavations is reduced and disturbance of the groundwater table is limited. Leaving the insulators with the aggregate producer and using them as mineral substrates also reduces the amount of waste deposited in landfills. On a macro scale, such action reduces the area of landfills, which has a positive impact on the natural landscape.

Considering the results of the evaluation of the ecological effects of recycling of waste electrical insulators, the implementation of the described systems is worth recommending for implementation in industrial operations.

Research also shows that a proper system of circulation of this waste has a positive impact on the environment.

References

Environmental Management-Life Cycle Assessment-Principles and Framework; ISO 14040: 2006; ISO: International Organization for Standardization Geneva, Switzerland.

Geraldo, R. H., Souza, J. D., Campos, S. C., Fernandes, L. F. & Camarini, G. (2018). Pressured recycled gypsum plaster and wastes: Characteristics of eco-friendly building components. *Construction and Building Materials, 191*, 136-144.

Halicka, A., Ogrodnik, P., Zegardło, B. (2013). Using ceramic sanitary ware waste as concrete aggregate. *Construction and Building Materials, 48*, 295-305.

Higashiyama, H., Yagishita, F., Sano, M. & Takahashi, O. (2012). Compressive strength and resistance to chloride penetration of mortars using ceramic waste as fine aggregate. *Construction and Building Materials, 26*(1), 96-101.

Kowalski, Z., Kulczycka, J., Góralczyk, M., (2007). *Ecological assessment of the life cycle of manufacturing processes (LCA)*, PWN, Warsaw (in Polisch).

Liu, T., Zhang, J., Wu, J., Liu, J., Li, C., Ning, T. ... & Lu, A. (2019). The utilization of electrical insulators waste and red mud for fabrication of partially vitrified ceramic materials with high porosity and high strength. *Journal of cleaner production, 223*, 790-800.

Ogrodnik, P., Zegardło, B. (2016). Analysis of possibilities of using waste ceramic substances in building and engineering structures of transport construction. *TTS, 12*, 1732-1738.

Ogrodnik, P., Zegardło, B., Radzikowska, M. (2017). Use of post-production sanitary ceramic waste as a filler for cement composites with high chemical resistance. *Chemical Industry, 96*(5), 1100-1104.

Ogrodnik, P., Zegardło, B., Szeląg, M. (2017). The use of heat-resistant concrete made with ceramic sanitary ware waste for a thermal energy storage. *Applied Sciences, 7*(12), 1-16.

PN-EN ISO 14040 Environmental management – Life cycle assessment – Principles and structure, PKN, Warsaw 2000 (in Polisch).

PN-EN ISO 14041 Environmental management – Life cycle assessment – Objective and scope definition and set analysis, PKN, Warsaw 2000 (in Polisch).

PN-EN ISO 14042 Environmental management – Life cycle assessment – Impact assessment, PKN, Warsaw 2000 (in Polisch).

PN-EN ISO 14043 Environmental management – Life cycle assessment – Interpretation of life cycle, PKN, Warsaw 2000 (in Polisch).

Sabarinathan, P., Annamalai, V. E. & Rajkumar, K. (2019). Evaluation of thermal stability and damping behavior of electrical insulator waste reinforced thermoset polymer composite. Proceedings of the Institution of Mechanical Engineers, Part C: *Journal of Mechanical Engineering Science, 233*(10), 3603-3618.

Salam, N. A. (2018). Usage of Porcelain Insulators Wastes in the Preparation of Cement Based Building Units. *Matéria (Rio de Janeiro), 18*, 1549-1562.

Senthamarai, R.M., Devadas, M. (2005). Concrete with ceramic waste aggregate. *Cement and Concrete Composites, 27,* 910-913.

Senthamarai, RM., Devadas, M., Manoharan, P., Gobinath D. (2011). Concrete made from ceramic industry waste: Durability propertis. *Construction and Building Materials, 25*, 2413-2419.

Xu, N., Li, S., Li, Y., Xue, Z., Yuan, L., Zhang, J. & Wang, L. (2015). Preparation and properties of porous ceramic aggregates using electrical insulators waste. Ceramics International, 41(4), 5807-5811

Zegardło, B. (2020). Recycling of Electrical Insulators, by their Secondary Use, as Substitutes for Mineral Aggregates in Artificial Composites Based on Orthophthalic Polyester Resins. *Journal of Ecological Engineering, 21*(7), 241-248.

Zegardło, B., Szeląg, M., Ogrodnik, P. (2016). Ultra-high strength concrete made with recycled aggregate from sanitary ceramic wastes – The method of production and the interfacial transition zone. *Construction and Building Materials, 122*, 736-742.

Zegardło, B., Szeląg, M., Ogrodnik, P. (2018). Concrete resistant to spalling made with recycled aggregate from sanitary ceramic wastes – The effect of moisture and porosity on destructive processes occurring in fire conditions. *Construction and Building Materials, 173*, 58-68.

Zegardło, B., Ogrodnik, P., Woliński, P. (2016). Attempt to use waste electrical insulators as aggregate for concrete – own research. *Electrotechnical News, 5*, 43-44.

Zegardło, B., Ogrodnik, P., Woliński P. (2016). Attempt to use waste electrical insulators as aggregate for concrete. *Electrotechnical News, 4*, 6-7.

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Analysis of the Influence of the Application of Effective Microorganisms on the Dynamics of Spring Wheat Emergence

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Abstract: Deterioration of the natural environment as a result of violation of its natural structures and self-regulatory mechanisms causes an urgent need to replace chemicals with effective and multidirectional biopreparations. Reduction of the amount of chemicals used in agriculture becomes possible through the use of Effective Microorganisms. This will reduce the burden on the environment. Agriculture that uses EM technology can count on help with germination rates; emergence uniformity; and crop yields, for example. EM formulations contain a mixture of different coexisting microorganisms. The following paper presents the results of own research on the use of Effective Microorganisms in seed dressing of spring wheat. It was shown that the microbial preparation EM Naturally Active affects the increase of wheat seed germination dynamics.

Keywords: Effective Microorganisms, wheat

1. Introduction

Recently, the state of the natural environment has attracted much attention. This is due to the unconscious disruption of biological homeostasis through human activities (Szymanek et al. 2020). Significant amounts of pesticides used in agriculture that persist in the soil can have long-term effects on the survival and functioning of Rhizobia (Ahemad & Khan 2012). Reducing the amount of chemicals used, according to Janas (2009), is possible through the use of a microbial preparation that is becoming increasingly popular in Poland and the world (Western Europe, Japan, USA, Brazil) Effective Microorganisms (Kosicka et al. 2015).

Effective Microorganisms are formed by selected and properly chosen smallest organisms on Earth. A composition of more than 80 different strains of aerobic and anaerobic microorganisms such as photosynthetic bacteria, lactic fermentation bacteria, *Actinobacteria*, yeast and fungi. The Effective Microorganisms technology was developed by Professor of Horticulture Teruo Higa of the Ryukyus University Agricultural Academy in Okinawa, Japan (Armand et al. 2021, Kolasa-Więcek 2010, Schulz et al. 2013).

The last several years has shown an increasing tendency towards the use of biopreparations with substances of natural origin. The aim of this action is to improve the health of plants, to allow them to better uptake nutrients and, as a result, to obtain an increased yield (Jilani et al. 2010, Kumar & Kumar 2019, Gao et al. 2020).

An important group of EMs are lactic acid bacteria that produce various metabolites, mainly in the form of bacteriocins, which have inhibitory effects on microbial growth (Chmielowski et al. 2020). Yeast produces many biologically active substances such as amino acids and polysaccharides that nourish other microorganisms. Phototrophic bacteria play a major role in the nitrogen cycle and carbon cycle. The use of EM in the soil or plant ecosystem can improve soil quality and health. It also stimulates plant growth, increasing yields and thus improving crop quality (SI 2016).

Effective Microorganisms technology is based on inoculating the soil with a mixture of beneficial microorganisms to create a favorable environment for plant growth and development (Olle & Williams 2015). When injected into the soil, they exert beneficial effects on plants by increasing the assimilation of nutrients that are difficult for plants to access on their own, reducing decay processes, improving humus-forming capacity, eliminating pathogens, and affecting growth and crop quality (Kosicka, et al. 2015).

The range of action of EM preparations is wide due to the fact that they have the ability to increase the biological activity of soils thus as a result, decay processes will be stopped. They can contribute to improving soil structure and fertility by dissolving certain compounds that are not available in non-dissolved form to plants. Their effect can also be seen by improving the physical and chemical properties of soils (Piskier 2007). EMs have the ability to break down organic matter and synthesize nutrient substances needed for plant growth (Devi & Manimaran 2012).

Seed quality is among the key factors that determine plant development and yield. Pre-sowing treatment of seeds is aimed at improving their germination capacity as well as seedling vigor. With this treatment, young plants will gain greater resistance to environmental stress and thus faster development and greater plant vigor will be noticed (Rhodes & McCarl 2020, Seran & Suthamathy 2013). Seed treatment before sowing affects germination rate and seedling growth, which in turn determines higher yield (Dziwulska-Hunek et al. 2020, Siyami et al. (2018).

The mechanism of action of Effective Microorganisms is a mapping of natural processes occurring in nature. Microorganisms are able to function in vast range of conditions such as a slurry tank, in sewage sludge remaining after wastewater treatment, in water and in soil. Those numerous microorganisms possess various enzymes that give them the ability to break down non-organic matter. They also have the ability to produce substances that prevent the functioning of fungal pathogens. Particular groups of microorganisms form certain compounds that constitute food for the others. In this way, the necessary food for continued growth is provided. Effective Microorganisms, while having constant access to food, are secreting vitamins, antioxidants and organic acids, contributing to changes in soil morphology, inhibiting the development of pathogenic processes (Janas 2009).

A composition of EM cultures has found its way into plant and animal production and into the regeneration of soils where their natural biological barrier has been breached. Agriculture using Effective Microorganisms can count on support in as the intensity of germination and yield. These preparations can improve the assimilability of nutrients in the deeper soil layers and influence the intensity of photosynthesis (Faltyn & Miszkieło 2008).

Since composing a mixture of Effective Microorganisms and their practical application, the importance of EM in various areas of the economy has increased rapidly. They have found their use in agriculture, horticulture, animal husbandry, medicine, industry, construction, food processing and environmental protection. Despite the advancing technology, there is still a conviction about the undiscovered possibilities of these organisms (Paśmionka & Kotarba 2015).

2. Materials and methods

The research was conducted in the Department of Technology in Environmental Engineering, Bialystok University of Technology in 2020. The aim of the research was to obtain information on the use of Effective Microorganisms and to present the effectiveness of EM Naturally Active preparation in the cultivation of spring wheat. The research was also aimed at determining the effect of the Naturally Active EM dose on the seed germination dynamics and the impact of seed treatment time on their ability to germinate depending on the applied EM concentration.

The research was conducted on sterile Petri dishes in two repetitions. Grains of spring wheat cultivar FEELING intended for analysis were sieved on strainers with diameter of 2.5-2.8 mm. The EM Naturally Active preparation used for the research contains a rich complex of alive, active microorganisms, including lactic acid bacteria, phototrophic bacteria, actinomycetes, yeasts and fungi, as well as nitrobacteria. This preparation comes from the company Greenland Technologia EM Sp. z o.o., which since 2008 has been producing and selling products based on the original Japanese technology of Effective Microorganisms, which are widely used in agriculture and horticulture and in biological environmental purification. EM Naturally Active has been registered as an organic fertilizer by the decision of the Minister of Agriculture and Rural Development No. 281/11 of March 31, 2011.

In the first test, appropriate dilutions of EM Naturally Active were prepared: 0.1%, 1%, 5%, and then the grain was soaked in them for 30 min, 1 h, and 3 h. Blotting paper was placed on sterile Petri dishes as a substrate. Then 20 grains were placed on each Petri dish, 5 grains per each quadrant. The grains on the plates were watered with water according to their requirement.

In the second test, appropriate dilutions of EM Naturally Active preparation of 0.5%, 1%, 5%, 15%, 30%, 50% were prepared and the grains were soaked in them for about 30 minutes. Blotting paper was placed on sterile Petri dishes as a substrate. Then 20 grains were placed on each of the Petri dishes, 5 grains for each quarter. The grain on the plates in the control trial was watered with water. In the test trials, the grains were watered with six different concentrations of EM Naturally Active solution according to their requirement.

Both dish experiments were conducted at 20°C and no light until the third day, and then the access to light for 12/12h day/night was provided. The dynamics of wheat emergence started being recorded from the third day after experiment commencement until the end of germination (Faltyn & Miszkieło 2008).

Experimental setup:

Object 1: grain not treated with EM solution;
Object 2: grain was treated for 30 minutes with 0.1% EM solution,
Object 3: grain was treated for 30 minutes with 1% EM solution,
Object 4: grain was treated for 30 minutes with 5% EM solution,
Object 5: grain was treated for 1 hour with 0.1% EM solution,
Object 6: grain was treated for 1 hour with 1% EM solution,
Object 7: grain was treated for 1 hour with a 5% EM solution,
Object 8: grain was treated for 3 hours with 0.1% EM solution,
Object 9: grain was treated for 3 hours with 1% EM solution,
Object 10: grain was treated for 3 hours with 5% EM solution,
Object 11: grain watered only with water,
Object 12: grain was watered with 0.5% EM solution,
Object 13: grain was watered with 1% EM solution,
Object 14: grain was watered with 5% EM solution,
Object 15: grain was watered with 15% EM solution,
Object 16: grain was watered with 30% EM solution,
Object 17: grain was watered with 50% EM solution.

3. Results and disscusion

Observations of wheat emergence dynamics are placed on individual graphs. The experiment was conducted for seven days. At that time the end of wheat germination was observed.

Treating grains with 0.1% EM solution for 3 hours resulted in 85% of grain emergence as early as day 3 of the dish test, and this contributed to the fastest germination of wheat compared to the control and 30 minutes, 1 hour grain treatment (Fig. 1).

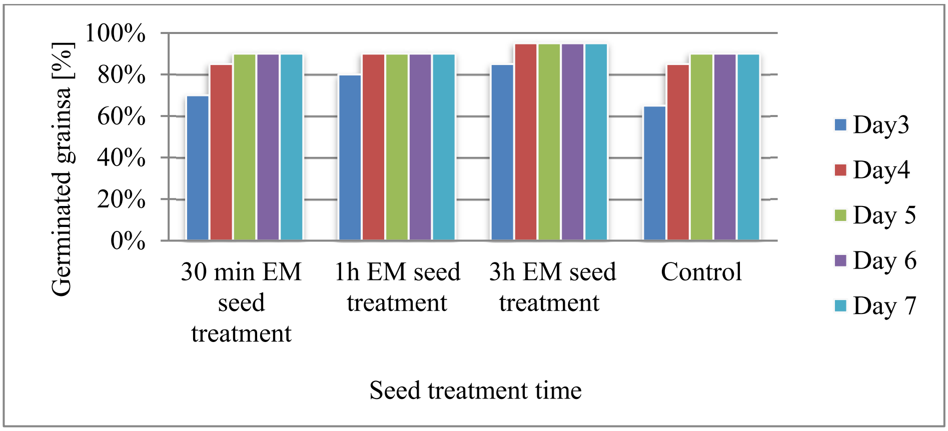

Fig. 1. A graph containing percentage comparison of germination strength results for grain dressed with 0.1% EM Natural Active solution

Treating grains with 1% EM solution in 3 hours time resulted in 85% of germinated grains as early as on the 3rd day from the day of the dish test, and this contributed to the fastest germination of wheat in comparison to the control and 30 minutes, 1 hour dressing of grains (Fig. 2).

In the case of 0.1% and, 1% concentration of EM preparation, the 30 minutes grain treatment time on the third day of observation is manifested by fewer germinated kernels than after 3 hours of treatment. On the third day of observation, grains treated with 0.1% and, 1% EM solution during 1 hour germinated fewer grains than after 3 hours of seed treatment.

Treating grain with 5% EM solution during 1 hour resulted in 75% of grain emergence already on the 3rd day after the plate test, and this contributed to the fastest germination of wheat compared to the control and 30 minutes, 3 hours grain treatment (Fig. 3).

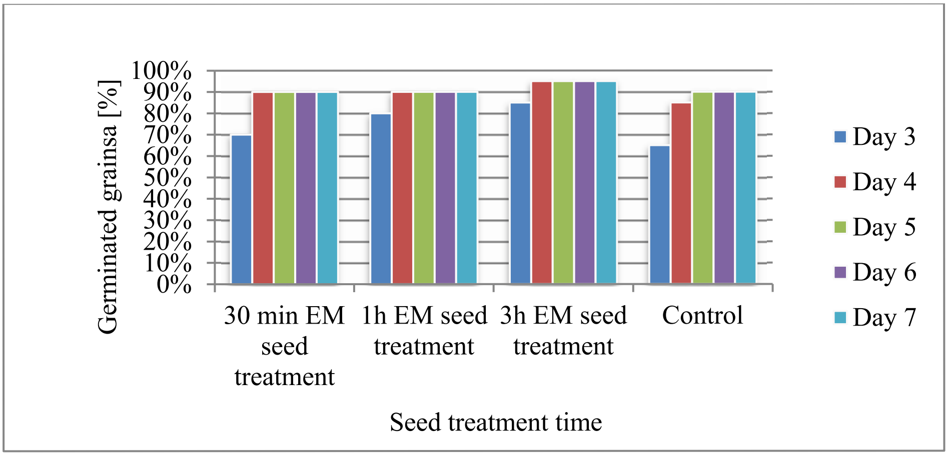

Fig. 2. A graph containing percentage comparison of germination strength results for grain dressed with 1% EM Natural Active solution

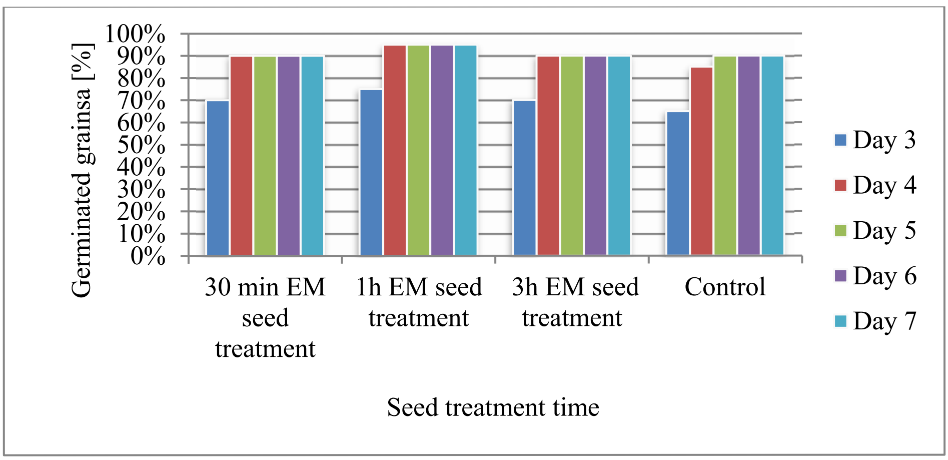

Fig. 3. A graph containing percentage comparison of germination strength results for grain dressed with 5% EM Natural Active solution

On the third day of observation, the seeds treated with 5% EM solution germinated in greater number in 1 hour than after 30 minutes and 3 hours of treatment

On the third day of observation, seed treatment with 0.1%, 1% and 5% concentrations accelerated kernel germination compared to the control. In the lower concentrations of 0.1%, 1% of EM preparation, a longer time of seed treatment is needed, while at the concentration of 5% the most seeds germinated after treatment in 1 hour.

On the seventh day, 95% wheat emergence was observed after seed treatment with 0.1%, 1% EM solution for 3 hours and 5% EM solution for 1 hour.

On the seventh day of observation the control germinated 90% which indicates that treating seeds with 0.1%, 1% EM solution at 3 hours and with 5% EM solution at 1 hour accelerates the increase in germination intensity and increases the number of germinated kernels.

Siqueira (1993) showed significant differences in germination percentage of EM treated pea, beet, bell pepper, tomato, cucumber, maize, carrot, bean and burdock grains. The application of EM increased the germination capacity of the seeds and accelerated their growth.

Faltyn and Miszkieło (2008) observed that the best emergence dynamics was after application of a standard dose of EM. Increasing the concentration of this mixture from 1.5 l to 3 l caused a decrease in the percentage of germinated kernels both in the initial and final germination period. Comparing the control treatment with water alone to the standard dose of EM-A, the percentage of germinated kernels was 10 percentage points lower.

Watering the kernels with 0.5% and 1% solutions of EM Naturally Active will result in a higher number of germinated kernels compared to the control. Watering with a 5% solution of EM Naturally Active will result in the same number of germinated kernels as the control. Watering with a 15% and 30% solution of EM Naturally Active reduced the number of germinated kernels compared to the control, while a 50% solution of EM Naturally Active inhibited the germination and development of the kernels.

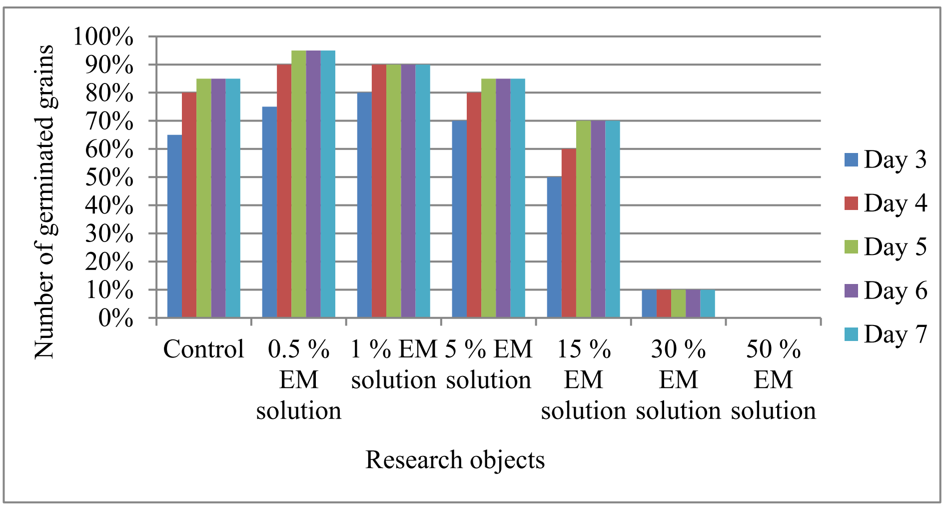

Fig. 4. Graph showing summary of spring wheat emergence dynamics measurements

On the third day of the experiment, 80% of the kernels irrigated with a 1% solution of EM Naturally Active germinating the fastest, while a slightly lower number of kernel emergence was observed in test sample 12 in which 75% of the kernels irrigated with a 0.5% solution of EM Naturally Active germinated.

On the seventh day of observation, the highest intensity of wheat emergence was 95%, which was watered with EM 0.5% solution, in relation to the control in which 85% of kernels germinated.

On the seventh day of observation the test sample 13 in which the grains were watered with 1% solution of EM Naturally Active showed a higher number of germinated grains than the control with 90% of germinated grains. On the seventh day of observation, the lowest intensity of wheat emergence was 0.1%, which was watered with 30% EM solution, and complete absence of kernel emergence was observed when watered with 50% EM Natural Active solution. The application of 50% EM Naturally Active solution concentration for watering was found to be too high, causing lack of germinated grains.

On the seventh day of the experiment, watering the kernels with a 0.5% EM solution will result in the sprouting of 95% of the kernels and the identical effects can be obtained by dressing the grains for 3 hours with 0.1% and 1% EM solutions. Treatment of seeds with 0.1% and 1% EM for 3 hours will cause faster germination already on the 3rd day of the experiment, at the level of 85%, while by watering with a 0.5% EM solution on the 3rd day of the experiment, the emergence is lower and amounts to 75% of the germinated seeds. Dressing the grain with 5% EM solution for 1 hour will result in 95% of germinated grains on the seventh day of observation, and watering with a 5% EM solution will result in 10% less sprouted grains on the seventh day of observation.

A study, which was conducted by Wolnej-Maruwki et al. (2010), says that the application of EM reduces the amount of mold fungi in the substrate, thus affecting the growth of healthy seedlings. According to Szydłowska and Małuszyńska (2011), seed treatment with a preparation containing Effective Microorganisms reduced the number of dead seeds and the number of abnormal seedlings formed as a result of pathogen infection.

Nowakowska (2005) found that seed dressing of sugar beet with Effective Microorganisms effectively reduces the death of seedlings. The research conducted by Janas and Grzesik (2006) indicates that the presowing treatment of seeds with Effective Microorganisms increased the number of germinated seeds of species with low germination capacity, such as marjoram, sage, dill, echinacea, coriander.

4. Conclusions

1. Presented results of dish experiments clearly show that the application of the EM preparation for seed dressing at an appropriate concentration of the preparation and time of dressing causes an acceleration of germination and increases the number of germinated kernels.
2. Watering the seeds with 0.5% and 1% solutions of EM Naturally Active increased the dynamics of seed germination as compared to the control, while too high concentration of the preparation caused lack of seed germination.
3. The conducted research indicates that the addition of Effective Microorganisms to soil is advisable and worth recommending.

References

Ahemad, M., Khan, M. S. (2012). Effects of pesticides on plant growth promoting traits of Mesorhizobium strain MRC4. *Journal of the Saudi Society of Agricultural Sciences, 11*(1), 63-71.

Armand, N. D., Fosah, M. R., Oscar, W. F., Bruno, N. B., Duthie, T. V., Jacques, N. K. P., Carnot, A. C. (2021). Evaluation of soils fertility, growth, nutrient uptake and yield traits of peanut under indigenous and effective microorganism fertilizers in sandy ferralitic soils in Douala, Cameroon. *African Journal of Agricultural Research, 17*(3), 432-441.

Chmielowski, K., Pawełek, J., Dacewicz, E. (2020). Treatment of high strength domestic sewage on filters filled with polyurethane foam with addition of effective microorganisms. *Archives of Environmental Protection*, 21-32.

Devi, S., Manimaran, S. (2012). Study of effective microorganisms (EM) on different organic wastes and their effect on growth and yield of rice. *International Journal of Pharmacy & Life Sciences, 3*(6), 1773-1776.

Dziwulska-Hunek, A., Szymanek, M., Stadnik, J. (2020). Impact of presowing red light treatment of sweet corn seeds on the quality and quantity of yield. *Agriculture, 10*(5), 165.

Faltyn, U., Miszkieło, T. (2008). Effect of effective microorganisms (eM®) on the germination capacity of spring wheat grain. *Zeszyty Naukowe Uniwersytetu Przyrodniczego w Wrocławiu*, 31-35 (in Polish).

Gao, C., El-Sawah, A. M., Ali, D. F. I., Alhaj Hamoud, Y., Shaghaleh, H., Sheteiwy, M. S. (2020). The integration of bio and organic fertilizers improve plant growth, grain yield, quality and metabolism of hybrid maize (Zea mays L.). *Agronomy, 10*(3), 319.

Janas, R. (2009). Possibilities of using effective microorganisms in organic crop production systems. *Problemy Inżynierii Rolniczej, 17*, 111-119 (in Polish).

Janas, R., Grzesik, M. (2006). Efficiency of biological methods of protection in seed crops of medicinal and ornamental plants. *Progress in Plant Protection, 46*(2), 727-731 (in Polish).

Jilani, G., Hussain, T., Javid, T., Jamil, M. (2010). Role of EM to Sustain Crop Production in Pakistan. *Access on, 15*, 2011.

Kolasa-Więcek, A. (2010). Will efficient microorganisms revolutionize the world? *Advances in Food Processing Technology, 1*, 66-69 (in Polish).

Kosicka, D., Wolna-Maruwka, A., Trzeciak, M. (2015). Effect of microbial preparations on soil and plant growth and development. *Cosmos, 64*(2), 332 (in Polish).

Kumar, M., Kumar, K. (2019). Role of Bio-fertilizers in vegetables production: A review. *Journal of Pharmacognosy and Phytochemistry, 8*(1), 328-334.

Nowakowska, H. (2005). Antagonistic activity of fungi and Actinomycetes against pathogens of seedling or seedling dieback of sugar beet. Plant Breed. *Seed Sci, 52*, 69-78 (in Polish).

Olle, M., Williams, I. (2015). The influence of effective microorganisms on the growth and nitrate content of vegetable transplants. *J. Adv. Agric. Technol, 2*(1).

Paśmionka, I., Kotarba, K. (2015). Possibilities of using effective microorganisms in environmental protection. *Cosmos, 64*(1), 173-184 (in Polish).

Piskier, T. (2006). Response of spring wheat to application of biostimulants and soil absorbers. *Journal of Research and Applications in Agricultural Engineering, 51*(2), 136-138 (in Polish).

Rhodes, L. A., McCarl, B. A. (2020). An analysis of climate impacts on herbicide, insecticide, and fungicide expenditures. *Agronomy, 10*(5), 745.

Schulz, S., Brankatschk, R., Dümig, A., Kögel-Knabner, I., Schloter, M., Zeyer, J. (2013). The role of microorganisms at different stages of ecosystem development for soil formation. *Biogeosciences, 10*(6), 3983-3996.

Seran, T. H., Suthamathy, N. (2013). Effect of combined application of cattle manure and EM on the yield and yield components of groundnut (*Arachis hypogaea* L.). *Bangladesh Journal of Agricultural Research, 38*(1), 1-9.

SI, S. N. (2016). Application of effective microorganism (EM) in food waste composting: A review. *Asia Pacific Environmental and Occupational Health Journal, 2*(1).

Siqueira, M. F. B., Sudre, C. P., Almeida, L. H., Pegorerl, A. P. R., Akiba, F., Foundation, M. O., de Janeiro, R. (1993). *Influence of Effective Microorganisms on seed germination and plantlet vigor of selected crops*. In Proceedings of the Third Intern. Conf. on Nature Farming, eds. JF Parr, SB

Hornick, ME Simpson. Washington, DC: US Department of Agriculture, 22-45.

Siyami, R., Mirshekari, B., Farahvash, F., Rashidi, V., Tarinejad, A. (2018). The effect of physical priming of seed on traits and yield of corn (Zea mays L.) under water deficit conditions in Iran. *Appl. Ecol. Environ. Res, 16*, 617-627.

Szydłowska, A., Małuszyńska, E. (2011). Application of preparations containing Effective Microorganisms for the assessment of seed germination capacity. *Nowości Warzywnicze, 52*, 51-58 (in Polish).

Szymanek, M., Dziwulska-Hunek, A., Zarajczyk, J., Michałek, S., Tanaś, W. (2020). The Influence of Red Light (RL) and Effective Microorganism (EM) Application on Soil Properties, Yield, and Quality in Wheat Cultivation. *Agronomy, 10*(8), 1201.

Wolna-Maruwka, A., Schroeter-Zakrzewska, A., Borowiak, K. (2010). Effect of the EM preparation on the microbiological status of the substrate intended for the cultivation of Pelargonium (Pelargonium×hortorum). *Nauka Przyroda Technologie, 4*(6), 98 (in Polish).

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Statistical Analysis of Electrical and Non-Electrical Parameters of Photovoltaic Modules in Controlled Tracking Systems

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Abstract: The paper presents statistical analysis of measurement results of electrical parameters for photovoltaic modules installed in stationary and dual-axis configurations. The parameters which were taken into account included: coefficient of variation, skewness and standard deviation. Also a correlation was determined between independent variables such as insolation, sunshine duration, cloudiness, ambient temperature and atmospheric pressure, and the dependent variable in the form of the daily electricity from photovoltaic conversion. In order to determine the repeatability of electricity waveforms occurring between summer months as well as between summer and winter months, the non-parametric U Mann-Whitney test was used. In order to analyse the repeatability of daily peak hours in which the highest value of the hourly electricity production is observed, the non-parametric Kruskal-Wallis test was used. The tested systems were connected to the power grid and operated independently. Test stands consisting of polycrystalline photovoltaic modules, single-phase on-grid inverters, irradiance sensors and a temperature recorder, were located on the building rooftop of the Faculty of Control Robotics and Electrical Engineering of the Poznan University of Technology in Poland (Central Poland, 52°24.4152′N, 16°55.7958′E) at the height of 30 metres above the ground level. A significant increase in the production of electricity using the PV module spatial positioning system was demonstrated in relation to modules based on the year-round modified design.

Keywords: tracking PV system, photovoltaic conversion, energy gain, spatial optimization, statistical analysis

1. Introduction

Functionally, electricity is the most beneficial form of energy which can be used and converted into other forms of energy both in all kinds of business units and in the existential sphere (in private life). Worldwide, electricity demand is constantly increasing. Conventional energy sources have a definitely negative effect on the environment. For this reason, the constantly growing interest of researchers and users is focused on unconventional thermal and electrical energy sources. As far as thermal energy is concerned, solar collectors are in use. Their geometrical characteristics and the scope of diagnostics are presented, among other things, in publications (Kuczynski et al. 2021, Znaczko et al. 2021). On the other hand, in the area of electricity sources, wind turbines, PV plants and their hybrid systems play the leading role.

In the majority of their activities in the economic sphere and in everyday life, people act in such a way as to achieve optimal results of their undertakings. Such conduct can be observed, for instance, in the optimisation of logistic processes (Hanczar et al. 2017, Izdebski 2014, Izdebski & Jacyna 2018, Jacyna et al. 2018, Karkula & Stryhunivska 2017, Kostrzewski 2017, Kostrzewski 2017a, Woźniak et al. 2016), storage (Duda et al. 2019, Jacyna et al. 2016), travel (Chamier-Gliszczynski 2011c, Chamier-Gliszczynski 2017), waste recycling (Chamier-Gliszczynski & Krzyzynski 2005, Chamier-Gliszczyński 2010, Chamier-Gliszczyński 2011, Chamier-Gliszczyński 2011a, Chamier-Gliszczyński 2011b, Merkisz-Guranowska 2010, Merkisz-Guranowska 2012, Merkisz-Guranowska 2018, Wędrychowicz et al. 2019). Also, all elements of the power supply systems are subject to optimisation analyses. Various criteria are adopted for this optimisation. These can include the minimisation of the consumption of raw materials (investment costs) or electricity (operational costs), maximisation of profits or generation capacity (Woźniak et al. 2017), reduction in the process implementation time, (Bednarek et al. 2009, Kasprzyk et al. 2010, Kasprzyk et al. 2017, Nowak et al. 2015, Tomczewski et al. 2018, Jajczyk et al. 2008, Jajczyk 2016), and occupational safety issues (Gabryelewicz et al. 2018). In the light of the current climatic crisis (global warming), ecological issues are extremely important objectives and criteria for optimal human activities. All activities which bring positive effects in this respect deserve special attention.

This paper deals with the issues related to the conversion of solar energy into electricity. The subject of analysis concerns photovoltaic systems for electricity production: the stationary system (with the unchangeable, possibly most beneficial positioning) and the tracking system (with the dual-axis control system for the position of panels in relation to the incident sunlight).

In view of the stochastic nature of electricity generation by such types of systems, the issue which has drawn particular attention of the authors is statistical analysis of electrical and non-electrical parameters related to their operation and generating capacities. Owing to the properly prepared results of measurements and calculations regarding these systems (which take into account their random nature and use appropriately selected statistical techniques), it is possible to make relatively reliable estimations as to the energy gain, which can be obtained as a result of conversion of the stationary system into the tracking system. Such considerations are very important as the possibility of obtaining energy efficiency improvements in PV systems is always the expected outcome of any scientific-technical activities.

2. Current status of the problem

In an era of global climate warming, any action aimed at limiting the occurrence of this disastrous state for the Earth is extremely valuable. One of such environmentally friendly measures is to generate electricity by means of renewable sources. The work of many scientific-research centres is focused on applying unconventional, new ideas, as well as increasing the energy efficiency of the existing technical solutions for green energy sources, i.e. ultimately achieving the highest possible energy gains from these technologies. With these objectives in mind, a wind resource assessment (WRA) was performed around high-rise buildings in realistic urbanised areas, in order to investigate the feasibility of installing wind turbines in relation to the urban wind energy generation. The results of this wind resource assessment suggest an effective strategy of wind turbine installations in order to implement the potential of urban wind energy in a realistic, compact urban area of high-rise buildings (European Commision 2020). It has been demonstrated that economic analysis of electricity supply systems for buildings and industry should include a detailed feasibility study, as well as the prospect of life cycle of electricity generation facilities. Electricity demand of the facility under consideration was assessed by means of pre-design modelling and simulation, and suitable configurations of the system were identified taking into account the costs of its life cycle. The potential for using photovoltaic (PV) panels as wall claddings was investigated in order to achieve the most advantageous energy management (both for electrical and thermal reasons) in commercial facilities (Dobrzycki et al. 2020). The subject of verification was also whether the presence of PV modules had a noticeable effect on heat transfer by the external building wall, on which the system was located. Owing to these measures, an improvement in the thermal performance of the building wall (by increasing the thermal resistance of the wall) and reduction in the consumption of gas to heat the facility are both achieved (this is also related to a reduction in carbon dioxide emissions into the atmosphere), while generating electricity in the PV system for internal needs of the factory. The use of photovoltaic roof tiles that integrate PV cells with the roof cover was taken into account (Kurz et al. 2019). Energy balance of the systems investigated (the PV tile and the entire roof) was presented, and on this basis, changes in the temperature of the PV cells of the tile, operating under different environmental conditions, were determined. Thermal and electrical parameters of these systems were identified.

In many centres around the world, scientists have been working on optimising generation of electricity from wind, i.e. by means of wind turbines. In order to ensure the correct operation of the power system and reliability of electricity supplies from generation systems, whose output power varies in time and additionally has a stochastic character, solutions are proposed to improve reliability indicators of electricity supply from such sources as wind farms, through their cooperation with a kinetic energy storage. This ensures the achievement of partial stabilisation of their output power. Optimisation of the wind farm-energy storage system, operating in a specific geographical location, is carried out. Algorithms are developed to minimise the unit discounted cost of electricity generation in systems containing a wind farm and a kinetic-type storage (Tomczewski et al. 2019). Research is carried out into the aerodynamic properties of horizontal axis wind turbines in static and dynamic flow deflection conditions, which may significantly affect the aerodynamic properties of the turbines (Bugała et al. 2020). More and more perfect fault monitoring systems are developed to ensure the highest possible reliability of operation of these power generation systems and to avoid their unplanned shutdowns and electricity blackouts. Stochastic dynamic analyses of offshore wind turbine structures are carried out to evaluate the safety and reliability of their structures, the efficient design of their support structures is implemented, and the control of the energy produced by a floating offshore wind turbine disturbed by sea waves is considered in detail (Malhotra 2007). Furthermore, this study focuses on investigating the aerodynamics and motion characteristics of the floating vertical axis wind turbine (VAWT), whereby the wind turbine is of the H-type, and the floating foundation has a truss structure. Also, analyses of energy efficiency of vertical axis (two-rotor) wind turbines, used in household electrical micro-installations in areas with less advantageous wind conditions are carried out. (Bugała et al. 2020). The introduction of simple and cheap wind turbine designs (vertical-axis hybrid turbines) in spaces with less favourable climatic conditions would allow for the achievement of the technical and economic justification for their widespread use in most areas throughout the country.

Technologies of photovoltaic panel production are also subject to intensive modifications. The search is on for innovative solar cell designs as an alternative to standard silicone solar cells. One such alternative design is the heterojunction solar device with a carbon/silicone nanotube (CNT/Si), in which a new organic material is added as an intermediate layer between the CNT film and the silicone surface (Markosea et al. 2020). Special multi-junction solar cells are being developed, which results in the achievement of higher efficiencies of these energy conversion components. Newer and newer chemical additives are incorporated into photo-active layers of cells, which results in the improvement of the overall photovoltaic efficiency of such energy sources (Wei 2010). Techniques of mechanical final panel treatment are being upgraded (e.g. the introduction of the ultrasonic vibratory treatment of the perovskite substrate). A variety of maximum power point tracking control algorithms are being investigated for reliability (Nelatury 2013, Ramos-Hernanz et al. 2020). Algorithms for the detection of various anomalies in PV systems are being developed, including sub-optimal orientation, daytime shading, sunrise/sunset, short and prolonged daytime zero and low maximum power production. The impact of shading on the operation of PV installations is being considered and statistical methods for assessment of the performance of systems operating under such conditions are being developed (Trzmiel et al. 2020). The interaction between photovoltaic panels and their associated converters is being improved. Possibilities of the most beneficial interoperation of photovoltaic systems with energy storages (super capacitors, batteries) and power grid are analysed in order to achieve the best energy management (Ciccarelli et al. 2018, Fahmi et al. 2015, Jajczyk et al. 2019, Jajczyk et al. 2020). There are also discussions regarding the profitability of investments in solar photovoltaics in the light of the national laws on renewable energy sources being introduced.

Large-scale research is being conducted on the optimisation of operation of hybrid renewable electricity generation systems that consist of wind turbine units and photovoltaic panels. Maps of territorial locations are being created in different regions of the world, where both wind and sun have great potential for energy generation. Various correlations of photovoltaic systems and wind turbines are being implemented in order to achieve the highest energy gains from an appropriately selected structure of these electricity sources in the given location. Different types of mechanical designs are being developed, the task of which is to direct and improve the intensity of air flow into wind turbines in order to increase the rotational efficiency and energy production (particularly in areas characterised by low wind speed) and, at the same time, to use this air motion for cooling the photovoltaic installations to improve their energy efficiency and limit excessive penetration of thermal (solar) radiation into building premises, where these installations are being set up.

The improvement of the energy efficiency of photovoltaic sources can be further achieved by applying tracking systems that allow photovoltaic panels to be continuously repositioned in relation to the Sun in order to achieve the largest possible energy gain from the installed generation infrastructure (Awasthi et al. 2020, Roth et al. 2004, Rubio et al. 2007).

The presented literature review shows unambiguously that the interest in various areas of use of green energy sources is very vivid, gains more and more significance, and brings huge benefits pro-climate activities.

This paper presents the study of photovoltaic energy generation systems, i.e. the stationary and analogue ones, equipped with a tracking system that controls the most beneficial positioning of panels in relation to the sun. The results of measurements are of stochastic nature definitely. When repeated multiple times, they give different results because of the unique weather conditions currently existing at the given time. In the comparative analyses of these systems in terms of energy gain – resulting from the use of the tracking system that controls the changes in positions of panels that convert solar energy into electricity – in order to achieve representative results which provide the possibility of their practical use, the statistical processing of measurement results has been introduced.

3. Measurement results

The measurements were conducted on a test stand that consisted of 220 W polycrystalline photovoltaic modules, Enecsys 240 W single-phase on-grid inverters, LB-900 irradiance sensors and the PT-100 temperature recorder.

The inverters used in the maximum power point tracking system use the Perturbation and Observation method *P&O.* In the *P&0* method, the operating voltage of the PV generator is disturbed by a small increase in dU_{PV}, as a consequence there is a change in power dP_{PV}. If the increase in power occurs, changes in operating voltage in the same direction should be continued. Otherwise, the direction of voltage increase should be changed.

Diagram of operation of *P&O* method implemented in microinverter is presented in Figure 1.

The photovoltaic modules were installed in a location with geographical coordinates 52°24′24″N, 16°55′47″E and were set at an optimum tilt angle towards the Sun, determined as a result of using an active two-axis tracking system controlled by an astronomical clock, with an additional position correction system operated by means of photo-optical sensors. In addition to this, the PV module identical in terms of electrical parameters was installed in a stationary system at a constant tilt angle (in the annual cycle). The comparison of the recorded measurement results from these two systems makes it possible to determine the percentage energy gain resulting from a change in the spatial orientation of this solar energy converter into electricity. Figure 2 presents the production of electricity for a selected month from the entire study period (June 2017 -May 2018) for the tracking and stationary systems.

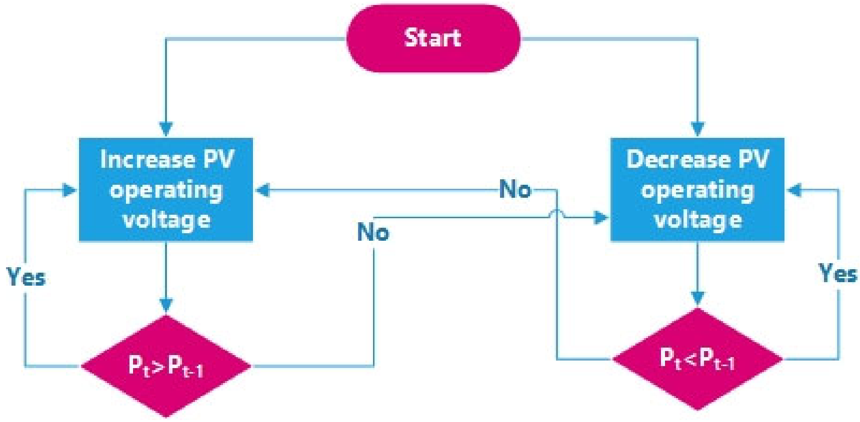

Fig. 1. Diagram of operation of *P&O* method (P_t – power at a given moment *t*, P_{t-1} – power at a previous moment *t-1*)

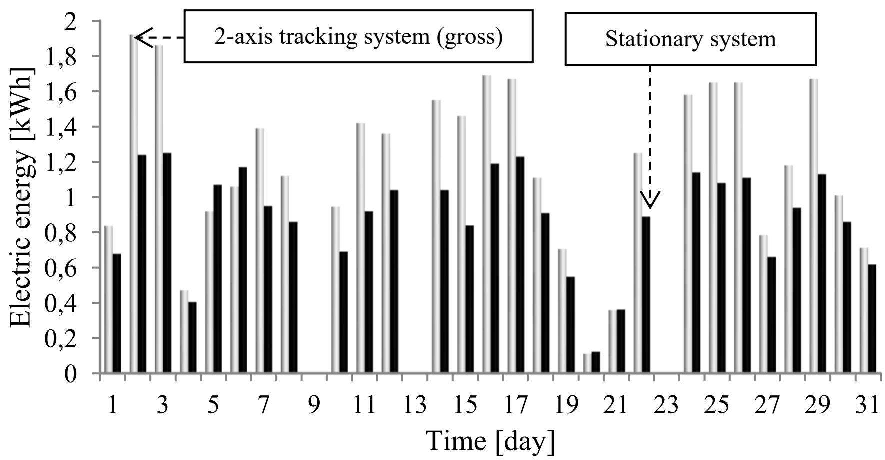

Fig. 2. Monthly production of electricity by the photovoltaic module in the stationary and tracking systems, August 2017

Figures 3 and 4 present results of measurements of irradiance and insolation for photovoltaic modules for a selected month of the year.

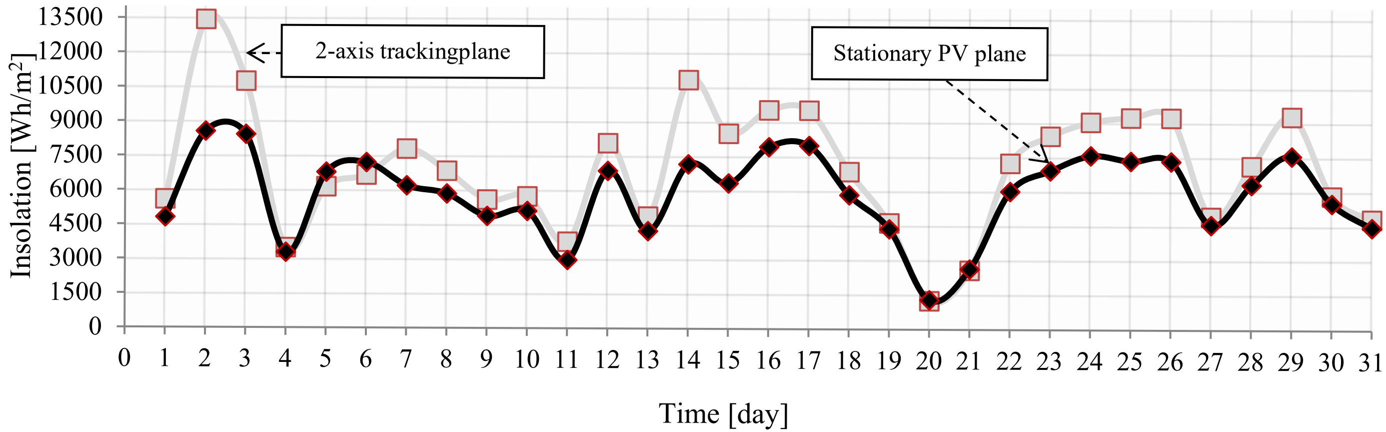

Fig. 3. Distribution of insolation on stationary and tracking planes, August 2017

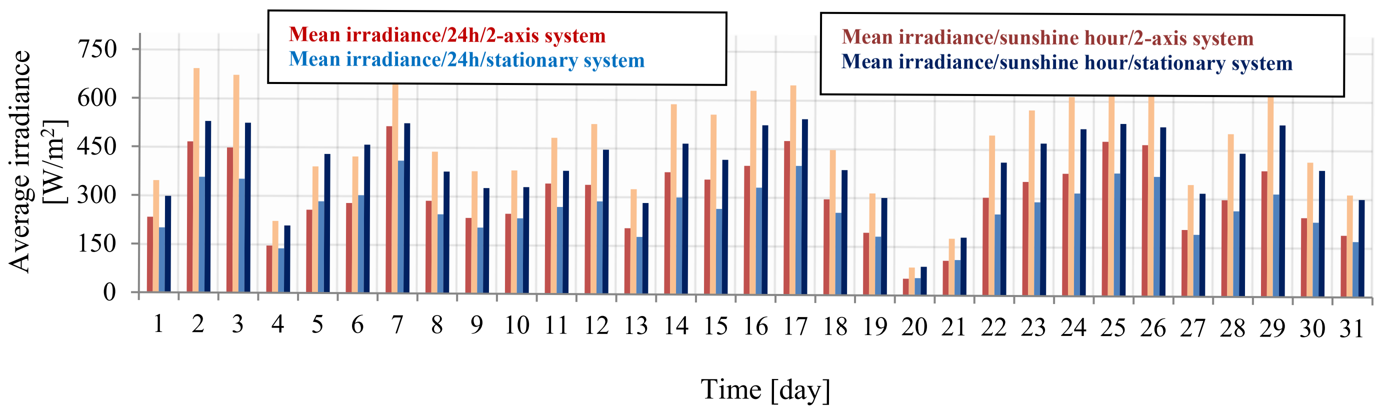

Fig. 4. Average irradiance on the stationary and tracking planes in an all-day cycle for sunshine hours

4. Statistical analysis of measurement results

The following results of measurements were subjected to statistical analysis: electricity (treated as a response variable), as well as irradiance, insolation, sunshine duration, cloudiness, air temperature, day length, atmospheric pressure (assumed as explanatory variables), recorded in the period between June 2017 and May 2018. Because of the association of the electricity variable, which is analysed in detail, with more than one explanatory variable, in order to present the mutual relationship between the variables, the multiple regressionmodel is used.It allows for analysis of the relationship between the response variable and the set of other predictors.The general form of the regression model is described by the following relationship:

$$\hat{x} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon \quad (1)$$

where:
x_n – the n-th independent variable in the model,
β – model parameters describing the effect of the given variable
on the dependent variable,
ε – random component.

A 123-element sample from the whole measurement period was used to estimate the β parameters. Production of electricity from photovoltaic conversion, considering the four explanatory variables occurring with the highest rank, is described by equation (2):

$$\hat{x} = 0.13 \cdot n + 28.64 \cdot u + 35.90 \cdot z - 9.69 \cdot t + 108.40 \quad (2)$$

where:
n – insolation,
u – sunshine duration,
z – cloudiness,
t – maximum air temperature.

Pearson's correlation coefficient $r_{x,y}$ between the variables used in the regression model has been calculated on the basis of relationship (3) and the results have been presented in Table 1.

$$r_{x,y} = \frac{\frac{1}{n} \cdot \sum_{i=1}^{n} (x_i - \overline{x}) \cdot (y_i - \overline{y})}{\sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} \left(x_i - \overline{x}\right)^2} \cdot \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} \left(y_i - \overline{y}\right)^2}} = \frac{\mathrm{cov}(x, y)}{S_x \cdot S_y} \tag{3}$$

where:
S_x, S_y – standard deviation of variable x and y,
N – size of the population.

Table 1. Correlations between variables used in the regression model determined with the Statistica software

Variable	Correlation analysis				
	Insolation	Skycloud	Temperature	Number of sunny hours	Electricenergy
Insolation	1.000000	0.650988	0.510682	0.924923	0.966914
Skycloud	0.650988	1.000000	0.424817	0.652897	0.678909
Temperature	0.510682	0.424817	1.000000	0.566304	0.442228
Number of sunny hours	0.924923	0.652897	0.566304	1.000000	0.924317
Electricenergy	0.966914	0.678909	0.442228	0.924317	1.000000

Statistical analysis allows for the indication of potentially excessive variables in the regression model. This is evidenced by the low tolerance value ($1 - r^2$) for the analysed variables (Table 2). Variables with a tolerance below 0.1 participate in the creation of the model, which may turn out to be statistically useless. This provides grounds for exclusion of variables that contribute to the increase of the standard estimation error of the regression model. The low value of the tolerance determined for such variables as insolation and sunshine duration and the high value of the coefficient of determination r^2 may be due to the strong correlation between them. Due to the fact that the results of the determined correlation between the explanatory variables and between the explained variable, in selected cases, assume close values, the accuracy of the results was increased.

Table 2. Tolerance values determined for independent variables in the regression model

Variable	Redundancy of independent variables			
	Tolerance	R^2 value	Partial correlation	Semi-partial correlation
Insolation	0.140189	0.859811	0.784536	0.276389
Skycloud	0.553175	0.446825	0.267678	0.060690
Temperature	0.671802	0.328198	-0.387213	-0.091745
Number of sunny hours	0.129874	0.870126	0.383443	0.090696

For additional verification of the correlation between the independent variables (such as insolation, sunshine duration and cloudiness) and the dependent variable, correlation diagrams were created as shown in Figure 5.

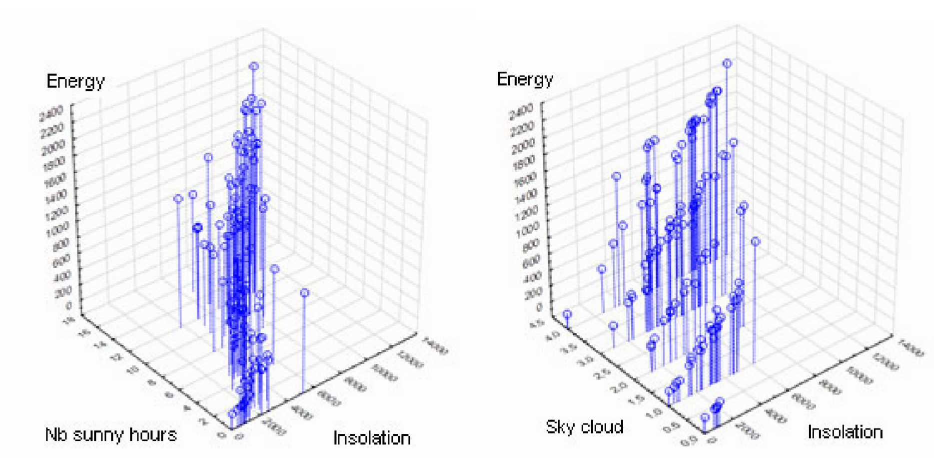

Fig. 5. Three-dimensional scatter plot for the dependent variable "electricity" [Wh] and the independent variables "insolation" [Wh/m^2], "sunshine duration" [h] and dimensionless"sky cloudiness"

In order to additionally check the correctness of the created model, a normality residual plot of the developed model was made (Fig. 6). It revealed the presence of few influential observations distorting the regression model.

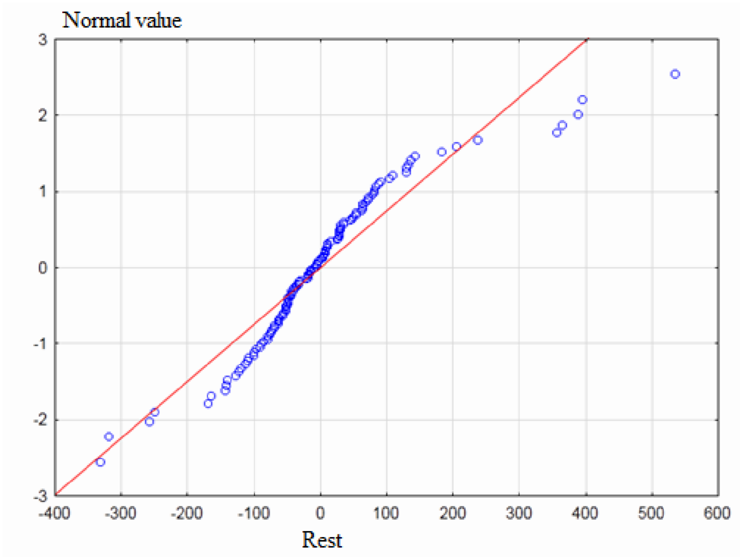

Fig. 6. Normality of residuals in the regression model for all analysed samples

Based on analysis of the temporal distribution of values of recorded electricity coming from photovoltaic conversion in the case of modules characterised by stationary installation as well as installation in the variable position system, it possible to indicate days with an almost symmetrical waveform of this electrical value in relation to midday hours, and days characterised by strong irregularities. The skewness coefficient was used as a measure of asymmetry while in order to assess the homogeneity of the daily waveform of electricity produced, the value of the coefficient of variation was calculated. The values of parameters were determined on the basis of sunshine hours and for the entire measuring day. The skewness coefficient was determined by the following relationship:

$$A_S = \frac{\overline{x} - M_o}{S} \tag{4}$$

where:
$\overline{x}$ – mean value,
M_o – median,
S – standard deviation.

Skewness is a measure of asymmetry of distribution in relation to the normal distribution, treated as the symmetrical one. For the symmetrical distribution, the value of this parameter is equal to zero. The higher is the value of the skewness coefficient, the higher is the asymmetry in relation to the mean value. The asymmetry coefficient equal to zero indicates the symmetry of distribution of the variable – a positive value means the right-sided asymmetry, while a negative value means the left-sided asymmetry. A positive value of skewness was obtained for the analysed data, which means a distribution with a slight asymmetry extending towards positive values. For a group of days of the summer month, it is close to zero, indicating an almost symmetrical distribution. For the winter months, with a strongly random distribution of the solar radiation power density, an increase in the asymmetry coefficient is observed both for the photovoltaic module in the tracking configuration and the stationary configuration. The highest values of this parameter, exceeding 2, are observed for winter months (Table 3).

Coefficient of variation v is the quotient of variation of a given parameter around the mean population value (standard deviation of a population) to the determined mean value. The range of variability of this dispersion measure for the PV module installed as a stationary system, determined for sunshine hours, indicates low and moderate variabilities on the basis of the adopted scale:

$v < 50\%$ – low variability,
$50\% < v < 100\%$ – moderate variability,
$v > 100\%$ – high variability.

The coefficient of variation determined for all hours of the day takes significant values, indicating high variability of the electricity parameter, especially for photovoltaic modules installed in a stationary configuration.

On the other hand, it is assumed that if the coefficient of variation does not exceed 10%, then the characteristics show statistically insignificant variation. High values of standard variation in relation to the mean value may lead to a reduction in the quality of the forecasting model.

Table 3. Results of statistical analysis for selected days of the month of July, December, April and January

Parameter	12/07/17		03/07/2017		26/07/2017	
	Track. system	Fixed system	Track. system	Fixed system	Track. system	Fixed system
Daily average [Wh]	84.63	49.92	74.29	45.75	70.67	44.58
Average sunshine hours [Wh]	135.40	85.57	111.44	78.43	113.07	76.43
Stand. dev./day [Wh]	76.91	62.19	69.06	57.93	69.08	54.54
Stand. dev./sunshine hours [Wh]	50.89	59.82	54.90	56.48	53.30	51.64
Skewness/day [-]	0.00	0.84	0.09	0.93	0.19	0.79

Table 3. cont.

Parameter	12/07/17		03/07/2017		26/07/2017	
	Track. system	Fixed system	Track. system	Fixed system	Track. system	Fixed system
Coefficient of variation/day [-]	0.91	1.25	0.93	1.27	0.98	1.22
Coefficient of variation/sunshine hours [-]	0.38	0.70	0.49	0.72	0.47	0.68
	18/12/2017		11/12/2017		29/12/2017	
Daily average [Wh]	0.79	1.25	9.29	6.83	6.83	4.79
Average sunshine hours [Wh]	4.75	6.00	37.17	27.33	23.43	16.43
Stand. dev./day [Wh]	1.98	2.70	22.71	15.21	14.07	9.70
Stand. dev./sunshine hours [Wh]	2.17	2.53	32.05	19.10	17.04	11.45
Skewness/day [-]	2.72	2.28	2.93	2.70	2.33	2.23
Coefficient of variation/day [-]	2.50	2.16	2.44	2.23	2.06	2.02
Coefficient of variation/sunshine hours [-]	0.46	0.42	0.86	0.70	0.73	0.70
	11/04/2018		25/04/2018		02/04/2018	
Daily average [Wh]	37.29	23.29	55.42	40.21	55.54	41.58
Average sunshine hours [Wh]	63.93	46.58	95.00	74.23	111.08	83.17
Stand. dev./day [Wh]	49.01	30.95	69.14	55.76	69.60	59.00
Stand. dev./sunshine hours [Wh]	49.13	28.81	66.59	56.69	59.31	59.19
Skewness/day [-]	1.34	0.99	0.74	1.04	0.85	1.17
Coefficient of variation/day [-]	1.31	1.33	1.25	1.39	1.25	1.42
Coefficient of variation/sunshine hours [-]	0.77	0.62	0.70	0.76	0.53	0.71
	18/01/2018		08/01/2018		15/01/2018	
Daily average [Wh]	1.29	1.71	1.42	1.75	11.71	8.46
Average sunshine hours [Wh]	6.20	8.20	8.50	7.00	46.83	29.00
Stand. dev./day [Wh]	3.21	3.52	3.58	3.92	22.58	17.06
Stand. dev./sunshine hours [Wh]	4.35	2.48	4.09	4.97	19.84	20.05
Skewness/day [-]	3.06	1.94	2.88	2.59	1.71	2.12
Coefficient of variation/day [-]	2.48	2.06	2.53	2.24	1.93	2.02
Coefficient of variation/sunshine hours [-]	0.70	0.30	0.48	0.71	0.42	0.69

In order to determine the repeatability of waveforms of electricity obtained from photovoltaic conversion, occurring between summer months as well as between summer and winter months, the non-parametric U Mann-Whitney test, which consists of the comparison of two independent groups (months of the year), was used. In this case, the normal distribution of quantitative variables and equivalence of groups are not required. The fulfilment of the last condition in the analysed cases is difficult due to a different number of days of the respective months of the year. In addition to this, the non-parametric method used is suitable for small populations where the variables are measured on the quantitative, ordinal or dichotomous scale. The starting point was the formulation of null (H0) and alternative (H1) research hypotheses:

- H0: distribution of mean observation ranks in analysed groups (months of the year) does not differ significantly,
- H1: there are significant differences in distributions of variables in both groups (months of the year).

Observations with an equal value in the created ordered series have been assigned ranks – also the tied ranks. If the probability parameter p takes a value that is lower than the assumed significance level $\alpha = 0.05$ there are justified grounds to reject the null hypothesis H0 and accept the alternative hypothesis H1. Detailed results of the U Mann-Whitney test for the months of June, July, August, December and January are presented in Table 4.

The determined value of the test probability p indicates that when comparing summer and winter months with each other (June-January, July-December), the assumed significance level α assumes higher values. For this reason, there are grounds to reject the null hypothesis and accept the alternative hypothesis, according to which there are significant differences in monthly distributions of production of electricity from photovoltaic conversion for both-periods using systems for the positioning of photovoltaic modules. In the case of summer months (June-July, June-August), there are no grounds to reject the null hypothesis. The lack of statistically significant differences was also demonstrated for the two winter months – December 2017 and January 2018.

In order to analyse the repeatability of daily peak hours, in which the highest value of the hourly production of electricity from the whole day is observed, appropriate 60-minute daily periods were indicated for each day of the analysed month of May, June, July and August 2017/2018. The comparison of four independent groups was made using the non-parametric Kruskal-Wallis test, which is an extension of the U Manna-Whitney test. None of these two tests require the fulfilment of many conditions characteristic of parametric tests. Statistical significance of the Kruskal-Wallis test points to differences between the tested groups. The starting point was the formulation of zero (H0) and alternative (H1) research hypotheses:

- H0: distribution of mean ranks in analysed groups (months of the year) does not differ significantly,
- H1: there are significant differences between groups in the repeatability of peak hours.

Table 4. Results of the U Mann-Whitney test, including the correction of continuity for the months of June, July, August, December, January 2017 and 2018

Variable	Results of the U Mann-Whitney test, July 2017 & December 2017								
	Sum of rank A	Sum of rank B	U	Z	p	Z correction	p	Number of valid samples in group A	Number of valid samples in group B
Electric Energy	1239	714	218	3.6886	0.0002	3.7029	0.0002	31	31
Results of the U Mann-Whitney test, June 2017 & January 2018									
Electric Energy	1367	524	28	6.2970	0.00	6.2989	0.00	30	31
Results of the U Mann-Whitney test, June 2017 & July 2017									
Electric Energy	950	941	454	-0.1515	0.8796	-0.1515	0.8796	31	30
Results of the U Mann-Whitney test, June 2017 & August 2017									
Electric Energy	1008	882.5	386.5	1.1252	0.2605	1.1253	0.2605	30	31
Results of the U Mann-Whitney test, December 2017 & January 2018									
Electric Energy	860.5	1092.5	364.5	-1.6261	0.1039	-1.6542	0.0981	31	31

The value of $p = 0.3279$ determined by means of the *Statistica* software is higher than the assumed significance level $\alpha = 0.05$. Thus, there are no grounds to reject the null hypothesis which assumes the lack of significant differences in the occurrence of peak hours for the analysed months of the year. The differences are, therefore, statistically insignificant.

The additional U Mann-Whitney test, however, confirmed the occurrence of significant differences between peak hours (mean observation ranks) for summer and winter months with the assumed significance level of $\alpha = 0.05$. Test results for the selected pair of months are presented in Table 5.

Table 5. Results of the U Mann-Whitney test which confirm the significance of differences between the peak hours of the months of June 2017 and January 2018

Variable	Results of the U Mann-Whitney test, June 2017 & January 2018								
	Sum of rank A	Sum of rank B	U	Z	p	Z correction	p	Number of valid samples in group A	Number of valid samples in group B
Peak hour	354	207	54	-2.1626	0.0306	-2.1874	0.0287	24	13

Table 6 presents the percentage energy gain resulting from the use of the dual-axis positioning of the photovoltaic module in relation to the stationary system.

Table 6. Percentage gain resulting from the content of electrical energy produced by the dual-axis tracking system in the period between 07.2017 and 05.2018

Month	07.17	08.17	09.17	10.17	11.17	12.17	01.18	02.18	03.18	04.18	05.18
Energy gain [%]	51.5	45.51	35.12	35.61	27.25	32.31	22.62	34.44	39.21	33.32	52.42

5. Summary

The determined statistical parameters, including the asymmetry coefficient and coefficient of variation, may indicate that the daily distribution of electricity production for a representative 123-day measuring period, differs from the normal distribution. Additionally, the extension of the analysis to include days of winter months results in the increase in the standard error of electricity estimation using the determined regression model, and the further distortion of the shape of the actual distribution in relation to the normal distribution. This may be due to a strong correlation of electricity values with the insolation level (Table 1), which varies for the winter period and the pre-winter months. For this reason, it is necessary to consider the appropriateness of dividing the available measuring data into characteristic periods and using separate forecasting models for them.

Both the quantitative and qualitative comparative analysis of the monthly production of electricity from photovoltaic conversion shows less variability of its waveforms for the summer months. The main parameter in the presented analysis is the coefficient of variation, understood as the ratio of the standard deviation to the arithmetic mean. Its value varies from 0.36 to 0.51 for the months of June to August. This is almost 5 times lower than the results obtained for December and more than 3 times lower in the case of January the following year. The value of the coefficient of variation exceeding 0.6 indicates that a significant percentage of the mean value is its standard variation. The distribution of the values of the measure and is heterogeneous, therefore, the arithmetic mean should not be the main statistical measure. However, using only the value of the standard variation in comparative analysis may turn out to be insufficient because of significant differences in the average monthly value of electricity production for extreme months of the measuring year.

References

Awasthi, A., Shukla, A.K., Manohar, M., Dondariya, C., Shukla, K.N., Porwal, D. (2020). Review on sun tracking technology in solar PV system, *Energy Reports, 6*, 392-405.

Bednarek, K., Jajczyk, J. (2009). Effectiveness of optimization methods in heavy-current equipment designing. *Przegląd Elektrotechniczny, 85*(12), 29-32.

Bugała, A., Bednarek, K. (2020). Analiza wydajności energetycznej dwuwirnikowej turbiny wiatrowej o pionowej osi obrotu. *Przeglad Elektrotechniczny, 01*(96), 206-209. DOI: 10.15199/48.2020.01.4.

Bugała, A., Roszyk, O. (2020). Investigation of an Innovative Rotor Modification for a Small-Scale Horizontal Axis Wind Turbine, Energies, *2020, 13*(10), 2649-1-2649-18.

Chamier-Gliszczynski, N., Krzyzynski, T. (2005). On modelling three-stage system of receipt and automotive recycling. *REWAS'04, Global Symposium on Recycling, Waste Treatment and Clean Technology 2005*, 2813-2814, Madrid, Spain, 26-29 September 2004, Conference Paper, ISBN: 8495520060.

Chamier-Gliszczyński, N. (2010). Optimal Design for the Environment of the Means Transportation: a Case Study of Reuse and Recycling Materials. *Sold State Phenomena, 165*, 244-249. DOI: 10.4028/www.scientific.net/SSP.165.244

Chamier-Gliszczyński, N. (2011). Environmental aspects of maintenance of transport means, end-of life stage of transport means. *Eksploatacja i Niezawodnosc - Maintenance and Reliability, 50(2*), 59-71. http://ein.org.pl/podstrony/wydania/50/pdf/07.pdf

Chamier-Gliszczyński, N. (2011a). Reuse, Recovery and Recycling System of End-of Life Vehicles. *Key Engineering Materials, 450*, 425-428. DOI: 10.4028/www.scientific.net/KEM.450.425

Chamier-Gliszczyński, N. (2011b). Recycling Aspect of End-of Life Vehicles. Recovery of Components and Materials from ELVs. *Key Engineering Materials, 450*, 421-424. DOI: 10.4028/www.scientific.net/KEM.450.421

Chamier-Gliszczynski, (2011c). Sustainable operation of a transport system in cities. *Key Engineering Materials*, 486, 175-178. DOI: 10.4028/www.scientific.net/KEM.486.175

Chamier-Gliszczynski, N. (2017). Travelling cost an assessment criterion of the model of city logistics. Carpathian Logistics Congress (CLC'2016), TANGER Ltd, 287-292.

Ciccarelli, F., Di Noia, L., Rizzo, R. (2018). Integration of Photovoltaic Plants and Supercapacitors in Tramway Power Systems, *Energies, 11*, 410. DOI: 10.3390/en11020410.

Dobrzycki, A., Kurz, D., Mikulski, S., Wodnicki, G. (2020). Analysis of the impact of building integrated photovoltaics (BIPV) on reducing the demand for electricity and heat in buildings located in Poland, *Energies, 13*(10), 2549-1-2549-19. DOI: https://doi.org/10.3390/en13102549.

Duda, J., Karkula, M. (2019). A hybrid heuristics for order-picking and route planning in warehouses. 8th Carpathian Logistics Congress (CLC'2018), TANGER Ltd, 185-190.

European Commision (2020). Roof top wind turbine for urban areas. *Horizon2020*.

Fahmi, M., Rajkumar, R., Arelhi, R. (2015). Study on the Effect of Super capacitors in Solar PV System for Rural Application in Malaysia, *50th International Universities Power Engineering Conference*. DOI: 10.1109/UPEC.2015.7339921.

Gabryelewicz, I., Krupa, P., Sąsiadek, M., (2018),*Safety Culture: Influence of a Human Factor on the Process of Shaping Work Safety*, Proceedings of the 31 International Business Information Management Association Conference – IBIMA, Milan, Italy, 2018, 4720-4727, ISBN: 9780999855102 https://ibima.org/accepted-paper/safety-culture-influence-of-a-human-factor-on-the-process-of-shaping-work-safety/

Hanczar, P., Kaleta, J., Karkula, M. (2017). Combined use of simulation and optimization models as a decision support tool for robust inventory routing problems. Carpathian Logistics Congress (CLC'2016), TANGER Ltd., 105-111.

Izdebski, M. (2014). The use of heuristic algorithms to optimize the transport issues on the example of municipal services companies. *Archives of Transport, 29(1),* 27-36. DOI: 10.5604/08669546.1146961

Izdebski, M., Jacyna, M. (2018). The organization of municipal waste collection: The decision mode. *Rocznik Ochrona Środowiska, 20*, 919-933.

Izdebski, M., Jacyna-Gołda, I., Gołebiowski, P., Plandor, J. (2020). The optimization tool supporting supply chain management in the multi-criteria approach. *Archives of Civil Engineering, 66*(3), 505-524. DOI: 10.24425/ace.2020.134410

Jacyna, M., Wasiak, M., Lewczuk, K., Chamier-Gliszczyński, N., Dąbrowski, T. (2018). Decision Problems in Developing Proecological Transport System. *Rocznik Ochrona Srodowiska, 20*(2), 1007-1025.

Jacyna, M., Klodawski, M., Szczepanski, E. (2016). *Designing and management of storage facilities: The SIMMAG3D as an advanced decision support system*. Transport Means Proceedings of the International Conference, 2016, 846-851.

Jajczyk, J. (2016). Use of Personal Computers with Multi-core Processors for Optimisation Using the Genetic Algorithm Method. *Proceedings of 2016 17th international conference computational problems of electrical engineering (CPEE).*IEEEXplore Electronic. DOI: https://doi.org/10.1109/CPEE.2016.7738731.

Jajczyk, J., Filipiak, M., Dąbrowski T. (2020) Reducing the Use of Electrochemical Sources of Electricity Through the Use of Wireless Power Supply, *Rocznik Ochrona Srodowiska, 22*(1), 444-455.

Jajczyk, J., Kasprzyk, L. (2008). The Use of Coupled Temperature and Electromagnetic Fields in Optimization Problems. *Proceedings of the 6th IASME/WSEAS International Conference on Heat Transfer, Thermal Engineering and Environment. WSEAS Mechanical Engineering Series*, 226-231.

Jajczyk, J., Słomczyński, K. (2019). A dedicated battery for an electric bike. *Computer applications in electrical engineering 28*. 01033. ITM Web of Conferences. DOI: 10.1051/itmconf/20192801033

Karkula, M., Stryhunivska, O. (2017). The use of virtual factory concepts and models for facilitating Logistics systems and operations. Carpathian Logistics Congress (CLC'2016), TANGER Ltd., 456-462.

Kasprzyk, L., Tomczewski, A., Bednarek, K. (2010). Efficiency and economic aspects in electromagnetic and optimization calculations of electrical systems. *Przeglad Elektrotechniczny, 12*, 57-60 (in Polish).

Kasprzyk, L., Tomczewski, A., Bednarek, K., Bugała, A. (2017). Minimisation of the LCOE for the hybrid power supply system with the lead-acid battery. *E3S Web of Conferences 19, 01030*, 1-6. DOI: 10.1051/e3sconf/20171901030.

Kostrzewski, M. (2017). Simulation methods in the comparative analysis of car spare-parts distribution systems. Carpathian Logistics Congress CLC'2016, TANGER Ltd, 204-209.

Kostrzewski, M. (2017a). Implementation of distribution model of an international company with use of simulation method. *12th International Scientific Conference of young Scientists on Sustainable, Modern and Safe Transport, Procedia Engineering, 192*, 445-450. DOI: 10.1016/j.proeng.2017.06.077

Kuczynski, W., Kaminski, K., Znaczko, P., Chamier-Gliszczynski, N., Piatkowski, P. (2021). On the Correlation between the Geometrical Features and Thermal Efficiency of Flat-Plate Solar Collectors. *Energies, 14*, 261. DOI: https://doi.org/10.3390/en14020261

Kurz, D., Nawrowski, R. (2019). Thermal time constant of PV roof tiles working under different conditions. *Applied Sciences, 9*(8). DOI: https://doi.org/10.3390/app9081626.

Malhotra S. (2007). *Design and Construction Considerations for Offshore Wind Turbine Foundations in North America.* Proceedings of the 26TH International Conference on Offshore Mechanics and Arctic Engineering, June 10-15, 2007, San Diego, California.

Markosea K., Jasna M., Subha P., Antony A. (2020). Performance enhancement of organic/Si solar cell using CNT embedded hole selective layer, *Solar Energy, 211*, 158-166.

Merkisz-Guranowska, A. (2010). Issues related to the optimization of location of vehicle recycling network entities. *Archives of Transport, 22(3),* 303-318. DOI: 10.2478/v10174-010-0018-x

Merkisz-Guranowska, A (2012). Bicriteria models of vehicles recycling network facility location. *Archives of Transport, 24(2)*, 187-202. DOI: 10.2478/v10174-012-0012-6

Merkisz-Guranowska, A. (2018). Waste recovery of and-of-life vehicles. *IOP Conference Series: Materials Science and Engineering, 421*(3), 032019. DOI: 10.1088/1757-899X/421/3/032019

Nelatury, S. (2013). A maximum power point tracking algorithm for photovoltaic Applications, Energy Harvesting and Storage: Materials, Devices, and Applications IV, edited by Nibir K. Dhar, Palani Balaya, Achyut K. Dutta. *Proc. of SPIE, 8728*.

Nowak, L., Knypiński, Ł., Jędryczka, C., Kowalski, K. (2015). Decomposition of the compromise objective function in the permanent magnet synchronous motor optimization. *COMPEL – The International Journal For Computation and Mathematics in Electrical and Electronic Engineering, 34*(2), 496-504.

Ramos-Hernanz, J., Uriarte, I., Lopez-Guede, J.M. et al. (2020). Temperature based maximum power point tracking for photovoltaic modules. *Science Report 10*, 12476. DOI: https://doi.org/10.1038.

Roth, P., Georgiev, A., Boudinov, H. (2004). Design and construction of a system for-Sun-tracking. *Renewable Energy 29*, 393-402. DOI: http://dx.doi.org/10.1016/S0960-1481(03)00196-4.

Rubio, F.R., Oretga, M.G., Gordillo, F., Lopez-Martinez, M. (2007). Application of new contro strategy for Sun tracking system. *Energy Convers. Manage. 48*, 2174-2284. DOI: http://dx.doi.org/10.1016/j.enconman.2006.12.020.

Tomczewski, A., Kasprzyk, L. (2018).Optimisation of the structure of a wind farm – kinetic energy storage for improving the reliability of electricity supplies. *Applied Science, 8*(1439), 1-18.

Tomczewski, A., Kasprzyk, L., Nadolny, Z. (2019). Reduction of Power Production Costs in a Wind Power Plant-Flywheel Energy Storage System Arrangement. *Energies 2019, 12*(10), 1942. DOI: https://doi.org/10.3390/en12101942.

Trzmiel, G., Głuchy, D., Kurz, D. (2020). The impact of shading on the exploitation of photovoltaic installations, *Renewable Energy, 153*, 480-498. DOI: https://doi.org/10.1016/j.renene.2020.02.010.

Wei D. (2010). Dye Sensitized Solar Cells, *International Journal of Molecular Sciences 11*, 1103-1113. DOI:10.3390/ijms11031103.

Wędrychowicz, M., Bydałek, A., Skrzekut, T., Noga, P., Gabryelewicz, I., Madej, A., (2019). Analysis of the mechanical strength, structure and possibilities of using waste phosphogypsum in aluminum powder composites, *SN Applied Sciences, 1*(9), 1-8. DOI: 10.1007/s42452-019-0995-1

Woźniak, W., Nawrocki, W., Stryjski, R., Jakubowski, J. (2017). *Identification and Reduction of Product Defects in Mass Production at Toyota Motor Manufacturing, Poland.* Proceedings of the 30th International Business Information Management Association Conference – IBIMA, Madrid, Spain 2017, 4774-4782. ISBN: 9780986041990 https://ibima.org/accepted-paper/identification-and-reduction-of-product-defects-in-mass-production-at-toyota-motor-manufacturing-poland/

Woźniak, W., Sąsiadek, M., Stryjski, R., Mielniczuk, J., Wojnarowski, T. (2016). An algorithmic concept for optimising the number of handling operations in an intermodal terminal node. *Proceedings of the 28th International Business-Information-Management-Association Conference, IBIMA Seville, Spain, 2016, 1-7*, 1490-1500. ISBN: 9780986041983

Znaczko, P., Szczepanski, E., Kaminski, K., Chamier-Gliszczynski, N., Kukulski, J. (2021). Experimental Diagnosis of the Heat Pipe Solar Collector Malfunction. A Case Study. *Energies, 14*, 3050. DOI: https://doi.org/10.3390/en14113050

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The Recycling of Secondary Waste in Polish Recycling Companies

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Abstract: This article analyses the recycling of secondary waste in Polish recycling companies. An innovative method of processing PCBs is presented and trends that should be followed by plants processing non-ferrous metal waste are indicated. In conclusion, it is emphasised that the Polish WEEE recycling market is still at the early development and growth stage and the most important goals that enterprises should set themselves include cost optimisation, improvement of waste management logistics and increases in the level of recycling.

Keywords: recycling industry, circuit boards, precious metals recovery

1. Introduction

Recycling secondary waste in Polish enterprises begins with the extraction of metallic waste of various types, after which, it is then separated. No company in Poland has yet developed a complete waste stream processing technology, i.e., a waste stream with more specific dimensions, density and chemical composition, etc; it is mainly copper scrap together with PCB scrap – printed circuit board scrap- as well as alkaline batteries. It is assumed that from one tonne of printed circuit boards – with one piece weighing approximately 150 g – it is possible to recover approximately 27 g of metals, such as, gold, copper and palladium (Woynarowska & Żukowski 2009). One tonne of processed alkaline batteries contains from 26% to 65% of steel in the form of a shield, from 4% to 10% of electrolyte in the form of potassium hydroxide, from 20% to 35% of manganese powder, from 20% to 35% of zinc oxide and trace amounts of carbon. The average recovery of these metals by Polish companies is 70-75%. The problem with today's processing of waste scrap, in terms of environmental protection, is the processing capacity of installations in Poland, which theoretically amounts to 12 million tonnes, of which 20% of enterprises do not have an address, which raises doubts as to their actual storage and operation.

The recycling industry is one of the most innovative branches of the economy. In less than 10 years, the extraction of raw materials from landfills will become an important business field, as the content of elements such as copper and gold, in waste, is higher than that for extracted ore (Burzyńska 2018).

2. The importance of recycling in waste management

In managing materials, raw materials and recycled materials are becoming ever more important. A clear upward trend can be observed in the recovery of materials. Due to ever increasing improvement in waste sorting systems and to a consistent policy favouring its use, the "return rate" of materials can, in some cases, be as high as 75%. The use of waste, that is, the recovery of secondary raw materials, both from production processes and from purchasing, is becoming increasingly important for ecological and economic reasons, related to the protection of the natural environment in the limiting of greenhouse gas emissions (Jacyna et al. 2018) and water pollution, as well as limiting the energy consumption of production (Woźniak et al. 2017a, Woźniak et al. 2017b); this entails an increase in the use of waste being a source of cheap and environmentally-friendly raw materials.

This applies, inter alia, to scrap steel and waste, along with non-ferrous metals, such as copper, aluminium, lead, zinc and tin. Extracting metals from waste materials is less energy intensive than from primary sources. End-of-life vehicles (Chamier-Gliszczyński 2010, Kosacka-Olejnik 2019, Merkisz-Guranowska 2018), waste batteries (Dobrzycki et al. 2019), waste electrical and electronic equipment and municipal waste enable the recovery of metals to a large extent (GUS 2016).

Table 1. Trade in recyclable waste in commercial units in 2016-2017 (Institute for Research on Market Economy 2017)

Waste	Year	Revenue			
		Total	From own activities	Purchase	Import
		in tonnes			
Steel and cast iron	2016	4373166	223083	4103038	47046
	2017	4564604	288082	4167234	109288
Copper	2016	238519	43957	141003	53559
	2017	218449	7258	167151	44040
Lead, zinc and tin	2016	32224	1353	27417	3454
	2017	27741	1220	23164	3357
Alumin-ium	2016	273130	3184	241881	28065
	2017	272121	3394	229216	39511

Customer expectations towards green-technology (Kanalikova et al. 2019, Marczewska et al. 2020), recycling companies are constantly growing, especially in the context of supporting the implementation of sustainable development goals (Zajac at al. 2020), including the implementation of the principles of the circular economy. The primary goal of companies is to maximise the recycling of production waste, which can be achieved through sorting-at-source, efficient internal logistics (Straka et al. 2020, Zajac et al. 2017) and transportation and above all, increasing the number of fractions that can be recycled. Effective recycling is also an important element of an increasingly important model of an innovative approach to business, which is the circular economy (Chamier-Gliszczynski & Krzyzynski 2005, Czwajda et al. 2019). The European Union is also working towards a circular economy. It is an idea that will significantly support enterprises in reducing the over-exploitation of raw materials and reduce environmental pollution (Gabryelewicz et al. 2020). Recycling materials from used products and reusing them is one way to save natural resources and, at the same time, meet the growing demand for these raw materials (Chamier-Gliszczyński 2011a, Chamier-Gliszczyński 2011b). In order to improve the recovery of materials from used cars, Directive 2000/53/EC (Chamier-Gliszczyński 2011) and Directive 2002/96/EC introduced minimum levels of recovery and minimum levels of re-use and recycling (Table 2).

Table 2. Target values of recovery and recycling rates for individual product categories (Institute for Research on Market Economy 2017)

Item	Product category	Recycling in %	Recovery in %
1	Large household appliances	75	80
2	Vending machines	75	80
3	IT and telecommunications equipment	65	75
4	Consumer devices	65	75
5	Small household appliances	50	70
6	Lighting equipment	50	70
7	Electrical and electronic instruments	50	70
8	Toys, recreation and sports equipment	50	70
9	Instruments for surveillance and control	50	70
10	Gas discharge lamps	80	

The recycling of copper and aluminium reduces the exploitation of these rare and valuable raw materials and also minimises the amount of waste produced during ore extraction. The re-use of plastic reduces the consumption of crude oil and avoids many years of storage in landfills. Thanks to the recovery of materials, water is a valuable resource. Recycling aluminium uses half as much water as when produced from primary raw materials (Duan et al. 2009). In addition, metals that end up in waters and soils pose a significant threat to the natural environment, through inappropriate management (Gabryelewicz et al. 2018). The recovery and re-use of copper and aluminium reduces the possibility of their leakage into the environment. The recycling process uses much less energy than the extraction of natural resources and also reduces carbon dioxide emissions (Reconomy 2017).

3. Recycling enterprises in Poland

In Poland, information on the management of the WEEE is published by the Chief Inspectorate of Environmental Protection in annual reports. It follows, from the reports, that in 2017, in total, more than 518.9 thousand tonnes of WEEE were introduced into the territory of Poland (Główny Inspektorat Ochrony Środowiska, 2018). The collection rate was 34.7%, which amounted to 4.1 kg of waste equipment per capita. The average for one EU citizen is around 15 kg. According to the Chief Inspectorate of Environmental Protection, there are 16,001 enterprises or organisations dealing with electronic waste in Poland; these are divided into collection companies, waste processing companies and companies involved in the recovery process, but there is no single comprehensive company dealing with processing, from start to finish. A very small number of companies – some 180, process about 905 thousand tonnes of waste. Comparing the data on the capacity and quantity of processed or recycled materials, it is clear that there are processing capacities, but these are used to a small extent only. This is due to the existing downturn in the metals market and the growing shadow economy. Analysing the market data, it is possible to confirm the assessment existing in J. Hausner's (Hausner 2017) report that the Polish WEEE recycling market is in the development and early growth phase, but is still very fragmented. None of the legal instruments used in Poland so far, e.g. a ban on depositing certain fractions of waste in landfills, changes in waste management at various levels of administration, introducing additional powers for municipalities and obligations for entrepreneurs, have brought any tangible environmental effect nor have they caused a dynamic development of the market. Pathologies in the WEEE system were also described in the PwC report of 2014, "Irregularities in the WEEE management system in Poland"(Narodowy Fundusz Ochrony Środowiska, 2015), which shows that as much as 40% of officially processed e-waste is only "paper recycling". This is evidenced, inter alia, by the heaps of unprocessed waste equipment lying around, in some processing plants.

The presented analysis of the amount of available scrap and the number of companies dealing with the collection and processing thereof, shows that at least 2.5 thousand potential recipients are registered in Poland. These are companies that are already active in the field of scrap processing and metal recovery. The largest enterprises in the copper scrap processing market in Poland can be mentioned here:

1. KGHM Polska Miedź S.A. – a national enterprise in the extraction and production of copper. In recent years, the Company has been expanding its plant in Legnica to include a scrap ironworks, producing about 65 thousand tonnes of copper from scrap annually and extends further activities in this regard through the combustible construction of a waste treatment centre.
2. KGHM METRACO – the largest company in Poland and central Europe engaged in the purchase, processing, recovery and trade in copper scrap. It is the main supplier of scrap metal to KGHM Polska Miedź S.A. and is one of the largest exporters of copper scrap.
3. OLMET – one of the largest companies in southern Poland dealing with the purchase and processing of scrap metal, including scrap copper.
4. Złomex S.A. – the largest company in Małopolska (Lesser Poland Region) engaged in the purchase and recycling of scrap metal.

In 2016, 140 million tonnes of waste were generated in Poland, 8% of which was municipal waste (12 million tonnes). The main sources of waste were: mining and quarrying (approximately 52% of the total amount of generated waste), industrial processing (21%) and electricity generation and supply (16%). In the last decade, the largest share in the amount of waste generated was waste generated during the exploration, extraction and the physical and chemical processing of ores and other minerals (56% in 2016) and waste from thermal processes (22%). Of the total amount of waste generated in 2016, 49% of waste was recovered, 42% was disposed of as landfill and 4% was disposed of by other means. The basic method of handling municipal waste in Poland was getting rid of it as landfill.

In 2016, 37% of the total quantity was earmarked for storage, that is, 4.3 million tonnes while 28% - some 3.2 million tonnes of waste – was recycled.

19%, 2.3 million tonnes, was thermally disposed of in incineration plants and 16%, 1.9 million tonnes, of municipal waste was biologically processed (Kulczycka & Karaś, 2016).

In 2016, a total of 233 million tonnes of waste electrical and electronic equipment was collected in Poland, including 224 million tonnes from households.

The largest amount of waste equipment was collected in the group consisting of large-sized household appliances – 50% of the total weight of the equipment collected, ICT and telecommunications equipment (14%) as well as consumer equipment and photovoltaic panels (9%).

In 2016, batteries and accumulators with a total weight of 131 thousand tonnes were placed on the market in Poland, including portable batteries and accumulators, approximately, 13,000 tonnes (10%) of car batteries and accumulators approximately 95,000 tonnes (72%) and industrial batteries and accumulators approximately 24,000 tonnes (18%) (Jajczyk et al. 2020). As was the case the year before, in 2016, it was not possible to reach the level of collection of used batteries and portable batteries specified for Poland. The level obtained was 39% against the required 45% (Raport GUS 2017).

According to the report entitled Countering the Illegal Trade of WEEE, only 35% of the WEEE produced (Huisman et al. 2015) is officially registered in EU countries. The report for individual EU countries shows that:

1. In the EU-28 countries, as well as in Norway and Switzerland, the total amount of WEEE generated was 9.45 million tonnes in 2012;
2. Only 35% (3.3 million tonnes) of WEEE were registered in official reports as having been collected and recycled. The remaining 65% (6.15 million tonnes) were recycled under conditions inconsistent with EU requirements, including 2.2 million tonnes of WEEE which had been mixed with other scrap, 1.5 million tonnes of which were exported, including 1.3 million tonnes which constituted non-documented WEEE exports and used EEE with only 0.2 mln tonnes constituting official exports. 750 thousand tonnes were thrown away with municipal waste with an additional 750 thousand tonnes of WEEE having had their valuable parts removed by collecting companies but not recorded, as such, in the statistics and 950 thousand tonnes having been managed contrary to the regulations, e.g. thrown into forests;

3. In the case of illegal exports, it was indicated that 30% of WEEE was marked as equipment intended for re-use or repair and not for storage;
4. It has been estimated that 4.65 million tonnes of waste is not properly managed or is illegally sold on the European market. This applies in particular to the trade in defective WEEE, from which parts, containing valuable metals are most often removed. In the international waste shipments register, the mass of waste exported and unprocessed in Polish enterprises in 2014/2015 amounted to a total of 778,960 kg; in 2013 this was 115,647 kg. The destination country for the export of used metallic waste was Finland. By 2022, the value of metallic waste in the world is expected to grow from $ 66 billion to $ 400 billion and the amount of waste *per capita* is expected to be about 19 kg.

This exponential increase in waste is mainly due to the fact that the average lifetime of electronic equipment does not exceed 4 years. The environmental management system promoted as being compliant with the requirements of EMAS and ISO 14001, based on the PDCA cycle model, encourages entrepreneurs to identify environmental problems and plan appropriate actions, in order to limit the negative impact on the export of this waste.

4. Innovative approach to recycling in Poland

Since 2019, Polish recycling plants have been applying an innovative approach to the processing of scrap through the innovative use of metallurgical equipment and aggregates, using newly developed metallurgical refiners, as well as using innovative separation methods. An innovative approach to the recovery of Cu and precious metals from low-copper, WEEE and PCB scrap, assumes the production of a metallic phase during processing, the main component of which will be copper, as a solvent for precious metals. This will reduce the loss of precious metals during the "fusion" of scrap, containing Au, Ag, to the metallic phase. The use of this innovative approach at the scrap melting stage, will allow the loss of precious metals, throughout the cycle, to be curtailed, because gold, silver and other precious metals will follow copper, thus avoiding losses in further technological operations.

Most scrap recycling companies and plants are limited to a very narrow scope of work which consists in obtaining a commercial product through a minimum amount of work and involvement in the processing of a given type of scrap. The effect of this approach is to extract a just large enough useful fraction of valuable metal from the entire mass of waste that can be easily sold. In such a procedure, the remaining part of the waste, often containing, for example, plastics, is not managed (Yazici & Daveci 2009). This results in the generation of processed waste, which is very difficult to be managed further and which, in many cases, ends up as landfill. However, this procedure does not contribute to the improvement of the recycling rate of scrap metal in Poland, nor to environmental protection. This procedure is mainly brought about by a lack of knowledge regarding the methods of processing polymetallic waste, including PCBs, which in many cases causes scrap processing plants to focus solely on mechanical separation.

Mechanical methods are an alternative technology for the recovery of precious metals. These technologies are various combinations of comminution and separation processes, using differences in shape, colour and the physical properties of the comminuted materials. There is a view (Havlik et al. 2010) that the process of shredding PCB waste causes losses of precious metals, which, due to the form in which they occur (*contacts, wires, ceramic components in multilayer capacitors*), pass into the dust fractions. Mechanical impacts on components rich in precious metals result in the formation of small-sized particles that pass into the dust fractions or, thanks to the adhesion phenomenon, settle on the elements of other fractions. In order to counteract the loss of precious metals, there is the manual removal of elements with a high content of precious metals. The manual disassembly of PCBs, however, requires knowledge of the board structure and incurring the costs of manual work.

Another method for recovering precious metals from PCBs is to convert the precious metals into a char by pyrolysis. The purpose of pyrolysis is to get rid of organic compounds and concentrate the material into copper and accompanying metals. The material, after pyrolysis, is dark and brittle; it is easy to distinguish the metallic components in it by their characteristic metallic gloss. The char, along with lead, is then melted with refining salts ($NaNO_3$, NaOH, NaCl), in order to maintain the appropriate proportions. The char is then crushed in a vibrating mill and the dark matrix, after grinding, is removed by a set of sieves placed on a vibrating machine, thanks to which the remaining metallic part remains on the sieves (Fig. 1).

Many companies, despite a willingness to develop a method for the complete processing and management of scrap metal, are not able to take up such a challenge. The way forward, for such companies to acquire appropriate knowledge and the appropriate tools, is the transfer of ready-made, technological and technical solutions by purchasing a ready, complete technological line. There are many innovative projects in Poland that respond to such market demands. For many plants, it will be easy to access "know how" in the field of processing polymetallic scrap waste, including PCBs, by purchasing a complete solution in the form of a ready technological line.

Fig. 1. Macro-photography of material rich in Cu and precious metals

The Polish recycling industry, which recovers metallic fractions from printed circuit boards, does not specify any so-called "waste stream", which is a stream with more clearly defined dimensions, density and chemical composition. Typically, this is done in such a way that all PCBs, consisting of about 70% plastic, are subjected to the pyrolysis process. The pyrolysis process of PCBs should take place at a temperature of 780°C, while the non-uniform composition of PCBs causes that the process takes place at a much higher temperature, i.e., 1,100°C, so much higher than it should. Therefore, on the one hand, solutions are sought to effectively separate materials from metals while, on the other hand, solutions are sought in order to define a specific waste stream, *from which non-ferrous metals can be selectively recovered* and then standardize it. Therefore, the authors of this article have attempted to solve the research problem by removing elements rich in non-ferrous metals from the surface of the scrap and categorising them by type, shape and size, as detailed in the article.

4.1. Innovative processing methods on the example of PCBs

One of the few methods of metal recovery is the process of stripping elements rich in non-ferrous metals from the scrap surface. This process is most often used in printed circuit boards, the main components of which are shown in Fig. 2. Plastic, which has been recycled using combined methods, i.e. stripping methods in which the electronic working groups are removed from the PCB surface, is then sent to be segregated (Figs. 3, 4) (Lee & Lee 2012).

The results of the innovative processing of printed circuit boards introduced, indicate that it is possible to recycle non-ferrous metals, especially copper, tin and other accompanying metals (Ag, Au, Pb) (Zhang & Xu 2016) from PCBs by removing EGR from the PCB surface, using combined methods, e.g. a grindstone, sandpaper or CNC machine tools. On the one hand, this is an effective recycling method because it separates metals from plastics and thus minimises the emission of harmful substances in the pyrolysis process. On the other hand, it is quite a tedious process lasting from two to even several hours, depending on the method in which the material is processed (Biswajit et al. 2018). The proposed method of innovation is an alternative to recycling using pyrolysis methods and combined methods of separation and pyrolysis. It is postulated that the proposed method can be applied to the recycling process already in use at the time.

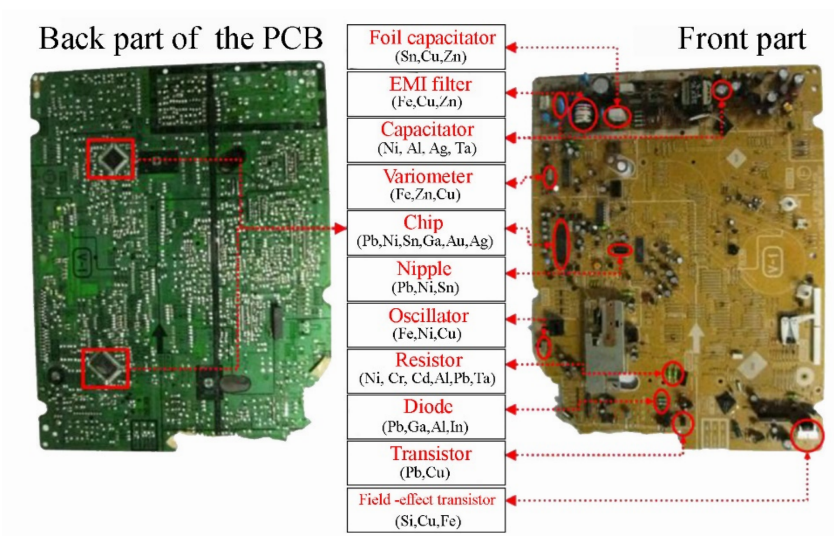

Fig. 2. Identification of the elements present in the isolated PCB

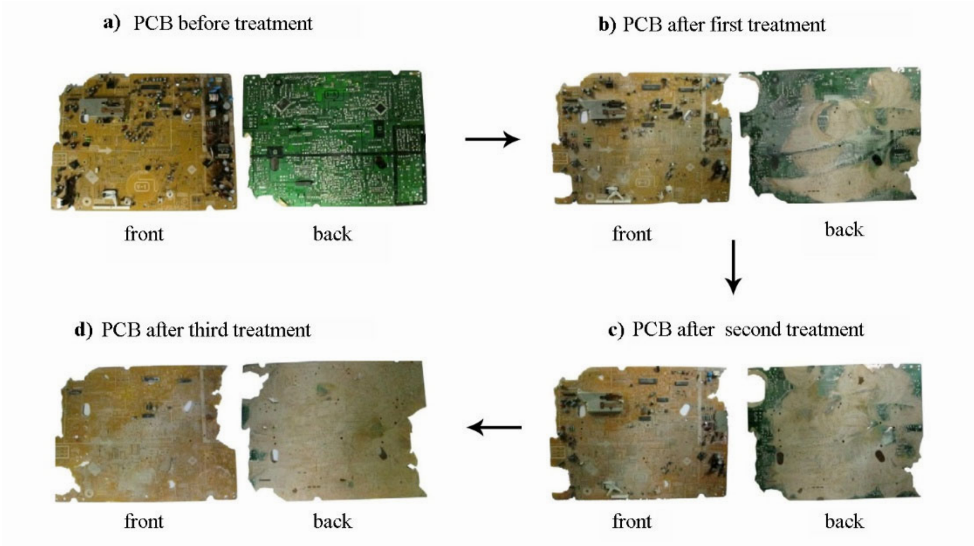

Fig. 3. PCB processing using three combined methods

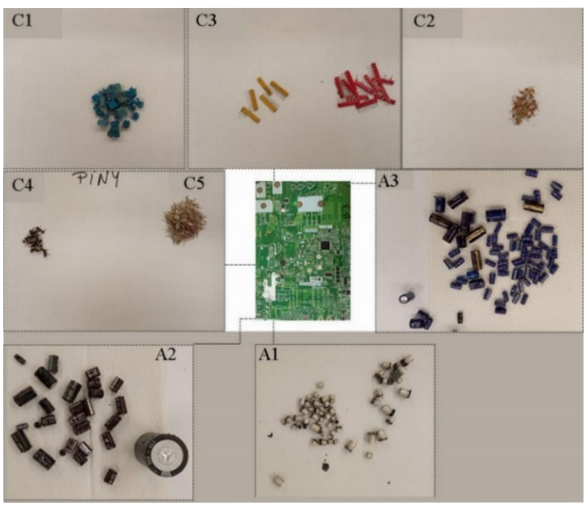

Fig. 4. Disassembled electronic workgroups categorised by type, shape and size

According to a study carried out by PBS, on behalf of Stena Recycling, (Stena Recycling Innovating, 2016) in January 2016, more than 75% of companies are willing to use uncomplicated methods in order to remove metallic materials and thus increase recycling levels. Sustainable waste management is gaining importance in the European Union. Environmental requirements are growing and steps are being taken to introduce a circular economy; environmental awareness is also growing. All this has a direct impact on the activities of companies in Poland and on introducing innovations to enterprises. Entrepreneurs have begun to combine the efficiency of waste management with responsibility and they attach ever more importance to both aspects. According to the above-mentioned study, measurable benefits of this approach are noticed by medium-sized and large companies, both from the industrial and from the manufacturing and service sectors. Therefore, it is important that recycling companies adopt the following scheme for conducting an innovative recycling process (Fig. 5).

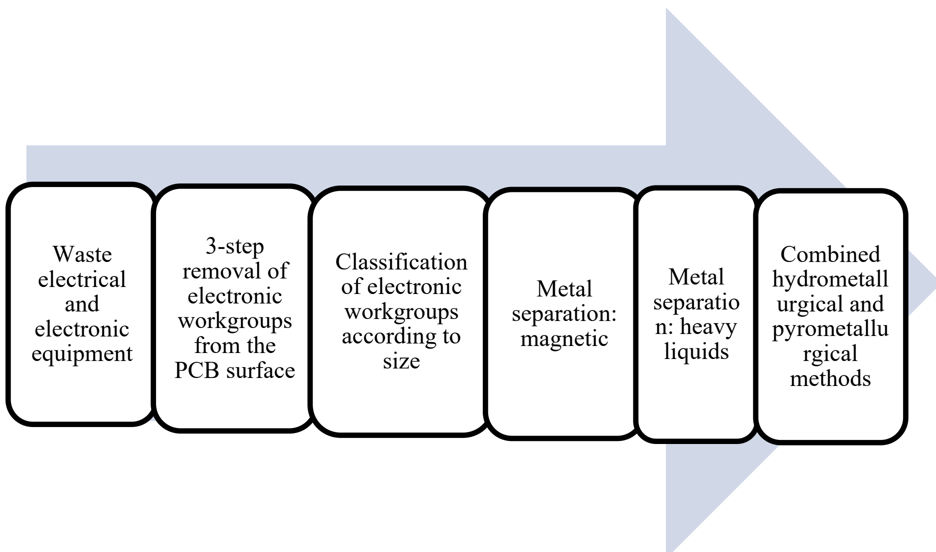

Fig. 5. A sample scheme of waste material flow which enterprises should use in their plants

Waste storage is the most problematic of issues for both medium and large enterprises. The challenges that medium and large enterprises anticipate in the area of waste management, in their industries, in the coming years include, inter alia, adjusting production to reduce the amount of waste generated (32%) and applying new technologies to improve waste management (28%), as well as materials with controlled biodegradability (Jachowicz at al. 2017). As goals or priorities for the coming years relate to waste management, medium-sized companies most often indicate cost optimisation (50% of responses), improvement of waste management logistics (31%) and an increase in recycling levels (30%). Large companies, in turn, emphasise, first of all, the improvement of waste management logistics and an increase in the level of recycling (42% of responses each) and further cost optimisation (32%) (Stena Recycling 2016).

5. Summary

The most important goals that recycling companies set themselves for the coming years include cost optimisation for medium-sized enterprises and improvement in waste management logistics along with increases in recycling levels for large enterprises. In accordance with applicable regulations, the required level of waste recycling is systematically increasing, thus prompting companies to introduce new processing methods, optimise waste management processes and design products in such a way that recycling them is possible to the highest degree. The elements of the waste management process, which are currently the biggest problem for medium-sized enterprises, are:

a. waste storage,
b. segregation,
c. waste management logistics,
d. contact with many operators,
e. inovative waste processing.

Increasing requirements, vis-à-vis the environment and the steps taken to introduce a circular economy, have a direct impact on the increase in new techniques and in innovation in Polish recycling companies.

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References

Biswajit, D., Chowdhury, R. Ghosh, K., (2018). Sustainability of metal recovery from E-waste. *Frontiers of Environmental Science and Engineering*, 1-12.

Burzyńska, K., (2018). Portal Komunalny. In: https://portalkomunalny.pl/gospodarka-odpadami-trendy-2018-r-369823/ (Date of Access: 01.04.2020).

Central Statistical Office (2017), *Material Economy in 2016*, Warsaw 2017

Chamier-Gliszczynski, N., Krzyzynski, T. (2005). On modelling three-stage system of receipt and automotive recycling. *REWAS'04, Global Symposium on Recycling, Waste Treatment and Clean Technology 2005*, 2813-2814, Madrid, Spain, 26-29 September 2004, Conference Paper, ISBN: 8495520060.

Chamier-Gliszczyński, N. (2010). Optimal Design for the Environment of the Means Transportation: a Case Study of Reuse and Recycling Materials. *Sold State Phenomena, 165*, 244-249. DOI: 10.4028/www.scientific.net/SSP.165.244

Chamier-Gliszczyński, N. (2011). Environmental aspects of maintenance of transport means, end-of life stage of transport means. *Eksploatacja i Niezawodnosc – Maintenance and Reliability, 50(2*), 59-71. In: http://ein.org.pl/podstrony/wydania/50/pdf/07.pdf

Chamier-Gliszczyński, N. (2011a). Reuse, Recovery and Recycling System of End-of Life Vehicles. *Key Engineering Materials, 450*, 425-428. DOI: 10.4028/ www.scientific.net/KEM.450.425

Chamier-Gliszczyński, N. (2011b). Recycling Aspect of End-of Life Vehicles. Recovery of Components and Materials from ELVs. *Key Engineering Materials, 450*, 421-424. DOI: 10.4028/www.scientific.net/KEM.450.421

Czwajda, L., Kosacka-Olejnik, M., Kudelska, I., Kostrzewski, M., Sethanan, K., Pitakaso, R. (2019). Application of prediction markets phenomenon as decision support instrument in vehicle recycling sector. *Logforum, 15(2)*, 265-278. DOI: 10.17270/J.LOG.2019.329

Dobrzycki, A., Filipiak, M., Jajczyk, J. (2019). Changes in the range of electric vehicles during operation, *ITM Web of Conferences, 28 (01009)*, DOI: https://doi.org/10.1051/itmconf/20192801009

Duan, C., Wen, X. & Shi, C. (2009). Recovery of metals from waste printed circuit boards by a mechanical method using a water medium. *Journal of Hazardous Materials*, *1*(166), 478-482.

Gabryelewicz, I., Stryjski, R., Wędrychowicz, M., Dąbrowski, T. (2020). The State of the Air Quality in Poland. *Rocznik Ochrona Środowiska, 22*(2), 998-1013.

Gabryelewicz, I., Krupa, P., Sąsiadek, M. (2018). *International Business Information Management Association Conference – IBIMA*: Innovation Management and Education Excellence through Vision 2020, Milan, Włochy, Norristown: International Business Information Management Association (IBIMA), 4720-4727.

Havlik, T. (2010). Leaching of copper and Tin from used printed circuit boards after thermal treatment. *Journal of Hazardous Materials, 183*, 866-873.

Hausner, J. (2017). *The future of the market economy – from opportunistic to relational economic gamej*, Cracow: Open Eyes Book (in Polish).

Huisman, J., Botezatu, I. i Herreras, L. (2015). *Countering WEEE Illegal Trade Summary Report*, Croatia: CWIT consortium.

Institute for Research on Market Economy, (2017). *Functioning and irregularities in the management system of waste electrical and electronic equipment (WEEE) in Poland*, Warszawa (in Polish).

Jachowicz, T., Sikora, J., Dulebova, L. (2017). Investigating effects of prodegradant content on selected properties of polymer composite materials. *Environmental Engineering and Management Journal, 16*(12), 2879-2886.

Jacyna, M., Wasiak, M., Lewczuk, K., Chamier-Gliszczyński, N., Dąbrowski, T. (2018). Decision Problems in Developing Proecological Transport System. *Rocznik Ochrona Środowiska, 20*(2), 1007-1025.

Jajczyk, J. (2016). Use of Personal Computers with Multi-core Processors for Optimisation Using the Genetic Algorithm Method, IEEEXplore Electronic. DOI: https://doi.org/10.1109/CPEE.2016.7738731.

Jajczyk, J., Filipiak, M., Dąbrowski T. (2020). Reducing the Use of Electrochemical Sources of Electricity Through the Use of Wireless Power Supply. *Rocznik Ochrona Środowiska, 22*(1), 444-455.

Kanalikova, A., Behunova, A., Mandicak, T., Mesaros, P. (2019) New technologies for sustaining development in infrastructure, logistics and construction industry. *Acta Logistica, 6*(4), 171-177. DOI: 10.22306/al.v6i4.145

Kosacka-Olejnik, M. (2019). How manage waste from End-of-Life Vehicles? – method proposal. *IFAC Papersonline*, 52, 13, 1733-1737. DOI: 10.1016/j.ifacol. 2019.11.451

Kulczycka, J., Karaś, H. (2016). Legal versus illegal trade in waste electrical and electronic equipment – effects and threats. *CUPRUM – Czasopismo Naukowo-Techniczne Górnictwa Rud, 78*(1), 65-75 (in Polish).

Lee, J., Lee, J. (2012). Disassembly and physical separation of electric/electronic components layered in printed circuit boards (PCB). *Journal of Hazardous Materials*, October, 241-242.

Main Environmental Inspectorate, (2018). *The state of the environment in Poland,* Report 2018. Warszawa: Biblioteka Monitoringu Środowisowego.

Marczewska, M., Jaskanis, A., Kostrzewski, M. (2020). Knowledge, Competences and Competitive Advantage of the Green-Technology Companies in Poland. *Sustainability, 12*(21), 8826. DOI: 10.3390/su12218826

Merkisz-Guranowska, A. (2018). Waste recovery of end-of-life vehicles. International Automotive Conference (KONMOT 2018), 421, 032019. DOI: 10.1088/1757-899X/421/3/032019

National Fund for Environmental Protection, (2015). Standards for the processing of individual types of waste equipment and requirements for waste equipment processing plants, Report Ministry of the Environment (in Polish).

Report of the Main Statistical Office, Environmental Protection 2. (2017). Environmental Protecion, Warszawa: Main Statistical Office.

Reconomy, Koalicja na rzecz Gospodarki Obiegu Zamkniętego. (2017). *Gospodarka obiegu zamkniętego – Biznes i konsument na ścieżce zmiany.* Warszawa: no name of the author.

Stena Recycling Innovating, (2016). In: https://odpady.net.pl/2016/04/20/przedsiebiorcy-stawiaja-na-odpowiedzialne-gospodarowanie-odpadami/ (Date of Access: 2020).

Stena Recycling, (2016). In: https://biznesalert.pl/raport-potrzeby-oczekiwania-i-obawy-przedsiebiorstw-wytwarzajacych-odpady/ (Date of Access: 04.05.2021).

Straka, M., Tausova, M., Rosova, A., Cehlar, M., Kacmary, P., Sisol, M., Ignacz, P., Farkas C. Big Data Analytics of a Waste Recycling Simulation Logistics System. *Polish Journal of Environmental Studies, 29*(3), 2355-2364, DOI: 10.15244/pjoes/108684.

Woynarowska, A., Żukowski, W., (2009). Modern methods of recycling electronic waste. *Chemia – Czasopismo Techniczne, 06*(10), 177-182.

Woźniak, W., Nawrocki, W., Stryjski, R., Jakubowski, J. (2017). *Identification and reduction of product defects in mass production at toyota motor manufacturing, Poland.* W: Proceedings of the 30th International Business Information Management Association Conference – IBIMA 2017 4774-4782, Madrid, Spain, 2017.

Woźniak, W., Nawrocki, W., Stryjski, R., Jakubowski, J. (2017). *Diagnosis of process parameters which reduce the defective parts in mass production.* W: Proceedings of the 29th International Business Information Management Association Conference – IBIMA 2017, 2628-2635, Vienna, Austria 2017.

Yazici, E., Daveci, H. (2009). Recovery of metals from E-wastes. *Journal of the Chamber of Mining Engineers of Turkey*, *3*(43), 3-18.

Zajac, P., Kwasniowski, S. (2017). *Modeling forklift truck movement in the VDI cycle and the possibility of energy recovery*. In 23rd International conference on engineering mechanics, 1094-1097. In: https://engmechx.it.cas.cz/improc/2017/1094.pdf

Zajac, P., Stas, D., Lenort, R. (2020). Noise Charge in Rail Transport-EU Regulations Versus Operation of Logistics Systems. *Rocznik Ochrona Środowiska, 22*.

Zhang, L. Xu, (2016). A review of current progress of recycling technologies for metals from waste electrical and electronic equipment. *Journal of Cleaner Production*.

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The Water Requirements of Grapevines (*Vitis vinifera* L.) Under Climatic Conditions of Central Poland

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Abstract: The purpose of this study was to estimate the water needs of grapevines in central Poland in 1981-2010. Water needs were calculated by the plant coefficients, which were assumed according to the Doorenbos and Pruitt method. Reference evapotranspiration was assessed by the Blaney-Criddle's equation, modified for Polish conditions. Rainfall deficit with the occurrence probability of normal, medium dry and very dry years was determined by the Ostromęcki's method. Water needs of grapevines during the growing season was 434 mm. Upward time trend in the water needs both in the periods May-October and June-August was estimated. Temporal variability in the water needs was significant for most of the provinces. The rainfall deficit was recorded with the occurrence probability of normal as well as medium or very dry years in the entire study area. Due to climate changes, vineyards will require irrigation in the near future. This research significantly broadens and refines the knowledge about the water needs of grapevines in central Poland, which will allow the design of resource-efficient irrigation programs for grapevines in the studied region of Poland.

Keywords: climate changes, evapotranspiration, irrigation, precipitation, rainfall deficit

1. Introduction

The tradition of viticulture in Poland dates back to the Middle Ages. Nowadays, the largest number of vineyards in Poland is located in the south-eastern, south-western and southern provinces of the country, where are the most favourable climatic conditions for viticulture (Bokwa & Klimek 2009, Kopeć 2009, Myśliwiec 2013, Adamczewska-Sowińska et al. 2016). However, many new vineyards are also created in eastern and central Poland, despite the fact that there are much less satisfactory climatic environments for viticulture (Adamczewska-Sowińska et al. 2016, Koźmiński & Michalska 2001). The development of new vineyards in Poland is the effect of people's enrichment and changes in consumer preferences, as well the increase of ecological agro-tourism, including oeno-tourism activities. A large rise in interest in viticulture in Poland is also the result of the great progress in breeding program aimed to obtain new cultivars with low susceptibility to fungal diseases and frost damage, as well the gradual warming of the climate (Szymanowski & Smaza 2007, Kopeć 2009, Łabędzki 2009a, Łabędzki 2009b, Lisek 2011, Kapłan 2013, Myśliwiec 2013, Bąk & Łabędzki 2014, Pink 2015, Rolbiecki & Piszczek 2016).

Orchard plantations in central Poland are exposed to the largest deficit of atmospheric precipitation in the growing season (Rojek 2006, Rzekanowski 2009). According to Rzekanowski (2009) in the case of fruit plants, the highest water deficit occur in the great valleys area, i.e. the central Poland, while more favourable water conditions are in the southern and northern region of the country. The most important factors that limiting the development of vineyards in central Poland is minimum winter temperature (-30°C occurring at least once in 10 years), as well spring and autumn frosts (Lisek 2008). The sum of active temperatures (SAT) above 10°C is considered to be the most important climatic criterion, which is particularly useful for assessing the conditions of viticulture (Myśliwiec 2006, Lisek 2008, Grabowski & Kopytowski 2009). In the last few decades climate change that is favourable for viticulture has been observed in Poland. As reported Lisek (2008), in central Poland in the years 1981-2000 the average SAT was almost 2500°C, while in 2003 the SAT was over 2700°C, and in 2006 the SAT was up to 2900°C. For comparison, the SAT in the north-eastern Poland is about 2200°C, in the highlands of central Poland 2600°C and 2700°C in the south-west and west part of the country (Myśliwiec 2006, Grabowski & Kopytowski 2009). According to Lisek (2008), as the result of climate change, especially due to the increase in temperature in the period from May 1 to September 30, viticulture in central Poland is today much more effective than twenty years ago. On the one hand, due to climate warming, the subsequent phenological stages of the plant development occur earlier, what increases the quality of fruit of the grapevines. On the other hand, an increase in the average summer (May-September) temperature of 1°C rises the water needs of grapevines by 50 mm of annual precipitation, assuming that at least 50% of annual precipitation occurs during the growing season (Słowik 1973, Dzieżyc 1988).

The purpose of the present study was to calculate the water needs of grapevine plants grown in central Poland. The results of the research will help to develop a program of resource-efficient irrigation of vineyards in central provinces of the country.

2. Materials and methods

In the present study, as a measure of water needs of grapevine (*Vitis vinifera* L.) was a crop evapotranspiration (Łabędzki et al. 1996). The water needs of grapevines were determined by the plant coefficients method. The reference evapotranspiration was calculated by the Blaney-Criddle's equation that was modified for Polish conditions (Żakowicz 2010, Rolbiecki 2018). The plant coefficients for grapevines (adjusted to the reference evapotranspiration that was considered by the Blaney-Criddle's method) were assumed according to Doorenbos and Pruitt (1977). It was supposed that vineyards are in the stage of full development, and the soil in the middle of the growing season is covered with plants at the level of 40-50%. It was also assumed that the grapevines are grown in the region with cold winter and severe spring, and autumn frosts; the first leaves appear in early May, while the harvest begins in mid-September.

The water needs of the grapevines were calculated on the basis of measurement data collected from five meteorological stations located in Bydgoszcz, Warszawa, Poznań and Łódź, which were representative for considered provinces situated in central Poland: Kuyavian-Pomeranian Province (K-P), Masovian Province (M), Greater Poland Province (G-P) and Lodz Province (L), respectively (Fig. 1). The calculations were carried out for the groving period of grapevines in Poland, considered from May 1 to October 31 in the years 1981-2010 (Doorenbos and Pruitt 1977, Rolbiecki 2018).

The precipitation deficit with the occurrence probability of the normal ($N_{50\%}$), medium dry ($N_{25\%}$) and very dry years ($N_{10\%}$) was determined for the six-month of intensive development of vines (May-October) by the Ostromęcki's method (Żakowicz & Hewelke 1995, Żakowicz & Hewelke 2009).

Among the studied provinces, in each month of the growing period, the lowest standard deviation of the grapevines water needs, which is a measure of the diversity of monthly sums of the water requirements, was estimated in the Masovian Province (Table 1). During the vegetation period, the highest standard deviation of the water needs, ranged from 7.0 to 8.0 mm depending on the province, was noted in July and the lowest standard deviation of the water needs, ranged from 3.0 to 3.4 mm depending on the province, was assessed in May.

Fig. 1. Provinces of central Poland

Table 1. Characteristics of the water requirements of grapevine plants

Characteristic	Province	Months of the growing season					
		May	Jun	Jul	Aug	Sep	Oct
Minimum (mm)	K-P	39	80	103	91	50	19
	M	41	79	100	91	52	21
	G-P	37	76	98	90	50	20
	L	38	75	96	88	49	19
Maximum (mm)	K-P	55	96	133	115	70	33
	M	54	93	132	119	68	34
	G-P	52	93	133	114	86	35
	L	52	90	127	115	67	35
Median (mm)	K-P	48	88	116	104	60	27
	M	48	88	114	103	59	27
	G-P	47	83	112	102	59	27
	L	45	83	110	101	57	27
Standard deviation (mm)	K-P	3.4	4.1	7.4	5.3	4.5	4.0
	M	3.0	4.1	7.0	4.7	4.2	3.6
	G-P	3.3	4.8	8.0	5.3	6.7	3.8
	L	3.1	4.2	7.6	5.0	4.7	3.9
Variability coefficient (%)	K-P	6.9	4.7	6.4	5.0	7.6	15.1
	M	6.4	4.7	6.1	4.6	7.1	13.2
	G-P	7.1	5.6	7.2	5.2	11.3	13.8
	L	6.8	5.0	6.9	4.9	8.2	14.6

K-P – Kuyavian-Pomeranian Province; M – Masovian Province; G-P – Greater Poland Province; L – Lodz Province

3. Results

The average water needs of grapevine plants during the vegetation period, i.e., from May 1 to October 31, in 1981-2010, in central Poland were 434 mm (Fig. 2a). The highest daily water needs of grapevines (over 3.64 mm) were calculated in July (Fig. 2b). A little lower values of daily water needs (3.31 mm) were estimated in August, as well in June (2.84 mm). The lowest water requirements were assessed in May (1.51 mm) and in October (0.87 mm).

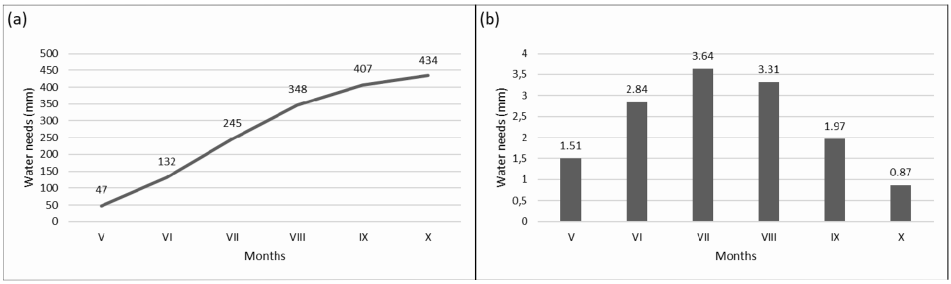

Fig. 2. Water needs (determined by the crop evapotranspiration) of grapevines in central Poland during the period of May-October (V-X) in the years 1981-2010 presented as the sum curve (a) and daily values in the particular months (b)

The highest water needs of grapevine plants in central Poland, in 1981-2010, both in the growing season (from May 1 to October 31) and during the period of increasing water needs by plants (from June 1 to August 31) occurred in the Kuyavian-Pomeranian and Masovian provinces (Fig. 3 a, b). In the above mentioned provinces, the value of crop evapotranspiration was 440 mm in the growing season and 307 mm (K-P), and 306 mm (M) in the period of increasing water needs by plants. The lowest water needs of grapevines, 423 mm in May-October and 293 mm in June-August, were noted in the Lodz Province.

In the studied thirty-year period, in each considered province of central Poland, was observed a visible tendency to increase the water needs of the grapevine plants both in the growing season (May-October), and during the period of increasing water needs by plants (June-August), as well as in the month with the highest water needs, i.e. in July (Table 2).

With the except of the Kuyavian-Pomeranian Province, a significant temporal variability in the grapevine water needs was noted in the entire studied area. The temporal variability in grapevine water needs during the growing season (May-October) indicate that in 1981-2010 the water requirements increased in each decade from 11.2 mm in Greater Poland Province to 4.1 mm in Kuyavian-Pomeranian Province. In June-August, during the period of increasing water needs by plants, the crop evapotranspiration rose in each following decade from

8.4 mm in Greater Poland Province to 4.2 mm in Kuyavian-Pomeranian Province. In July, the month when the water needs of the grapevines are the highest, the crop evapotranspiration increased in the range from 3.7 mm in Greater Poland Province to 2.0 mm in Kuyavian-Pomeranian Province.

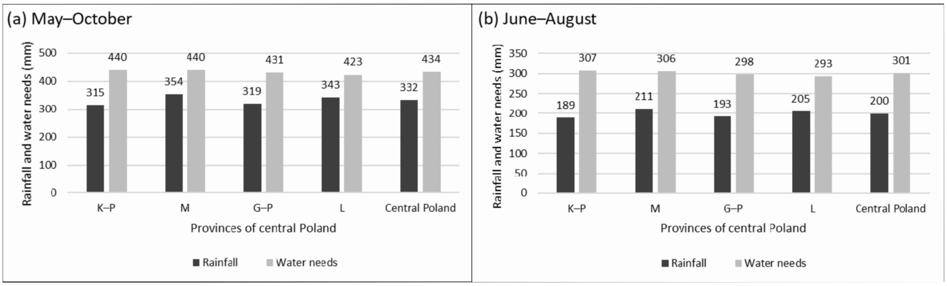

Fig. 3. Water needs (determined by the crop evapotranspiration) of grapevines and the average precipitation in the growing season (a) and in the period of increasing water needs by plants (b) in the considered provinces of central Poland (K-P – Kuyavian-Pomeranian, M – Masovian, G-P – Greater Poland and L – Lodz)

Table 2. Time trend equations of the grapevines water needs in the years 1981-2010

Period	Provinces			
	Kuyavian-Pomeranian	Masovian	Greater Poland	Lodz
Linear correlation coefficient (r)				
May-October	0.260 n.s.	0.473***	0.552***	0.421***
June-August	0.299 n.s.	0.521***	0.520***	0.476***
July	0.237 n.s.	0.422**	0.398**	0.409**
Tendency of water needs (mm decade^{-1})				
May-October	4.1	6.9	11.2	6.6
June-August	4.2	6.8	8.4	6.8
July	2.0	3.4	3.7	3.6

n.s. – not significant; *** – significant at $p \leq 0.01$; ** – significant at $p = 0.05$

The highest rainfall deficit in the studied six-month period of the intensive development of grapevines (from May 1 to October 31) with the occurrence probability of the normal years ($N_{50\%}$) and medium dry years ($N_{25\%}$) was noted in the Kuyavian-Pomeranian Province and amounted to 132 mm and 258 mm, respectively (Table 3). The highest rainfall deficit with the occurrence probability of the very dry years ($N_{10\%}$) were found in the Masovian Province (370 mm). In the three-month period (June-August), during the increasing of water needs by plants, the highest rainfall deficit in the normal years ($N_{50\%}$) and medium dry years ($N_{25\%}$) were observed in the Kuyavian-Pomeranian Province (117 mm and 200 mm, respectively) and the highest rainfall deficit in the very dry years ($N_{10\%}$) was noted in the Masovian Province (302 mm). In July, the rainfall deficits $N_{50\%}$, $N_{25\%}$ and $N_{10\%}$ were evenly balanced. Generally, with the exception of the very dry years ($N_{10\%}$) the lowest rainfall deficit in the normal years ($N_{50\%}$) and medium dry years ($N_{25\%}$) was found in the Lodz Province.

4. Discussion

In Poland, atmospheric precipitations are the primary source of water for viticulture (Myśliwiec 2013). In areas suitable for the grapevines cultivation the annual precipitation ranged between 500 and 800 mm (Myśliwiec 2013, Adamczewska-Sowińska et al. 2016). Rzekanowski (2009), studying the water deficit during the growing season in Poland, on the basis of data from 27 meteorological stations, stated that the highest water deficit in the fruit plants cultivation occurs in central Poland. More favourable water conditions Rzekanowski (2009) noted in the southern and northern region of the country. Rolbiecki and Rzekanowski (1997), Rzekanowski and Rolbiecki (2000a, 2000b), Rolbiecki et al. (2002a, 2002b), Stachowski and Markiewicz (2011) observed also the highest need for irrigation supplementing atmospheric precipitation just in central Poland. A clearly negative effect of drought periods on the yielding of grapevine plants grown in Poland was published by Treder and Pacholak (2006). The water deficit occurring during the drought period contribute to the weak growth of shoots and fruits, drying of shoots growing from the buds in the corners of leafstalks and yellowing of leaves (Myśliwiec 2013). Consequently, the vineyards located in central Poland should be irrigated, especially during the periods of drought. Drip irrigation of the grapevine plantings in Poland was recommended previously by Treder and Pacholak (2006), and Myśliwiec (2013).

In general, in many countries and around the world the irrigation is a common cultivation treatment in vineyards (Ruiz-Sanchez et al. 2010). Much research work highlights the beneficial effects of micro-irrigation, including deficit irrigation, on the development and yielding of grapevines (Yunusa et al. 2000, Yunusa et al. 2005, 2007, Burg 2008, Intrigliolo & Castel 2008, Acevedo-Opazoa et al. 2010, Chaves et al. 2010, Ruiz-Sanchez et al. 2010, Intrigliolo et al. 2012, Nolz et al. 2016, Nolz & Loiskandl 2017). In the studies carried out in Spain, comparing to the rain-fed treatment, all applied irrigation methods increased the yield of grapevine fruit, even by 58% (Intrigliolo et al. 2012).

Table 3. Rainfall deficit (mm) in grapevines cultivation in central Poland

Probability of rainfall deficit occurrence	Provinces			
	Kuyavian-Pomeranian	Masovian	Greater Poland	Lodz
May-October				
$N_{50\%}$ = normal years	132	104	122	98
$N_{25\%}$ = medium dry years	258	250	256	218
$N_{10\%}$ = very dry years	335	370	305	309
June-August				
$N_{50\%}$ = normal years	117	95	104	88
$N_{25\%}$ = medium dry years	200	196	190	169
$N_{10\%}$ = very dry years	259	302	219	237
July				
$N_{50\%}$ = normal years	37	38	36	26
$N_{25\%}$ = medium dry years	94	89	83	86
$N_{10\%}$ = very dry years	128	123	100	131

The expected further climate changes may cause an increase in water needs of the plants, including also grapevines (Rolbiecki & Piszczek 2016, Rolbiecki et al. 2017, Jagosz et al. 2020, Piña-Rey et al. 2020). Therefore, some adaptation measures should be taken already today to protect plant crops against the effects of rising air temperature. These adaptation activities include the irrigation treatments, particularly the resource-efficient drip irrigation systems. The results of the research presented in this paper will allow for precise programming of irrigation treatments for vineyards located in central Poland. It was found that the water needs of grapevines during the growing season in the study area amounted to 434 mm, and this value was not covered by rainfalls.

In the presented research, the observations of the temporal variability analyzed on the basis of the 30-year period showed a significant gradual increase in the water needs of grapevine plants in most of the studied provinces. According to Łabędzki (2009a, 2009b), Kuchar and Iwański (2011), Stachowski and Markiewicz (2011), Kuchar and Iwański (2013), Łabędzki et al. (2013), and Kuchar, et al. (2015, 2017), the importance of the irrigation treatments will gradually increase along with the intensification of adverse climate changes. Łabędzki (2009a, 2009b) reports that in Poland a temperature will rise in the range of 2°C to 4°C. It should be noted that individual scenarios for temperature and precipitation changes, developed for Poland in the coming (2020) and following (2050 and 2080) years, differ significantly, especially in the summer months (from June to August). On the one hand, all scenarios, in fact, assume an increase in air temperature. It is expected that the average monthly air temperature in July and August may exceed even 25°C. On the other hand, only some scenarios predict an increase in precipitation, while others assume a decrease in precipitation. This research has shown that in vineyards located in central Poland, there is already a significant deficit in precipitation.

5. Conclusions

It was found that during the growing season, i.e. from May 1 to October 31, the average water needs of grapevines grown in vineyards located in central Poland amounted 434 mm and it is not covered by rainfall. Both in the growing season and during the period of increasing water needs by plants, i.e. from June 1 to August 31, an upward time trend in the water needs of grapevines was noted. Except the Kuyavian-Pomeranian Province the significant temporal variability in water needs was significant for each provinces. Regardless of the occurrence probability of the normal, medium or dry years, the rainfall deficit in the growing season in grapevine cultivation was recorded in the entire studied area of central Poland. The presented research results constitute the basis for designing resource-efficient irrigation programs necessary in agricultural and horticultural crops in the light of the observed global warming of the climate.

References

Acevedo-Opazoa, C., Ortega-Fariasa, S., Fuentes, S. (2010). Effects of grapevine (*Vitis vinifera* L.) water status on water consumption, vegetative growth and grape quality: An irrigation scheduling application to achieve regulated deficit irrigation. *Agricultutal Water Management*, *97*(7), 956-964. DOI: 10.1016/j.agwat.2010.01.025

Adamczewska-Sowińska, K., Bąbelewski, P., Chohura, P., Czaplicka-Pędzich, M., Gudarowska, E., Krężel, J., Mazurek, J., Sosna, I., Szewczuk, A. (2016). *Agrotechniczne aspekty uprawy winorośli [Agrotechnical aspects of viticulture]*. Wrocław: Druk-24h (in Polish).

Bąk, B., Łabędzki, L. (2014). Thermal conditions in Bydgoszcz region in growing seasons 2011–2050 in view of expected climate change. *Journal Water and Land Development, 23*, 21-29. DOI: 10.1515/jwld-2014-0026

Bokwa, A., Klimek, M. (2009). Warunki klimatyczne Pogórza Wielickiego dla potrzeb uprawy winorośli [Climate conditions of the Wieliczka Foothills for the purposes of viticulture]. In: A. Zborowski, Z. Górka (Editors). *Człowiek i rolnictwo [Man and agriculture]* (pp. 103-111). Kraków: IGiGP UJ (in Polish).

Chaves, M.M., Santos, T.P., Souza, C.R., Ortuño, M.F., Rodrigues, M.L., Lopes, C.M., Maroco, J.P., Pereira, J.S. (2007). Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. *Annals of Applied Biology, 150*(2), 237-252. DOI: 10.1111/j.1744-7348.2006.00123.x

Chaves, M.M., Zarrouk, O., Francisco, R., Costa, J.M., Santos, T., Regalado, A.P., Rodrigues, M.L., Lopes, C.M. (2010). Grapevine under deficit irrigation: hints from physiological and molecular data. *Annals of Botany*, *105*(5), 661-676. DOI: 10.1093/aob/mcq030

Doorenbos, J., Pruitt, W.O. (1977). Guidelines for predicting crop water requirements. *FAO Irrigation and Drainage Paper 24,* 176.

Burg, P. (2008). The influence of drip irrigation on the quality of vine grapes. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, *56*(1), 31-36.

Dzieżyc, J. (1988). *Rolnictwo w warunkach nawadniania [Irrigationin agriculture]*. Warszawa: PWN (in Polish).

Grabowski, J., Kopytowski, J. (2009). Czas aktywnego wzrostu roślin w Polsce północno-wschodniej, a warunki uprawy winorośli [The time of active plant growth in north-eastern Poland and the conditions of viticulture]. *Zeszyty Problemowe Postepów Nauk Rolniczych*, *536*, 87-94 (in Polish).

Intrigliolo, D.S., Castel, J.R. (2008). Effects of irrigation on the performance of grapevine cv. Tempranillo in Requena, Spain. *American Journal of Enology and Viticulture*, *59*, 30-38.

Intrigliolo, D.S., Pérez, D., Risco, D., Yeves, A., Castel, J.R. (2012). Yield components and grape composition responses to seasonal water deficits in Tempranillo grapevines. *Irrigation Science*, *30(5)*, 339-349. DOI: 10.1007/s00271-012-0354-0

Jagosz, B., Rolbiecki, S., Stachowski, P., Ptach, W., Łangowski, A., Kasperska-Wołowicz, W., Sadan, H.A., Rolbiecki, R., Prus, P., Kazula, M.J. (2020). Assessment of water needs of grapevines in western Poland from the perspective of climate change. *Agriculture 10*, 0477. DOI: 10.3390/agriculture10100477

Kapłan, M. (2013). Możliwości uprawy winorośli w Polsce [Possibilities of viticulture in Poland]. *Nauki Przyrodnicze*, *2*, 4-12.

Kopeć, B. (2009). Uwarunkowania termiczne wegetacji winorośli na obszarze południowo-wschodniej Polski [Thermal conditions of grape's vegetation in south-eastern Poland]. *Infrastructure and Ecology of Rural Areas*, *4*, 251-262.

Koźmiński, C., Michalska, B. (2001). *Atlas klimatycznego ryzyka uprawy roślin w Polsce [Atlas of climatic risk to crop cultivation in Poland]* (pp. 17-18). Szczecin: Usz. (in Polish).

Kuchar, L., Iwański, S. (2011). Symulacja opadów atmosferycznych dla oceny potrzeb nawodnień roślin w perspektywie oczekiwanych zmian klimatycznych [Rainfall simulation for the prediction of crop irrigation in future climate]. *Infrastructure and Ecology of Rural Areas*, *5*, 7-18 (in Polish).

Kuchar, L., Iwański, S. (2013). Ocena opadów atmosferycznychdla potrzeb produkcji roślinnej w perspektywie lat 2050-2060 i wybranych scenariuszy zmian klimatu w północno-centralnej polsce. [Rainfall evaluation for crop production until 2050-2060 and selected climate change scenarios for North Central Poland]. *Infrastructure and Ecology of Rural Areas*, *2*(I), 187-200 (in Polish).

Kuchar, L., Iwański, S., Diakowska, E., Gąsiorek, E. (2015). Symulacja warunków hydrotermicznych w północnej części centralnej polski w perspektywie lat 2050-2060 dla potrzeb produkcji roślinnej i wybranych scenariuszy klimatycznych. [Simulation of hydrothermal conditions for crop production purpose until 2050-2060 and selected climate change scenarios for North Central Poland]. *Infrastructure and Ecology of Rural Areas*, *II*(1), 319-334 (in Polish).

Kuchar, L., Iwański, S., Diakowska, E., Gąsiorek, E. (2017). Ocena suszy meteorologicznej w 2015 roku w północnej części centralnej polski z wykorzystaniem wskaźnika hydrotermicznego (htc) w kontekście zmian klimatycznych [Assessment of meteorological drought in 2015 for North Central part of Poland using hydrothermal coefficient (HTC) in the context of climate change]. *Infrastructure and Ecology of Rural Areas*, *I*(2), 257-273. DOI: dx.medra.org/10.14597/infraeco.2017.1.2.019 (in Polish).

Lisek, J. (2011). *Winorośl w uprawie przydomowej i towarowej [Vines in home and commercial cultivation].* Warszawa: Hortpress (in Polish).

Lisek, J. (2008). Climatic factors affecting development and yielding of grapevine in Central Poland. *Journal of Fruit and Ornamental Plant Research*, *16*, 286-293.

Łabędzki, L. (2009a). Przewidywane zmiany klimatyczne a rozwój nawodnień w Polsce [Foreseen climate changes and irrigation development in Poland]. *Infrastructure and Ecology of Rural Areas*, *3*, 7-18.

Łabędzki, L. (2009b). Expected development of irrigation in Poland in the context of climate change. *Journal Water and Land Development*, *13b*, 17-29. DOI: 10.2478/v10025-010-0002-0

Łabędzki, L., Szajda, J., Szuniewicz, J. (1996). Ewapotranspiracja upraw rolniczych – terminologia, definicje, metody obliczania. Przegląd stanu wiedzy [Evapotranspiration of agricultural crops – terminology, definitions, calculation methods. Review]. *Materiały Informacyjne IMUZ Falenty*, *33*, 1-15 (in Polish).

Łabędzki, L., Bąk, B., Liszewska, M. (2013). Wpływ przewidywanej zmiany klimatu na zapotrzebowanie ziemniaka późnego na wodę [Impact of climate change on water demand of late potato]. *Infrastructure and Ecology of Rural Areas*, *2*(I), 155-165.

Myśliwiec, R. (2013). *Uprawa winorośli [Viticulture].* Warszawa: PWRiL (in Polish).

Myśliwiec, R. (2006). *Winorośl i wina [Vines and wines]*. Warszawa: PWRiL (in Polish).

Nolz, R., Loiskandl, W., Kammerer, G., Himmelbauer, M.L. (2016). Survey of soil water distribution in a vineyard and implications for subsurface drip irrigation control. *Soil and Water Research, 11*, 250-258. DOI: 10.17221/170/2015-SWR

Nolz, R., Loiskandl, W. (2017). Evaluating soil water content data monitored at different locations in a vineyard with regard to irrigation control. *Soil and Water Research, 12*, 152-160. DOI: 10.17221/9/2016-SWR

Piña-Rey, A., González-Fernández, E., Fernández-González, M., Lorenzo, M.N., Rodríguez-Rajo, F.J. (2020). Climate change impacts assessment on wine-growing bioclimatic transition areas. *Agriculture*, *10*, 605. DOI: 10.3390/agriculture10120605

Pink, M. (2015). Polska jako kraj winiarski? Od tradycji do rodzących się możliwości [Poland as a wine country? From tradition to emerging possibilities]. *Problemy Problems of Small Agricultural Holdings*, *2*, 37-56. DOI: 0.15576/PDGR/ 2015.2.37 (in Polish).

Rojek, M. (2006). Potrzeby nawadniania w Polsce [Irrigation needs in Poland]. In: S. Karczmarczyk, L. Nowak (Editors). *Nawadnianie roślin [Plant irrigation]* (pp. 91-108). Poznań: PWRiL (in Polish).

Ruiz-Sanchez, M.C., Domingo, R., Castel, J.R. (2010). Review. Deficit irrigation in fruit trees and vines in Spain. *Spanish Journal of Agricultural Research*, *8*, 5-20. DOI: 10.5424/sjar/201008S2-1343

Rolbiecki, S. (2018). O szacowaniu potrzeb wodnych drzew owocowych w Polsce na podstawie temperatury powietrza [On the estimation of the water needs of fruit trees in Poland based on air temperature]. *Infrastructure and Ecology of Rural Areas*, *II*(1), 393-406. DOI: 10.14597/INFRAECO.2018.2.1.02 (in Polish).

Rolbiecki, S., Piszczek, P. (2016). Effect of the forecast climate change on the grapevine water requirements in the Bydgoszcz region. *Infrastructure and Ecology of Rural Areas*, *IV*(4), 1847-1856. DOI: 10.14597/infraeco.2016.4.4.13

Rolbiecki, S., Piszczek, P. Chmura, K. (2017). Attempt at comparison of the grapevine water requirements in the regions of Bydgoszcz and Wrocław. *Infrastructure and Ecology of Rural Areas*, *III*(2), 1157-1166. DOI: 10.14597/infraeco.2017.3.2.088

Rolbiecki, S., Rolbiecki, R., Rzekanowski, C. (2002a). Response of black currant (*Ribes nigrum* L.) cv. 'Titania' to micro-irrigation under loose sandy soil conditions. *Acta Horticulture*, *585*(2), 649-652. DOI: 10.12911/22998993/109859

Rolbiecki, S., Rolbiecki, R., Rzekanowski, C. (2002b). Effect of micro-irrigation on the growth and yield of raspberry (*Rubus idaeus* L.) cv. 'Polana' grown in very light soil. *Acta Horticulture*, *585*(2), 653-657. DOI: 10.17660/ActaHortic.2002.585.108

Rolbiecki, S., Rzekanowski, C. (1997). Influence of sprinkler and drip irrigation on the growth and yield of strawberries grown on sandy soils. *Acta Horticulture*, *439*(2), 669-672. DOI: 10.17660/ActaHortic.1997.439.112

Rzekanowski, C. (2009). Kształtowanie się potrzeb nawodnieniowych roślin sadowniczych w Polsce [Shaping of irrigation needs for fruit plants in Poland]. *Infrastructure and Ecology of Rural Areas*, *3*, 19-27 (in Polish).

Rzekanowski, C., Rolbiecki, S. (2000a). The influence of drip irrigation on yields of some cultivars of apple trees in central Poland under different rainfall conditions during the vegetation season. *Acta Horticulture*, *537*(2), 929-936. DOI: 10.14597/infraeco.2017.3.2.094

Rzekanowski, C., Rolbiecki, S. (2000b).The influence of drip irrigation on yields of some cultivars of stone fruit-bearing trees in central Poland under different rainfall conditions during the vegetation season. *Acta Horti*culture, *537*(2), 937-942. DOI: 10.17660/ActaHortic.2000.537.114

Słowik, K. (1973). *Deszczowanie roślin sadowniczych [Sprinkling of fruit plants]*. Warszawa: PWRiL (in Polish).

Stachowski, P., Markiewicz, J. (2011). Potrzeba nawodnień w centralnej Polsce na przykładzie powiatu kutnowskiego. [The need of irrigation in central Poland on the example of Kutno county]. *Rocznik Ochrona Środowiska*, *13*, 1453-1472 (in Polish).

Szymanowski, M., Smaza, M. (2007). Zmiana zasobów klimatycznych a możliwości uprawy winorośli na Dolnym Śląsku [Change of climatic resources and possibilities of viticulture in Lower Silesia]. *Proceedings of the XXXII National Congress of Agrometeorologists and Climatologists, Kołobrzeg, Poland*, September 13-15, 69-70.

Treder, W., Pacholak, E. (2006). Nawadnianie roślin sadowniczych [Irrigation of fruit plants]. In: S. Karczmarczyk, L. Nowak, (Editors). *Nawadnianie roślin [Plant irrigation*] (pp. 333-365). Poznań: PWRiL (in Polish).

Yunusa, I.A.M., Walker, R.R., Loveys, B.R., Blackmore, D.H. (2000). Determination of transpiration in irrigated grapevines: comparison of the heat-pulse technique with gravimetric and micrometeorological methods. *Irrigation Science*, *20*(1), 1-8.

Yunusa, J., Bota, J., Escalona, J.M., Medrano, H., Flexas, J. (2005) Phyisological tools for irrigation scheduling in grapevine (*Vitis vinifera* L.): An open gate to improve water-use efficiency? *Agriculture, Ecosystems & Environment*, *106*(2-3), 159-170. DOI: 10.1016/j.agee.2004.10.005

Żakowicz, S. (2010). *Podstawy technologii nawadniania rekultywowanych składowisk odpadów komunalnych [Fundamentals of irrigation technology for reclaimed municipal waste Dumas]*. Warszawa: SGGW (in Polish).

Żakowicz, S., Hewelke, P. (1995). *Wybrane materiały meteorologiczne [Selected meteorological materials]* (p. 356). Warszawa: SGGW (in Polish).

Żakowicz, S., Hewelke, P., Gnatowski, T. (2009). *Podstawy infrastruktury technicznej w przestrzeni produkcyjnej [Basics of technical infrastructure in production space]* (p. 192). Warszawa: SGGW (in Polish).

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Modelling of CO_2 Emissions in Driving Tests on the Example of a Compression Ignition Engine Powered by Biofuels

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Abstract: Climate change, environmental degradation and the introduction of increasingly restrictive legal regulations mean that the automotive industry is facing tremendous challenges. The paper presents a computer tool that uses the results of tests carried out on a chassis dynamometer for a Fiat Panda 1.3 Multijet, to simulate driving tests. As a result of the work of a computer tool, the impact on CO_2 emissions was analysed in the context of CADC – Artemis (Common Artemis Driving Cycles) road tests for the following fuels: diesel oil, FAME (Fatty Acid Methyl Esters), rapeseed oil and butanol. Mass consumption of fuels and CO_2 emissions were analysed in driving tests for the vehicle in question. The highest mass consumption of fuel and carbon dioxide emissions occurred in the case of FAME (respectively 2.283 kg and 6.524 kg).

Keywords: engine, CO_2 emission, CADC

1. Introduction

Climate change and the deteriorating condition of the natural environment are currently the leading problems for the countries of the European Union and the world (Fekete et al. 2021, Capros et al. 2018, Jacyna et al. 2018). With the constant development of economic industrialization, it is necessary to introduce an appropriate environmental policy so that further technological progress does not pose a threat to health and life in developing areas (Tutak et al. 2021). The new strategy of the European community, also known as the "European Green Deal", is an action plan that aims to make Europe a neutral continent in terms of greenhouse gas emissions by 2050, while maintaining a competitive, modern and sustainable economy (Gunfaus et al. 2021). The possibilities of implementing the plan are pursued in all economic and social areas, including, to a large extent, the transport sector which is currently responsible for about ¼ of greenhouse gas emissions (Zhao et al. 2020). By 2050, emissions from transport are expected to be reduced by around 90%. For this purpose, integrated and consistent actions are required, through cleaner and healthier solutions that can replace current conventional technologies (Olabi et al. 2021, Pyza et al. 2018). It is not possible to completely switch to electric mobility, therefore, for internal combustion engines, an increase in the share of biofuels and biocomponents that can reduce CO_2 emissions from these vehicles is expected, in addition to more stringent exhaust emission standards (Puricelli et al. 2020, Commission Regulation (EU) No 407/2011, Regulation No 85 of the Economic Commission for Europe of the United Nations (UN/ECE), Regulation No 101 of the Economic Commission for Europe of the United Nations (UN/ECE)). Further research on alternative fuels is therefore recommended, which will be used in the implementation of the reduction targets set (Javed et al. 2020).

From the point of view of the development of infrastructure and services in the field of transport and mobility, the transport behaviour of urban residents and the assessment of mobility in urban areas are also important issues (Chamier-Gliszczyński et al. 2016, Chamier-Gliszczyński et al. 2016).

This article focuses on vehicles with a compression ignition engine. For cars of this type, diesel fuel can be replaced by fatty acid methyl esters, vegetable oils with appropriate parameters as well as alcohols with properties similar to those of conventional fuel. These substances are usually used as additives, but some could be self-contained propellants. Fatty acid methyl esters (FAME), rapeseed oil and butanol were selected for the analyses carried out in the study. FAME fuel is a substance produced from vegetable oils or animal fats in the process of trans-esterification of fatty acids (Bemani et al. 2020). Depending on the climatic conditions and the crops grown, the basis can be rapeseed oil, e.g. in Germany or Poland, sunflower oil, e.g. in Spain or soybean oil, e.g. in the United States. Methyl esters have better lubricating properties than diesel oil, which extends the life of the engine, and has a more favourable carbon dioxide emission balance (Alves-Fortunato et al. 2020). Butanol is also known as butyl alcohol – which is an organic chemical compound from the group of alcohols (Bharathiraja et al. 2017). On a massive scale, it is obtained from fossil fuels, but it can also be obtained by fermentation, e.g. of plant biomass. As a result, it supports the EU's policy of promoting alternative energy sources, whether as an additive or a standalone fuel. Its advantage is the possibility of direct application without the need for additional actions to modify the properties to make them even more similar to conventional fuel. Raw rapeseed oil is mainly used for food purposes. It could however, under certain conditions, replace classic diesel oil, due to the similarity of some physicochemical characteristics (Mikulski et al. 2020). This would be advantageous as there would be no need to carry out costly and energy-consuming technological operations required to transform the oil into e.g. esters.

In order to assess the possibilities of reducing carbon dioxide emissions for the indicated alternative fuels, computer simulations were carried out using the physicochemical properties of these substances. The simulation was performed according to the CACD (Common Artemis Driving Cycles) test procedure (Sileghem et al. 2014). It is a test procedure carried out on a chassis dynamometer, whose formula was defined as a result of the international research project called Artemis. The program improved European methods for estimating and inventorying emissions from the transport sector. About 50 participants (laboratories, project teams and institutions) from 17 countries took part in the project. As a result, a test procedure was obtained that reflects the real movement of vehicles in road traffic and thus produces reliable emission results from these vehicles. The CADC consists of three main parts: the urban cycle, the extra-urban cycle, and the motorway cycle (Common Artemis Driving Cycles 2021).

As a result of the simulations, the results of fuel consumption and carbon dioxide emissions from the vehicle were obtained when running on the indicated fuels. However, to assess the functionality of alternative fuels, the power, torque and mechanical energy value generated during the test were also compared.

2. Methodology

As part of the project, a quantitative model was prepared of specific fuel consumption as a function of rotational speed and torque of a compression ignition engine, on the basis of data published by EPA (Environmental Protection Agency). The publications on which the simulations were based included studies of a compression ignition engine (Ambrozik et al. 2012, Ambrozik et al. 2016).

Then, simulations of the operation of the selected vehicle in driving tests were carried out in order to obtain the amount of CO_2 emissions and fuel demand for the fuels used (diesel oil, FAME, rapeseed oil and butanol). It was assumed in the developed model that, at a given simulation point of the engine resulting from the instantaneous rotational speed and instantaneous torque for various fuels, the efficiency of this engine is the same.

Table 1 summarizes the basic properties of the fuels used (Kordylewski et al. 2008, Baczewski et al. 2008, Gwardiak, et al. 2011, Regulation of the. Minister of Economy of 9 October 2015, PN-EN 590+A1:2017-06, PN-EN 16942+A1:2021-08).

Table 1. Parameters of the fuels used in the research for CADC driving tests

Parametr	Diesel	FAME	Rapeseed oil	Butanol
Carbon content [%]	86.5	78.0	77.4	64.8
Hydrogen content [%]	13.4	12.0	11.4	13.5
Oxygen content [%]	0.0	10.0	11.2	21.6
Air demand [g_{air}/g_{fuel}]	14.5	12.5	12.5	11.2
Lower heating value [MJ/kg]	44.0	37.1	37.5	33.0

The parameters of a 2014 Fiat Panda 1.3 Multijet II from were used to develop a simulation model for driving tests under the CADC standard (Fiat 2021). Table 2 below presents the most important technical parameters of the vehicle and the factors necessary to be used in driving tests and programs generating the required waveforms. The values of the "n/v coefficient" factor for individual gears were calculated on the basis of the following dependence:

$$\text{Ratio n/v} = \mathrm{n_{engine}} / \mathrm{v_{vehicle}} \ [\mathrm{h/(km \cdot min)}] \qquad (1)$$

where:
η_{engine} – measured value of the engine rotational speed [min^-1],
$v_{vehicle}$ – vehicle speed for the given gear number [km/h].

Table 2. Parameters of the vehicle used in the research for CADC driving tests

Parameter	Description	Unit
Vehicle (MY, Make, Model)	Fiat Panda 1.3 Multijet II 16V	–
Equivalent test mass	1170	Kg
Rated power (declared)	55	kW
Rated engine speed (declared)	4000	min^{-1}
Idling engine speed (declared)	800	min^{-1}
Max vehicle speed(declared)	168	km/h
Number of gears	5	–
Ratio n/v_1, gear 1	121.9	h/(km·min)
Ratio n/v_2, gear 2	64.10	h/(km·min)
Ratio n/v_3, gear 3	41.32	h/(km·min)
Ratio n/v_4, gear 4	29.49	h/(km·min)
Ratio n/v_5, gear 5	21.97	h/(km·min)
Target Coeff f0	86	N
Target Coeff f1	0.1694	N/(km/h)
Target Coeff f2	0.03202	$N/(km/h)^2$

Generating the required waveforms as part of the CADC simulation used data which enabled the determination of the characteristics of the maximum engine power as a function of rotational speed. The characteristic of the demand for fuel (diesel oil) as a function of rotational speed and torque was determined (Fig. 1).

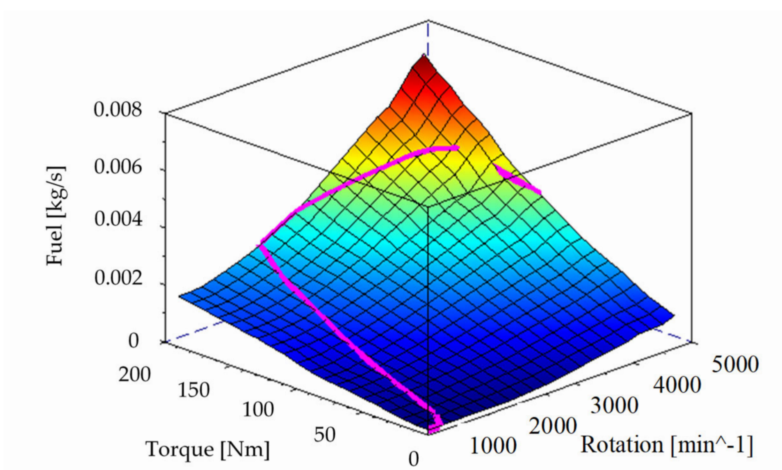

Fig. 1. A fuel consumption (Diesel) as a function of engine rotational speedand engine torque

The above fuel and engine parameters as well as the course of approval tests were input into the simulation model under development, which was used to obtain the results of carbon dioxide emission of the analysed vehicle powered by various fuels (Fig. 2).

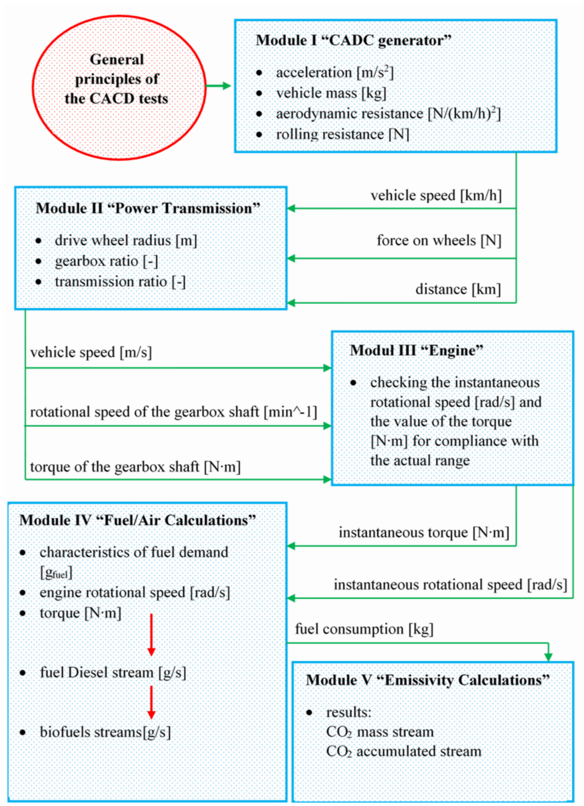

Fig. 2. Structure of the simulation model

In the developed computer simulation, the instantaneous values of the vehicle speed calculated in m/s and km/h units are available in parallel.

In module 1, using the instantaneous value of the vehicle speed, the differentiating element and the vehicle computational mass, the dynamic force is calculated:

$$\mathrm{F}_{Dyn} = \frac{dv}{dt} m \text{ [N]} \tag{2}$$

where:
m – mass of the vehicle [kg].

The values of the rolling resistance forces were calculated from the rolling coefficients assumed for the vehicle using the relationship:

$$F_{Sta} = f0 + f1 \cdot v + f2 \cdot v^2 \text{ [N]} \tag{3}$$

where:
v – vehicle speed [km/h],
$f0, f1, f2$ – target coefficient (Table 2).

In module II, on the basis of the instantaneous speed of the vehicle and the instantaneous values of the "Ratio n/v" coefficients resulting from the gear ratio, the instantaneous value of the rotational speed of the gearbox shaft is calculated according to the relation:

$$n_{engine} = (\text{Ratio n/v}) \cdot v \text{ [1/min]} \tag{4}$$

where:
v – vehicle speed [km/h],
Ratio n/v – coefficient (Table 2).

The instantaneous torque value at the engine crankshaft is then calculated:

$$T_{engine} = \frac{(F_{Sta} + F_{Dyn}) \cdot v}{\omega_{engine}} \text{ [N} \cdot \text{m]} \tag{5}$$

where:
v – vehicle speed [m/s],
ω_{engine} – instantaneous rotational speed [rad/s].

In module IV the fuel flux is calculated on the basis of fuel demand characteristics (Fig. 1), instantaneous values of engine rotational speed and engine crankshaft torque according to the relation:

$$\dot{Fuel}_{Diesel} = Fun(n_{engine}, T_{engine}) \text{ [kg/s)]} \tag{6}$$

where:
n_{engine} – engine rotational speed [1/min],
T_{engine} – engine crankshaft torque [N·m].

In the case of using a fuel other than diesel the instantaneous flux of this fuel is calculated according to the relation:

$$\dot{Fuel} = \dot{Fuel}_{Diesel} \frac{Cal_{Diesel}}{Cal} \text{ [kg/s)]} \tag{7}$$

where:
Cal_{Diesel} – calorific value for diesel fuel [J/kg],
Cal – calorific value for another fuel [J/kg].

Then, in Module V, the carbon dioxide emission stream is calculated according to the relation:

$$\dot{CO_2} = 3.664 \cdot \dot{Fuel} \cdot C\ [kg/s] \tag{8}$$

where:
C – mass fraction of carbon in the fuel [kg/kg].

In the subsequent calculations in this module, the carbon dioxide emissions are calculated on the basis of:

$$CO_2 = \int \dot{CO_2}\, dt\ [kg] \tag{9}$$

where:
$\dot{CO_2}$ – mass flux of carbon dioxide emissions [kg/s].

3. Research results and discussion

The results of independent simulations of the selected Fiat Panda 1.3 Multijet vehicle in the applied driving tests with change of fuel (Diesel, FAME, rapeseed oil, butanol) are presented below.

Figures 3-6 show the simulation results for the Fiat Panda 1.3 Multijet vehicle powered by diesel fuel: waveforms of instantaneous vehicle speed values; waveforms of the instantaneous values of the rotational speed of the vehicle engine; waveforms of the instantaneous values of the torque of the engine of the vehicle; waveforms of the instantaneous values of the engine power of the vehicle.

Figures 7 and 8 show the results of the developed computer simulations of the waveforms of instantaneous values of mass streams and the waveforms of the instantaneous values of mass consumption.

Figures 9 and 10 show the results of the developed computer simulations of the waveforms of the instantaneous values of carbon dioxide streams and the waveforms of the instantaneous values of carbon dioxide emissions for the CADC drive tests for the Fiat Panda 1.3 Multijet vehicle, with the use of diesel fuel, FAME, rapeseed oil and butanol.

Figures 11-13 and Figures 14-16 show the obtained simulation results concerning fuel consumption and carbon dioxide emissions with the use of various types of fuel in the analysed driving tests.

3.1. Simulation results for CADC tests of vehicle operating parameters

The figures below (Fig. 3-6) show the results of the developed computer simulations of CADC driving tests (urban, extra-urban and motorway cycles): course of instantaneous vehicle speed values; the waveforms of the instantaneous values of the rotational speed of the vehicle engine; the waveforms of the instantaneous values of the torque of the engine of the vehicle; the waveforms of instantaneous values of the engine power of the vehicle. The basis for the development of the computer simulations were the results of the driving tests carried out on a chassis dynamometer for the Fiat Panda 1.3 Multijet diesel powered vehicle.

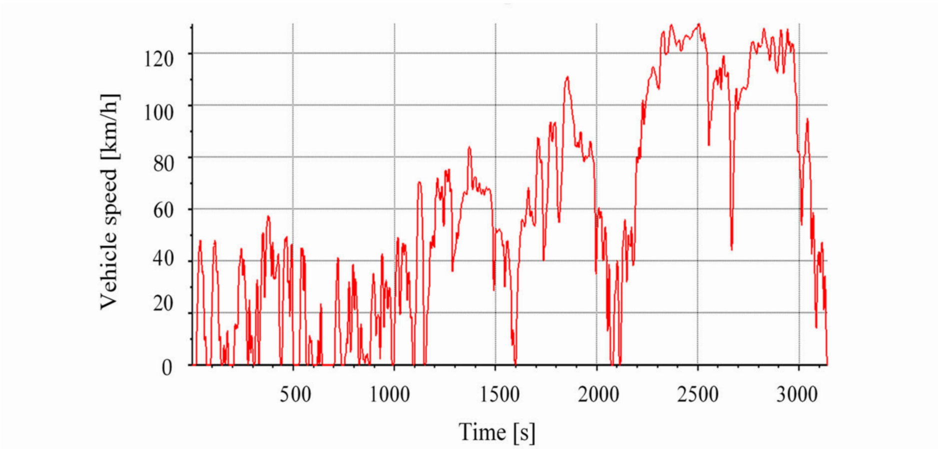

Fig. 3. The waveforms of the instantaneous vehicle speed values obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

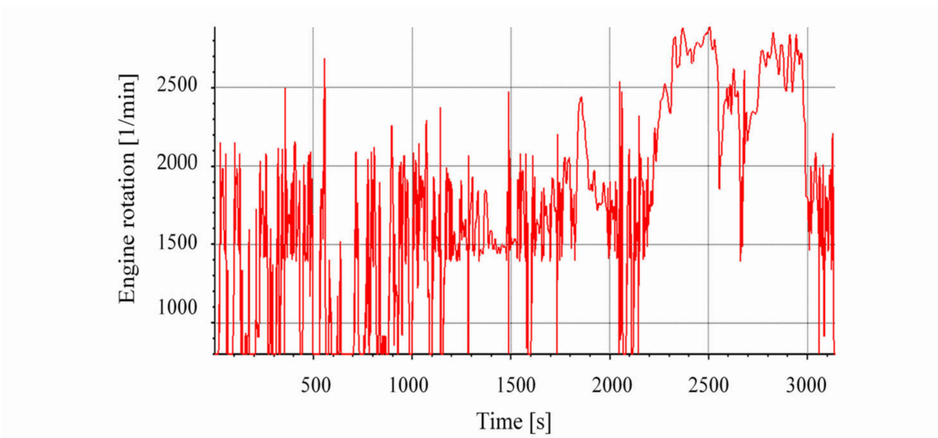

Fig. 4. The waveforms of the instantaneous values of the engine rotational speed obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

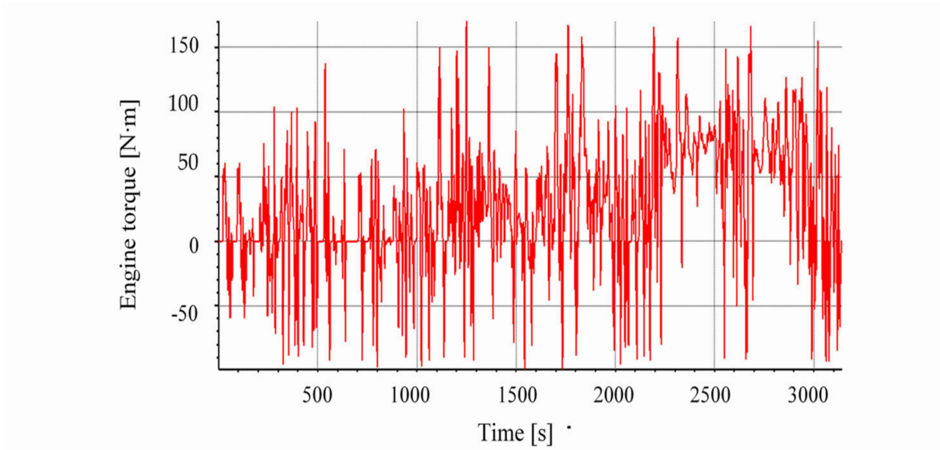

Fig. 5. The waveforms of the instantaneous values of the torque of the vehicle engine obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

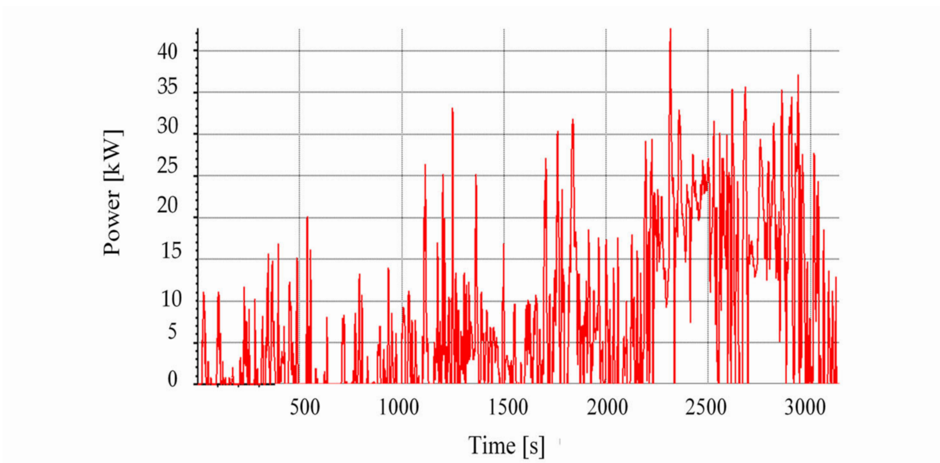

Fig. 6. The waveforms of the instantaneous values of the power of the vehicle engine obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

3.2. Simulation results for CADC fuel consumption tests

Below are the results of the developed computer simulations of CADC driving tests (urban, extra-urban and highway cycles) for the Fiat Panda 1.3 Multijet for the fuels used (diesel oil, FAME, rapeseed oil and butanol): the waveforms of the instantaneous mass stream values and the waveforms of the instantaneous mass consumption values.

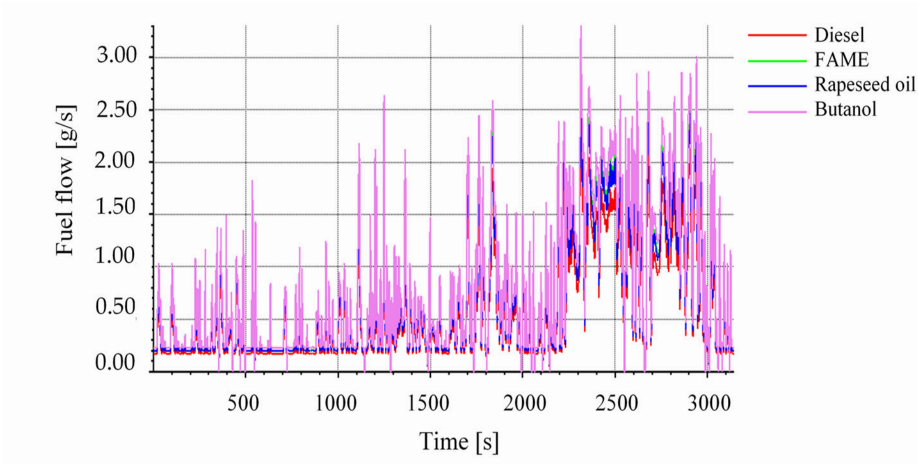

Fig. 7. The waveforms of the instantaneous values of mass streams [g/s] for selected fuels, obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

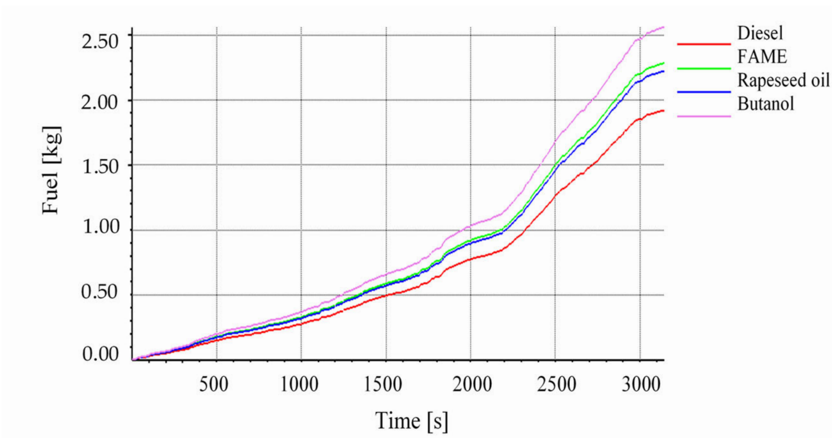

Fig. 8. The waveforms of the instantaneous values of mass consumption [kg] for selected fuels, obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

3.3. Simulation results for CADC carbon dioxide emission tests

Figures 9 and 10 show the results of the developed computer simulations of the waveforms of the instantaneous values of carbon dioxide streams and the waveforms of the instantaneous values of carbon dioxide emissions for CADC driving tests (urban, extra-urban and motorway cycles) – Fiat Panda 1.3 Multijet vehicle, used fuels: diesel oil, FAME, rapeseed oil and butanol.

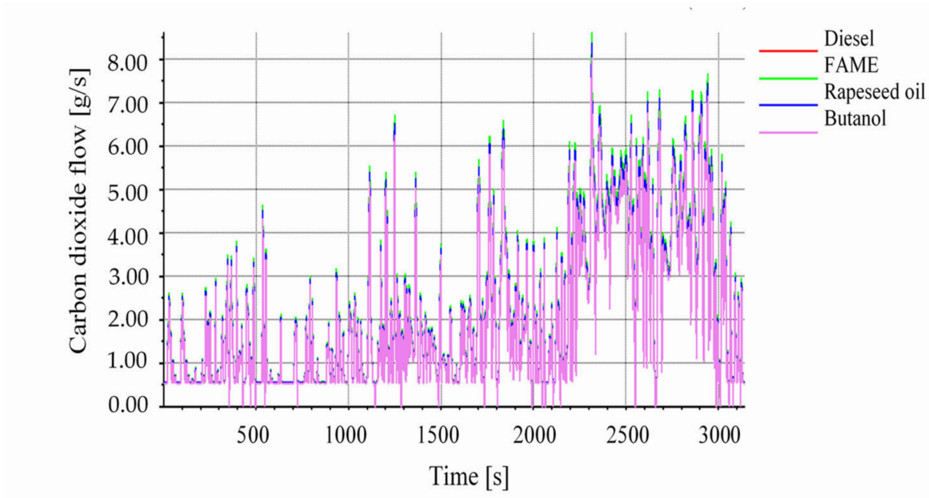

Fig. 9. The waveforms of the instantaneous values of carbon dioxide fluxes for selected fuels, obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

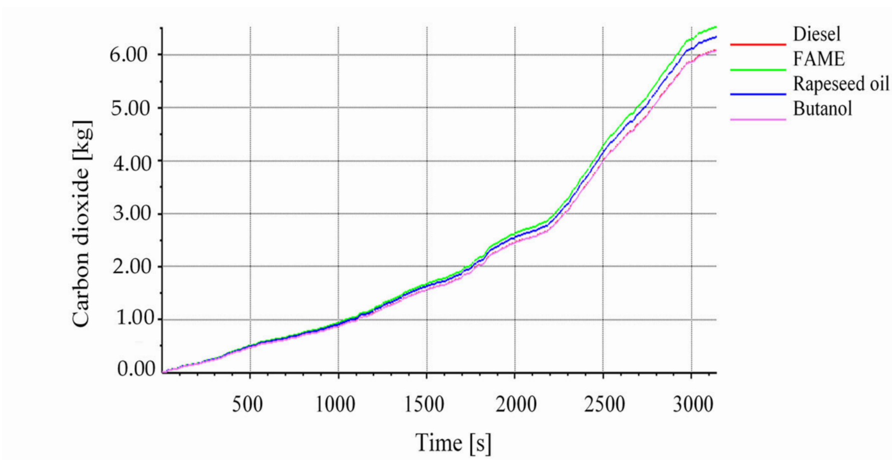

Fig. 10. The waveforms of the instantaneous values of carbon dioxide emissions for selected fuels, obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

3.4. Simulation results for CADC carbon dioxide emission tests

The figures below show a summary of the simulation results for the CADC tests of fuel consumption and carbon dioxide emissions. Sample parameters of the developed simulations of the CADC test variants are presented in Table 3.

Table 3. Summary of the results obtained from various variants of the CADC test: test duration, distance, mechanical energy

Parameter	CADC full	CADC urban	CADC extra urban	CADC motorway
Duration [s]	3142	992	1082	1068
Distance [km]	50.887	4.874	17.275	28.738
Mechanical energy [MJ]	24.139	1.865	6.156	16.118

3.4.1. Summary of simulation results for CADC fuel consumption tests

The figures below (Fig. 10-12) show the results of fuel mass consumption, fuel mass consumption per kilometre and fuel mass consumption per 1 MJ for various variants of the CADC test.

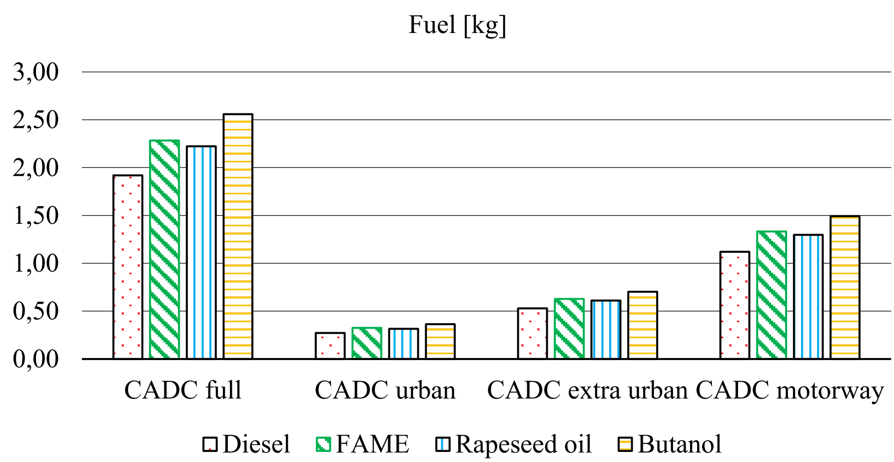

Fig. 11. Summary of fuel mass consumption results for selected fuels, obtained from different variants of the CADC test

Based on the test results shown in Figure 11, it can be concluded that in the driving test analysed, the highest fuel consumption [kg] was with butanol, while the lowest was for Diesel fuel. This is due to the calorific value of these fuels. Diesel fuel provides more energy per unit mass than butanol. To meet the energy requirements to cover the same distance, more of a lower calorie carrier must be provided. The highest consumption of all fuels was for the motorway cycle. It is related to the route and duration of this part of the driving test. The motorway cycle compared to the urban and extra-urban cycle is over 60% longer.

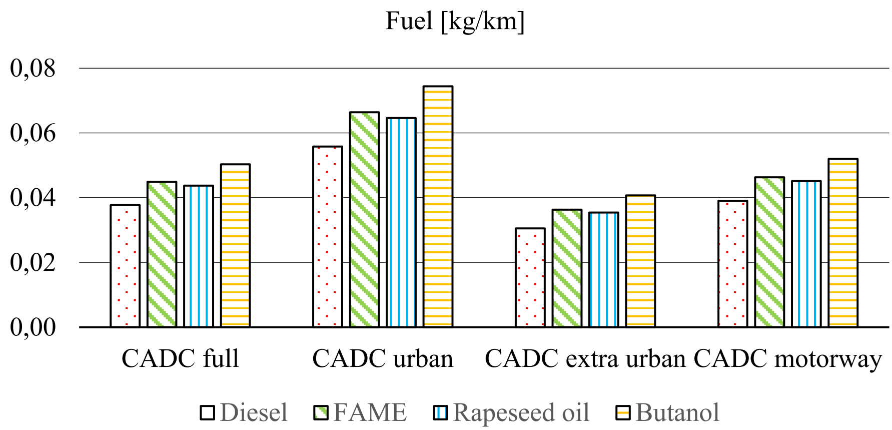

Fig. 12. Summary of the results of mass fuel consumption per 1 kilometre for selected fuels, obtained from different variants of the CADC test

The figure above shows the mass fuel consumption per 1 km for each part of the driving test. The highest amount fuel is consumed in the test's urban cycle (regardless of the type of fuel used). The vehicle does not move at a constant speed, and its dynamic changes significantly contribute to increased fuel consumption. The motorway cycle is in second place in terms of fuel economy. However, this consumption is clearly lower than in urban cycle. This is related to the characteristics of moving a vehicle through a metropolitan area.

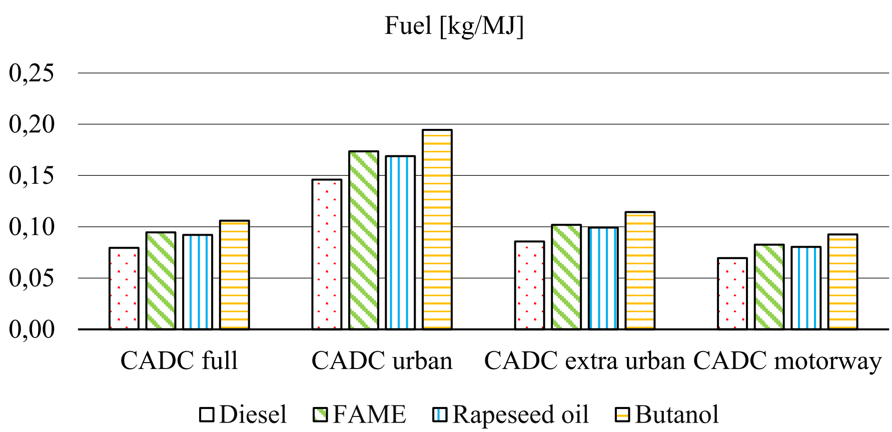

Fig. 13. Summary of the results of fuel mass consumption per 1 MJ for selected fuels, obtained from different variants of the CADC test

From the perspective of mass fuel consumption per 1 MJ of energy, most fuel is consumed in the urban cycle. The fuel whose consumption is the highest is butanol, which results from its physical and chemical properties.

3.4.2. Summary of simulation results for CADC carbon dioxide emission tests

The figures below (Figure 13-15) show the results of carbon dioxide emissions for selected fuels, obtained from different variants of the CADC test.

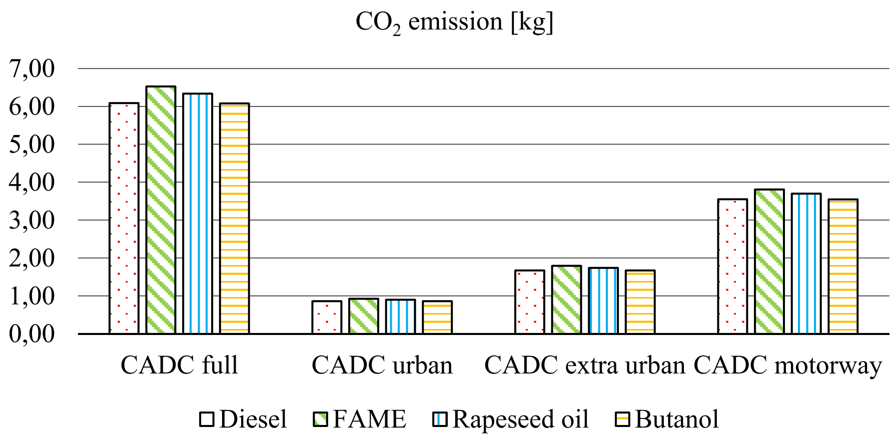

Fig. 14. Carbon dioxide emission results for selected fuels, obtained from different variants of the CADC test

As with mass fuel consumption carbon dioxide emissions also proved to be highest for the motorway cycle (Fig. 14). This is due to the largest mass consumption of energy carriers due to the largest distance travelled. In this figure, no reference to kilometres driven (as in Figure 15) is included, so that, emissions are determined directly by the amount of fuel conversion.

The consideration of the specificity of moving the vehicle in the urban cycle is well shown in Figure 15. Considering the number of kilometers driven in a given driving cycle test, CO_2 emissions will be highest for the urban cycle, followed by the motorway cycle.

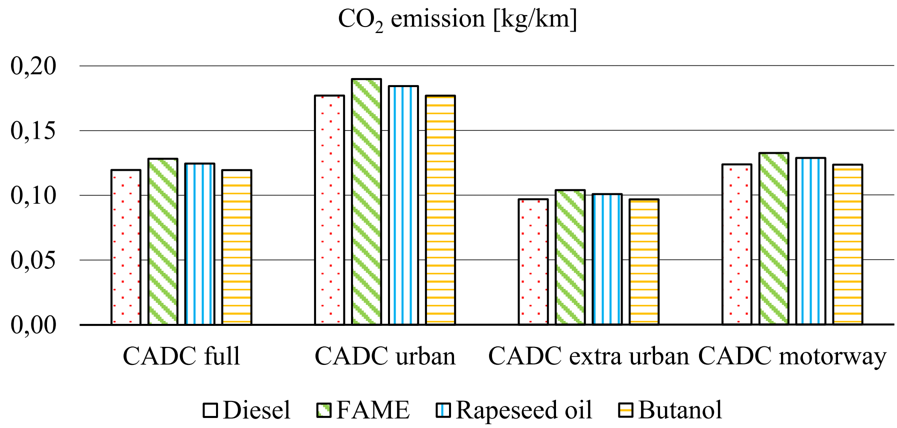

Fig. 15. Summary of the results of carbon dioxide emissions per kilometer for selected fuels, obtained from different variants of the CADC test

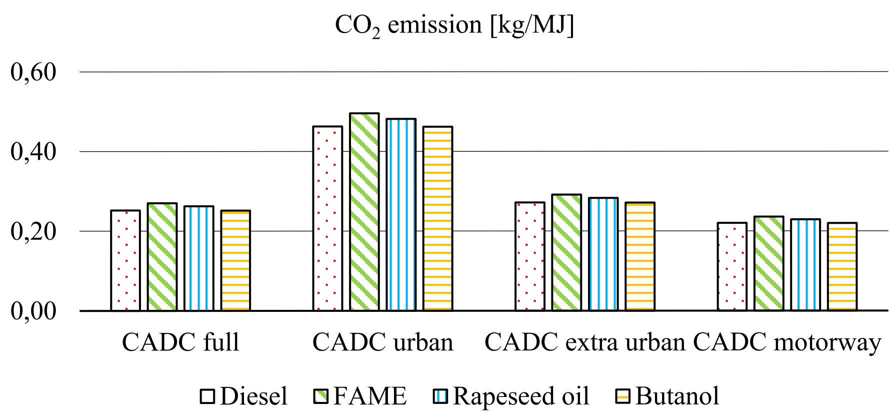

Fig. 16. Summary of the results of carbon dioxide emission per 1 MJ for selected fuels, obtained from different variants of the CADC test

On the basis of Figure 16 it can be stated that in the whole test, the highest CO_2 emission from 1 MJ of energy was characteristic for FAME fuel, while the lowest for butanol and diesel fuel. It should be noted that the differences in emission values are not significant. The fuels used in the analysis differ in the content of carbon hydrogen, sulphur and oxygen in their elemental composition and in their calorific value.

4. Summary

The driving cycle is currently the only standardised way to record vehicle movement. Vehicle approval tests, during which exhaust emissions from the exhaust pipe are collected and analysed, are performed on chassis dynamometers. During the test, it is checked that the permissible limits of pollutant emission into the atmosphere are not exceeded.

Fuel economy tests for new vehicles vary depending on the region of the world and the driving conditions associated therewith. Therefore, taking into account the migration of car brands in the world, it is important to develop computer tools that will make it possible to determine the amount of pollutants emitted into the atmosphere from vehicles.

The aim of the project was to build a computer tool using tests carried out on a chassis dynamometer to simulate driving tests. The built driving test simulator determines the amount of CO_2 emissions and fuel demand, including the parameters of the analysed vehicle for the given input parameters and the type of fuel (diesel oil, FAME, rapeseed oil and butanol).

On the basis of the tests carried out with one CADC, it is concluded that:

1. the highest mass consumption of fuel for the CADC full test occurred for FAME (2.283 kg) and butanol (2.559 kg);
2. in the case of mass fuel consumption per kilometre and fuel consumption per 1 MJ for the CADC full test, the lowest values were recorded for diesel fuel (0.0377 kg/km and 0.0795 kg/MJ respectively);
3. the highest carbon dioxide emissions occurred for FAME (6.524 kg) and rapeseed oil (6.336 kg);
4. when analysing carbon dioxide emissions per kilometre and carbon dioxide emissions per 1 MJ, the lowest values were noticed for butanol (0.1194 kg/km and 0.2518 kg/MJ).

The parameters of the fuels used had undoubtedly influenced the obtained results of computer simulations.

References

Alves-Fortunato, M., Ayoub, E., Bacha, K., Mouret, A., Dalmazzone, C. (2020). Fatty Acids Methyl Esters (FAME) autoxidation: New insights on insoluble deposit formation process in biofuels. *Fuel, 268*, 117074. DOI: doi.org/10.1016/j.fuel.2020.117074

Ambrozik, A., Kurczyński, D., Łagowski, P., Warianek, M. (2016). The toxicity of combustion gas from the Fiat 1.3 Multijet engine operating following the load characteristics and fed with rape oil esters. *Proceedings of the Institute of Vehicles, 1*, 23-36. ISSN 1642-347X

Ambrozik, A., Ambrozik, T., Kurczyński, D. (2012). Load characteristics of turbocharged 1.3 Multijet engine. *Advances in Science and Technology, 15*, 7-20. ISSN 1231-4005.

Baczewski, K., Kałdoński, T. (2008). *Fuels For Compression Ignition Engines.* 2nd ed.; Wydawnictwa Komunikacji i Łączności: Warszawa, Polska, 2017. ISBN: 978-83-206-1705-4 (in Polish).

Bemani, A., Xiong, Q., Baghban, A., Habibzadeh, S., Mohammadi, A.H., Doranehgard, M.H. (2020). Modeling of cetane number of biodiesel from fatty acid methyl ester (FAME) information using GA-, PSO-, and HGAPSO- LSSVM models. *Renewable Energy, 150*, 924-934. DOI: doi.org/10.1016/j.renene.2019.12.086

Bharathiraja, B., Jayamuthunagai, J., Sudharsanaa, T., Bharghavi, A., Praveenkumar, R., Chakravarthy, M., Yuvaraj, D. (2017). Biobutanol – An impending biofuel for future: A review on upstream and downstream processing techniques. *Renewable and Sustainable Energy Reviews, 68*, 788-807. DOI: doi.org/10.1016/j.rser.2016.10.017

Capros, C., Kannavou, M., Evangelopoulou, S., Petropoulos, A., Siskos, P., Tasios, N., Zazias, G., DeVita, A. (2018). Outlook of the EU energy system up to 2050: The case of scenarios prepared for European Commission's "clean energy for all Europeans" package using the PRIMES model. *Energy Strategy Reviews, 22*, 255-263. DOI: doi.org/10.1016/j.esr.2018.06.009

Chamier-Gliszczyński, N., Bohdal, T. (2016). Urban Mobility Assessment Indicators in the Perspective of the Environment Protection. *Rocznik Ochrona Środowiska, 18*(1), 670-681.

Chamier-Gliszczyński, N., Bohdal, T. (2016). Mobility in urban areas in environment protection. *Rocznik Ochrona Środowiska, 18*(1), 387-399.

Common Artemis Driving Cycles (CADC). Retrieved from: https://dieselnet.com/standards/cycles/artemis.php (accessed on 19 April 2021)

Commission Regulation (EU) No 407/2011 of 27 April 2011 amending Regulation (EC) No 661/2009 of the European Parliament and of the Council as regards the inclusion of certain Regulations of the United Nations Economic Commission for Europe on the type-approval of motor vehicles, their trailers and systems, components and separate technical units intended therefor Text with EEA relevance. Retrieved from: https://eur-lex.europa.eu/eli/reg/2011/407/oj (accessed on 19 October 2021)

Fekete, H., Kuramochi, T., Roelfsema, M., Den Elzen, M., Forsell, N., Höhne, N., Luna, L., Hans, F., Sterl, S., Olivier, J., Van Soest, H., Frank, S., Gusti, M. (2021). A review of successful climate change mitigation policies in major emitting economies and the potential of global replication. *Renewable and Sustainable Energy Reviews, 137*, 110602. DOI: doi.org/10.1016/j.rser.2020.110602

Fiat Panda Misc Documents Accessories Brochure PDF. Available online: https://manuals.co/ (accessed on 19 April 2021).

Gwardiak, H., Rozycki, K., Ruszkarska, M., Tylus, J., Walisiewicz-Niedbalska, W. (2011). Evaluation of fatty acid methyl esters (FAME) obtained from various feedstock. *Oilseed Crop, 32*, 137-147. ISSN 1233-8273.

Gunfaus, M.T., Waisman, H. (2021). Assessing the adequacy of the global response to the Paris Agreement: Toward a full appraisal of climate ambition and action. *Earth System Governance, 100102*. DOI: doi.org/10.1016/j.esg.2021.100102

Jacyna, M., Wasiak, M., Lewczuk, K., Chamier-Gliszczyński, N., Dąbrowski, T. (2018). Decision Problems in Developing Proecological Transport System. *Rocznik Ochrona Środowiska, 20*(2), 1007-1025.

Javed, S.A., Zhu, B., Liu, S. (2020). Forecast of biofuel production and consumption in top CO_2 emitting countries using a novel grey model. *Journal of Cleaner Production, 276*, 123997. DOI: doi.org/10.1016/j.jclepro.2020.123997

Kordylewski, W. (2008). *Burning and Fuel.* 5th ed.; Publishing House of the Wrocław University of Technology: Wrocław, Poland, 2008. ISBN: 978-83-7493-378-0 (in Polish).

Mikulski, M,, Ambrosewicz-Walacik, M., Duda, K., Hunicz, J. (2020). Performance and emission characterization of a common-rail compression-ignition engine fuelled with ternary mixtures of rapeseed oil, pyrolytic oil and diesel. *Renewable Energy, 148*, 739-755. DOI: doi.org/10.1016/j.renene.2019.10.161

Olabi, A.G., Wilberforce, T., Abdelkareem, M.A. (2021). Fuel cell application in the automotive industry and future perspective. *Energy, 214*, 118955. DOI: doi.org/ 10.1016/j.energy.2020.118955

PN-EN 590+A1:2017-06. Automotive fuels – Diesel oils - Requirements and test methods. Retrieved from: https://sklep.pkn.pl/pn-en-590-a1-2017-06e.html (accessed on 19 October 2021)

PN-EN 16942+A1:2021-08. Fuels – Identification of vehicle compatibility - Graphical expression for consumer information. Retrieved from: https://sklep.pkn.pl/pn-en-16942-a1-2021-08e.html (accessed on 19 October 2021)

Puricelli, S., Cardellini, G., Casadei, S., Faedo, D., Van den Oever, A.E.M., Grosso, M. (2020). A review on biofuels for light-duty vehicles in Europe. *Renewable and Sustainable Energy Reviews, 137*, 110398. DOI: doi.org/10.1016/j.rser.2020.110398

Pyza, D., Jacyna-Gołda, I., Gołda, P., Gołębiowski, P. (2018). Alternative Fuels and Their Impact on Reducing Pollution of the Natural Environment. *Rocznik Ochrona Środowiska, 20*(1), 819-836.

Regulation of the. Minister of Economy of 9 October 2015 on the quality requirements for liquid fuels (Journal of Laws of 2015, item. 1680). Retrieved from: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20150001680 (accessed on 19 October 2021)

Regulation No 85 of the Economic Commission for Europe of the United Nations (UN/ECE) – Uniform provisions concerning the approval of internal combustion engines or electric drive trains intended for the propulsion of motor vehicles of categories M and N with regard to the measurement of net power and the maximum 30 minutes power of electric drive trains. Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:42006X1124(03)&from=PL (accessed on 19 October 2021)

Regulation No 101 of the Economic Commission for Europe of the United Nations (UN/ECE) – Uniform provisions concerning the approval of passenger cars powered by an internal combustion engine only, or powered by a hybrid electric power train with regard to the measurement of the emission of carbon dioxide and fuel consumption and/or the measurement of electric energy consumption and electric range, and of categories M1 and N1 vehicles powered by an electric power train only with regard to the measurement of electric energy consumption and electric range. Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:42008X0222(02)&from=PL (accessed on 19 October 2021)

Sileghem, L., Bosteels, D., May, J., Favre, C., Verhelst, S. (2014). Analysis of vehicle emission measurements on the new WLTC, the NEDC and the CADC. Transportation Research Part D: *Transport and Environment, 32*, 70-85. DOI: doi.org/10.1016/j.trd.2014.07.008

Tutak, M., Brodny, J., Bindzár, P. (2021). Assessing the Level of Energy and Climate Sustainability in the European Union Countries in the Context of the European Green Deal Strategy and Agenda 2030. *Energies, 14*, 1767. DOI: doi.org/10.3390/en14061767

Zhao, X., Ke, Y., Zuo, J., Xiong, W., Wu, P. (2020). Evaluation of sustainable transport research in 2000-2019. *Journal of Cleaner Production, 256*, 120404. DOI: doi.org/10.1016/j.jclepro.2020.120404

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Intensive Animal Farming Operations – a Preliminary Analysis of a Number of Farm Animals, Ammonia Emission Values Variability and Methods of Reducing Odor Emissions and Assessing Health Impact Taking into Account Possible Solutions in Poland and Ukraine

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Abstract: The article seeks to review the standards (emission and immission) and legal solutions relating to odour-active compounds, as well asanalyse the variability in the number of farmed animals and the emission of ammonia in Poland and Ukraine. Furthermore, the article characterizesodour emission factors, methods of health risk assessment, ways of limiting emission of odorous compounds from animal farming facilities. The analysis indicated the necessity of applying good practices available in reference documents – including those drawn up by environmental agencies – and scientific works, as such practices may significantly contribute to minimising the impact of animal farming facilities on people and the environment. The introduction of, inter alia, immission standards (reference values) expressed in ou_E/m^3 in the legal regimes of the EU and Ukraine would also render it possible to carry out an assessment of odours treated as a mixture present in ambient air and optimise the assessment of odour nuisance and thus the discomfort directly affecting the well-being and health of inhabitants of areas in the vicinity of farming facilities.

Keywords: animal farming, odour emission sources, health impact assessment, BAT

1. Introduction

Poland ranks sixth among food producers in the European Union (EU) and eighth among its exporters. Approximately 30% of operators involved in food and beverages production are processors of products of animal origin, of which 20% are meat companies and about 4% – dairy companies. The share of the meat industry in the marketed production of the food industry is estimated at about 30% (Institute of Agricultural and Food Economics 2018). In Ukraine, in turn – at the level of 13.1% (State Statistics Service of Ukraine 2016).

The agri-food industry is significantly diversified in terms of odour emissions and impacts on olfactory air quality. In Poland, agriculture accounts for 94% ammonia pollution, thus being the main emitter of this pollutant (Ministry of Climate 2020). Animal manure management (79%) and mineral fertiliser use (21%) are considered to be the dominant sources of ammonia emissions in agriculture. As regards Ukraine, in 2017-2018, the share of agriculture in NH_3 emissions ranged from 66.2% to 73.1% (State Statistics Service of Ukraine 2020), while animal manure management and fertiliser production accounted for, respectively, 61.2% and 38.8% (Pinchuk & Borodai 2019). Ammonia is the main odorant emitted from animal facilities. However, the presence of other odorous compounds with lower concentration, but also lower odour threshold values forces one to study odours as a mixture (Sówka 2011).

Ammonia and odour emissions from livestock buildings are considered to have the highest environmental impact, with odour emissions usually related to odour nuisance effects, while NH_3 emissions are considered to be a pollutant of regional impact. Ammonia plays an important role in the formation of fine particles in the atmosphere. NH_3 emissions lead to nutrient N-enrichments, acidification and euthropication in both terrestial and aquatic ecosystems. In the atmosphere, ammonia reacts with other compounds to form ammonium sulphide and ammonium nitrate aerosols, leading to the formation of $PM_{2.5}$ (Conti 2020, Schauberger et al. 2018). Ammonia emissions have been found to be correlated with climate change, with an increase in global temperature by 5 OC resulting in an increase in global NH_3 emissions by approx. 42% (Sutton et al. 2013, Schauberger et al. 2018), which in the future may result in the necessity to increase the distance of livestock buildings from residential and public buildings (Schauberger et al. 2018). The main sources of odour emissions from animal facilities are litter fermentation and decomposition, as well asthe decomposition of faeces and food residue. Odorous compounds are also generated by respiration, digestion and evaporation from the skin of livestock (Grzelka et al. 2018, Korczyński et al. 2010, Saba et al. 2003). Odorants typically identified in the context of animal husbandry and maintenance are ammonia andhydrogen sulphide – usually present in high concentrations. Other compounds worthy of mention are thiols, sulphides, phenols, ketones, aldehydes, aliphatic acids, esters, amines, heterocyclic compounds containing sulphur and nitrogen or aliphatic alcohols (Tymczyna et al. 2010). The composition of gases generated in animal facilities depends on many factors, mainly on the species and age of livestock (Korczyński et al. 2010). As regards the incidence of odour nuisance from livestock farming facilities, one should mention significant environmental and technical factors such as: temperature in the premises, humidity, speed of air movement, available space, type of flooring, type of litter used (or litter-free systems) and design of ventilation systems, as well as methods of handling the produced manure (Herbut et al. 2010). An equally important factor is the way the animals are fed, which involves a proper balance of forage to reduce the amount of protein in animal faeces and reduce their pH (Jugowar et al. 2010).

As regards Ukraine, cattle, pig and poultry farming are of key importance (Pinchuk & Borodai 2019).

Table 1. Livestock in Poland and Ukraine in 2019

Livestock	Total number, thsd. heads	Total number, thsd. heads
Cattle (of which cows)	6358 (2461)	3092.0
Sheep	273	1204.5
Pigs (of which sows)	10781 (755)	5727.4
Hens (of which laying hens)	178342 (53190)	220485.8
Geese	1061	4015.8
Turkeys	15939	1939
Ducks	5704	11418.3

(Commission Implementing Decision 2017, State Statistics Service of Ukraine 2020)

The so-called large industrial farms, i.e. farms with a capacity of more than 40,000 heads of poultry or 2,000 pigs (fattening pigs >30 kg or 750 sows) are deemed to be the source of the most considerable odour nuisance (Commission Implementing Decision 2017). Farms of this type are characterised by a highly industrialised livestock production profile and have significant environmental impacts, primarily as a result of very large quantities of natural fertilisers produced. Table 2 shows the emission factors of odours and ammonia depending on the type of animals reared, while Table 3 shows the odour threshold values. Table 4, in turn, summarises the example results of odour concentration measurements carried out for various livestock farming facilities.

Table 2. Values of odour and ammonia emission factors for different livestock groups and rearing types

Species	Rearing type	NH_3 emission factor, kg/head/year	Odour emission factor, $ou_E/(s \cdot animal)$	Source
Chicken	Laying hens – cage system	0.01 to 0.15	0.102 to 0.68	(Commission Implementing Decision 2017)
Chicken	Laying hens – cage-free system	0.019 to 0.36	0.102 to 1.5	(CID 2017)
Chicken	Broilers	0.004 to 0.18	0.032 to 0.7	(CID 2017)
Turkey	females	0.045 to 0.387	0.4	(CID 2017)
Turkey	males	0.138 to 0.68	0.71	(CID 2017)
Duck	total	0.05 to 0.29	0.098 to 0.49	(CID 2017)
Pig	Gestating sows – slurry	0.42 to 9.0	5.6 to 100	(CID 2017)
Pig	Weaners – slurry	0.03 to 0.8	1.1 to 12.1	(CID 2017)
Pig	Weaners – manure/combined generation	0.11 to 0.7	2.25 to 3	(CID 2017)
Pig	Fattening pigs – slurry	0.1 to 4.6	1.14 to 29.2	(CID 2017)
Pig	Fattening pigs – manure/combined generation	1.9 to 7.53	4.2 to 7	(CID 2017)

Table 2. cont.

Species	Rearing type	NH_3 emission factor, kg/head/year	Odour emission factor, $ou_E/(s \cdot animal)$	Source
Domestic bovine	Dairy cows – slurry	41.8	–	(European Environment Agency 2019)
Domestic bovine	Dairy cows – manure	26.4	–	(EEA 2019)
Domestic bovine	Other bovine animals – slurry	15	–	(EEA 2019)
Domestic bovine	Other bovine animals – manure	10	–	(EEA 2019)
Domestic sheep	Total – manure	1.4	–	(EEA 2019)
Pig	Fattening pigs – slurry	6.5	–	(EEA 2019)
Pig	Fattening pigs – manure	5.6	–	(EEA 2019)
Pig	Sows – slurry	17.7	–	(EEA 2019)
Pig	Sows – manure	15.1	–	(EEA 2019)
Pig	Sows – outdoor rearing	9.3	–	(EEA 2019)
Chicken	Laying hens – manure	0.31	–	(EEA 2019)
Chicken	Laying hens – slurry	0.48	–	(EEA 2019)
Chicken	Broilers litter	0.17	–	(EEA 2019)
Turkey	litter	0.9	–	(EEA 2019)
Duck	litter	0.65	–	(EEA 2019)
Goose	litter	0.35	–	(EEA 2019)
Donkey	manure	15.8	–	(EEA 2019)
Horse	manure	15.8	–	(EEA 2019)
Goat	manure	1.4	–	(EEA 2019)

Table 3. Odour detection threshold values for substances emitted from livestock farming facilities

Chemical compound	Odour threshold value, (mg/m^3)	Source
Ammonia	0.5	(Czurejno 2005)
Ammonia	0.74	(Talaiekhozani at al. 2016)
Ammonia	1.10	(Nagata 2003)
Ammonia	4.07	(Devos at al. 1990)
Ammonia	0.0266	(Ruth 1986)
Ethylene	20.0	(Czurejno 2005)
Acetone	1.1	(Czurejno 2005)18]
Ethyl mercaptan	0.00004	(Czurejno 2005)8]
Ethyl mercaptan	0.48	(Talaiekhozani at al 2016)
Ethyl mercaptan	0.022	(Nagata 2003)
Ethyl mercaptan	0.00282	(Devos 1990)
Ethyl mercaptan	0.000032	(Ruth 1986)
Methyl mercaptan	0.000002	(Czurejno 2005)
Methyl mercaptan	2.16	(Talaiekhozani at al. 2016)
Methyl mercaptan	0.98	(Glindemann et al. 2006)
Methyl mercaptan	0.14	(Nagata 2003)
Methyl mercaptan	0.00209	(Devos 1990)
Methyl mercaptan	0.00004	(Ruth 1986)
Propyl mercaptan	0.404	(Talaiekhozani at al 2016)
Propyl mercaptan	0.404	(Nagata 2003)
Butyl mercaptan	0.01	(Talaiekhozani at al 2016)
Butyl mercaptan	0.01	(Nagata 2003)
Butyl mercaptan	0.00537	(Devos 1990)
Benzyl mercaptan	0.96	(Talaiekhozani at al 2016)
Benzyl mercaptan	0.96	(Nagata 2003)
Benzyl mercaptan	0.00813	(Devos 1990)
Benzene	1.8	(Czurejno 2005)
Benzene	12.0	(Devos 1990)
Acetaldehyde	0.014	(Czurejno 2005)

Table 3. cont.

Chemical compound	Odour threshold value, (mg/m^3)	Source
Ethyl alcohol	18.81	(Czurejno 2005)
Ethyl alcohol	55.0	(Devos 1990)
Ethyl alcohol	0.342	(Ruth 1986)
Butyl alcohol	1.2	(Czurejno 2005)
Butyl alcohol	2.57	(Devos 1990)
Isoamyl alcohol	0.1	Czurejno 2005)
Isoamyl alcohol	0.162	(Devos 1990)
Hydrogen sulphide	0.014	(Czurejno 2005)
Hydrogen sulphide	0.65	(Talaiekhozani at al 2016)
Hydrogen sulphide	0.97	(Glindemann et al. 2006)
Hydrogen sulphide	0.57 to 1.42.	(McGinley & McGinley 2004)
Hydrogen sulphide	0.57	(Nagata 2003)
Hydrogen sulphide	0.491-0.964.	(Mannebeck & Mannebeck 2002)
Hydrogen sulphide	0.0257	(Devos 1990)
Hydrogen sulphide	0.0007	(Ruth 1986)

Table 4. Odour concentration at various livestock farming facilities

Type of facilities		Odour concentration, ou_E/m^3
Pigsty	Weaned piglets	3473
	Fattening pigs	1019
	Sows	619
Poultry farm	Broilers	815

(Grzelka et al. 2018)

2. Characteristics of legal provisions on odorous compounds taking into account livestock farming

In Poland, legal provisions governing the issue of limiting human exposure to odours are laid down in several legal acts of the regulation rank. The Regulation of the Minister of Infrastructure of 12 April 2002 on technical conditions to be met by buildings and their location states that livestock buildings should be located at a distance of at least 8 metres from residential ones (Regulation of the Minister of Infrastructure 2015). The issue of location of livestock buildings is also addressed in the Regulation of the Minister of Agriculture and Food Economy of 7 October 1997 on technical conditions to be met by agricultural structures and their localization (Regulation of the Minister of Agriculture and Food Economy 2014). Said regulation establishes the obligation to include a row of medium- and high-growing vegetation between residential and livestock buildings in order to, *inter alia*, reduce odour nuisance. In addition, the mentioned Regulation also contains provisions stating that it is to store liquid animal faeces in sealed, closed containers in order to reduce ammonia and odour emissions.

In 2019, the draft of the first billrelating to the issue of odour nuisance, was published (Draft act on the minimum distance 2019). The draft act on the minimum distance for planned projects of the agricultural sector, the functioning of which may be associated with the risk of odour nuisance specifies that unless the investor obtains the prior consent of residents, newly-created projects related to livestock farming should be located at established minimum distances from residential buildings depending on the size of the stocking density of such a project:

- for animal production facilities with a stocking density of 210 livestock units (LU) to 500 livestock units (LU), the minimum distance shall be equal to the value of the LU;
- for facilities exceeding 500 LU, the minimum distance is 500 m.

These provisions were not intended to apply to existing livestock farming facilities. So far, the draft act has not been implemented.

In Poland, there are no legal provisions in the context of agriculture that would set i.e. limit values of odour emissions as a mixture. However, entrepreneurs pursuing agricultural activity in Poland – an EU Member State – should follow the recommendations provided in the Best Available Techniques (BAT) Conclusions for Intensive Rearing of Poultry or Pigs (Commission Implementing Decision 2017). The document sets forth principles for intensive pig and poultry farming in terms of, among others, farm management, animal feeding, manure collection and storage, and limit levels of emissions to air, including ammonia emissions. The BAT conclusions concern activities involving more than 40,000 places for poultry, more than 2,000 places for fattening pigs (over 30 kg) or more than 750 places for sows. The document emphasizes the obligation to periodically monitor odour emissions, *inter alia*, by using dynamic olfactometry in accordance with the PN-EN 13725 norm (PN-EN 13725). In addition, the installation owner is to set up, implement and regularly review an odour management plan. In order to prevent odour emissions and their impacts, BAT recommends for newly-built facilities to ensure adequate distances from sensitive receptors requiring protection or to apply one or a combination of other remedies, including the use of air cleaning systems or special recommendations for animal housing and floors.

Most European countries, including Poland and Ukraine, have not yet developed national odor emission standards for livestock farming. However, gas emission rates can be rigorously compared to legal regulations regarding air quality guidelines. The concentration of some specific and most common odor substances, such as hydrogen sulfide or ammonia can be compared with individual gas levels of airborne emission regulations. Ammonia and hydrogen sulfide are often more thoroughly investigated in previous studies as they can cause serious adverse health and environmental-related damage (Ruth 1986, Chen et al. 2021).

In Poland, limit values for odorants – ammonia and hydrogen sulphide – are established in the Regulation of the Minister of the Environment of 26 January 2010 on reference values for certain substances in the air (Regulation of the Minister of the Environment 2010). They are juxtaposed in Table 5. Limit concentration values for ammonia and hydrogen sulphide set forth in the State sanitary rules for ambient air protection in residential areas are presented in Table 6 (Legislation of Ukraine 1997). Poland and Ukraine lack set standards for livestock farming regarding odour concentration values expressed in units: ou_E/m^3.

Table 5. Reference values for ammonia and hydrogen sulphide set forth in the Regulation of the Minister of Environment of 26 January 2010 on reference values for certain substances in the air

Substance	Average concentration for a period of	
	one hour, $\mu g/m^3$	one year, $\mu g/m^3$
Ammonia	400	50
Hydrogen sulphide	20	5

(Regulation of the Minister of the Environment 2010)

Table 6. Reference values for ammonia and hydrogen sulphide set forth in the State sanitary rules for ambient air protection in residential areas (from pollution by chemical and biological substances) (Legislation of Ukraine 1997).

Substance	Maximum concentration limit [$\mu g/m^3$]		
	Maximum concentrations average for the period of 20-30 minutes	Average concentration for a period of 24 hours	Class of risk
Ammonia	200	40	4
Hydrogen sulphide	8	–	2

(Legislation of Ukraine 1997)

3. Analysis of the variability in the number of farmed animals and the emission of ammonia in Poland and Ukraine in 2000-2019

Data related to the number of farmed animals and emission values has been analysed on the basis of the information available in statistical yearbooks (GUS 2004-2020). The analysis of the data shows that the number of farmed animals in the years 2000-2019 in Poland and Ukraine differs depending on their type. In the case of poultry farming, an upward trend is noticeable in both Poland and Ukraine, from 50 to 180 million heads and from 120 to 220 million heads, respectively, with clear peaks in 2002 in Poland (as many as 220 million heads), and in 2013 in Ukraine (over 230 million heads) (Fig. 1a).

In the case of sheep farming, no significant changes in the number of animals were observed in Poland between 2000 and 2019: on average there were about 0.300 million heads. In Ukraine, in turn, a systematic decrease in the number of sheep reared may be observed, from about 2 to 1.3 million head (Fig. 1b).

A downward trend is also clearly visible in pig farming. Both in Poland and Ukraine, the number of animals reared decreased from 8 to 6 million and 17 to 11 million heads, respectively (Fig. 1c).

In the farming of cattle, including cows, a decrease in the number of animals was observed. However, in this case the changes were not so explicit. In Poland, between 2000 and 2004, the number of cattle decreased from 6 to 5 million, nd later increased gradually to about 6.5 million heads. In contrast, over these 20 years only a marginal decrease was recorded (from 3 to 2.5 million heads). In Ukraine, the decline was far more significant, from about 9.5 to 3 million heads. The number of cows reared there also systematically decreased (from 5 to less than 2 million heads) (Fig. 2).

Ammonia emissions from agriculture 2008 and 2016, including animal husbandry, both in Poland and Ukraine showed little change and remained at the level of 13-15 million tons of ammonia, with an observed temporary pick-up in Ukraine in 2010-2013 (to just below 20 million tons of NH_3), which may have been partly due to an increase in the number of poultry reared in those years (Fig. 3).

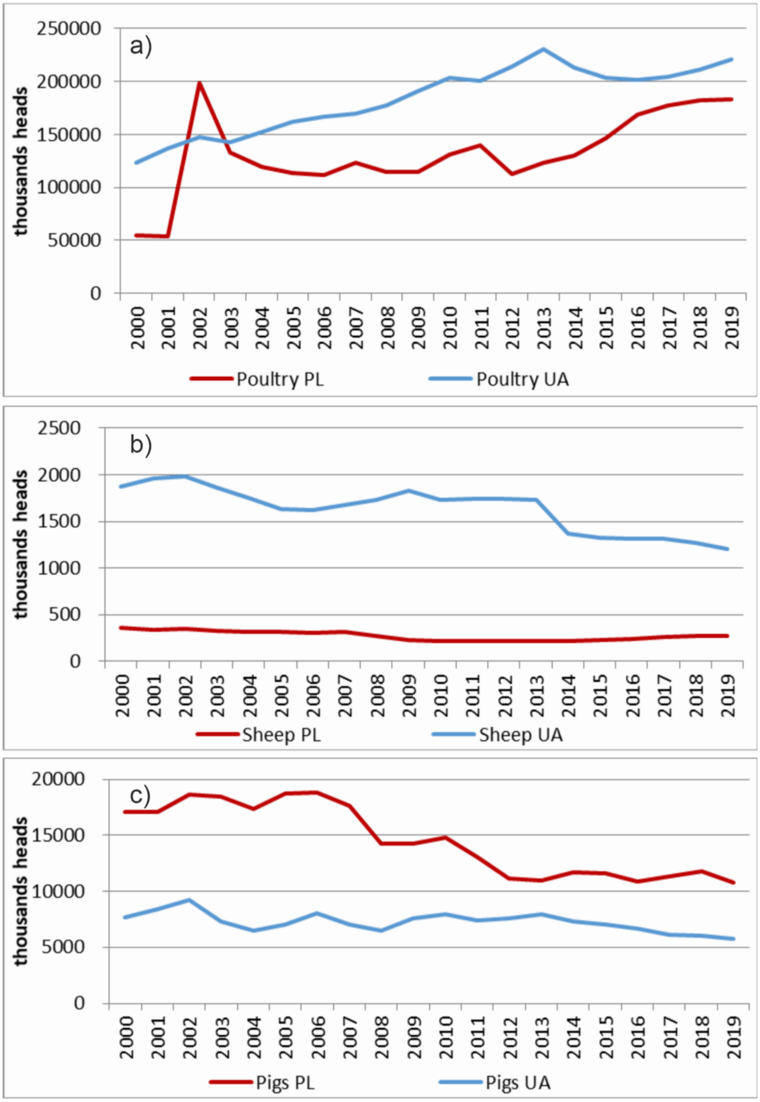

Fig. 1. Number of farmed animals (poultry- a), sheep -b, pigs -c) in 2000-2019 in Poland and Ukraine (source: authors' study based on (GUS 2004-2020))

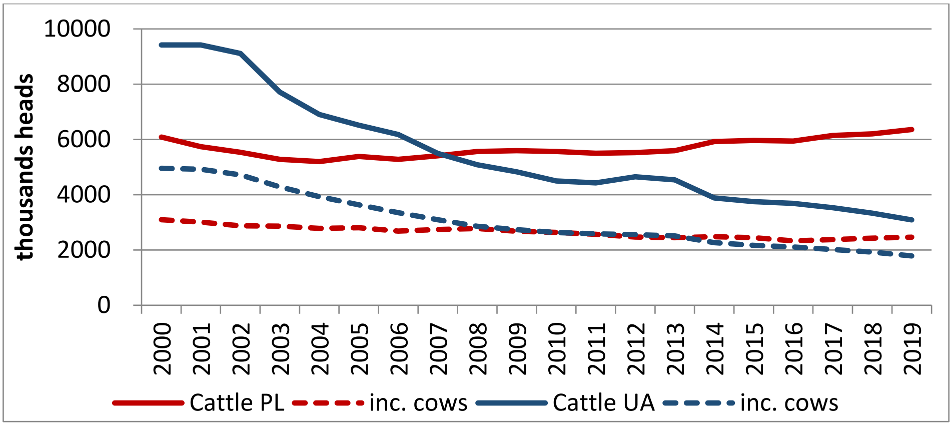

Fig. 2. Number of farmed animals in 2000-2019 in Poland and Ukraine (source: authors' study based on (GUS 2004 -2020))

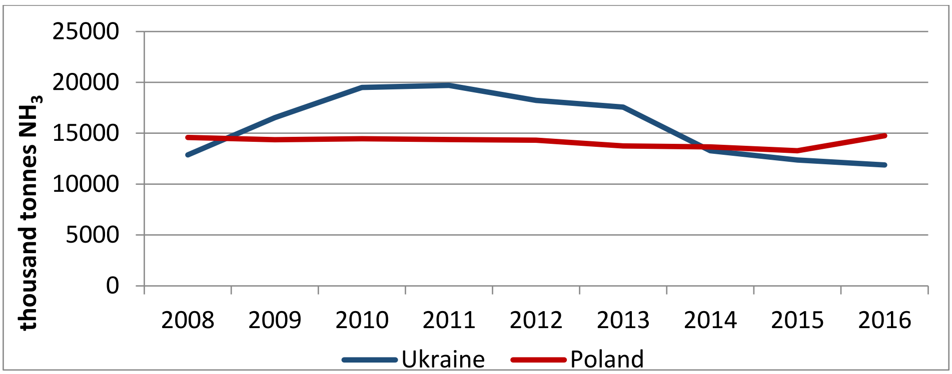

Fig. 3. Ammonia emissions from agriculture in 2008-2016 in Poland and Ukraine (source: authors' study based on (GUS 2004 -2020)

An analysis of the most current data on the number of animals reared in each voivodeship and oblast in 2019 makes it possible to distinguish several areas characterized by more intensive animal farming, regardless what animal is considered. In Poland, these are the following voivodeships: Mazowieckie, Podlaskie, Wielkopolskie, and Lubuskie, while in Ukraine, the Vinnytsia, Kyiv, Cherkasy, Dnipropetrovsk, Lviv, Khmelnytskyi, and Kharkiv oblasts. (Fig. 4-5).

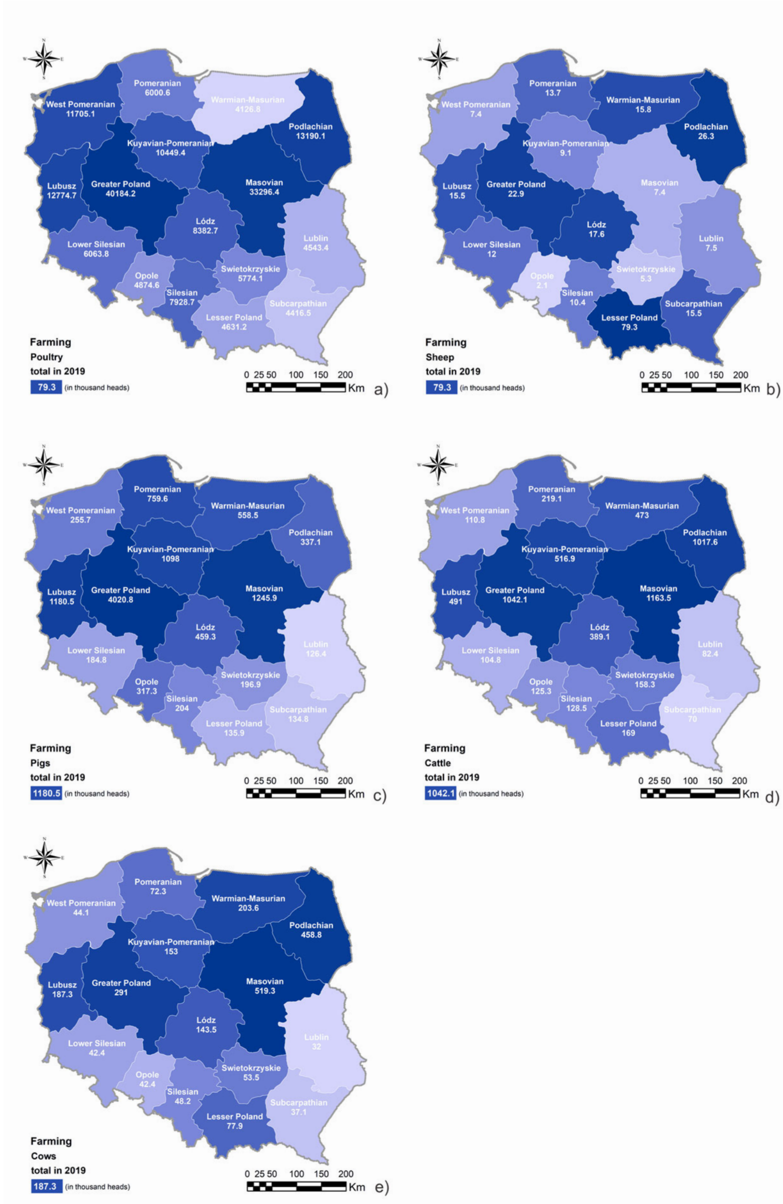

Fig. 4. Spatial distribution of the number of poultry (a), sheep (b), pigs (c), cattle (d) and cows (e) reared in 2019 in Poland (source: authors' study based on (GUS 2020))

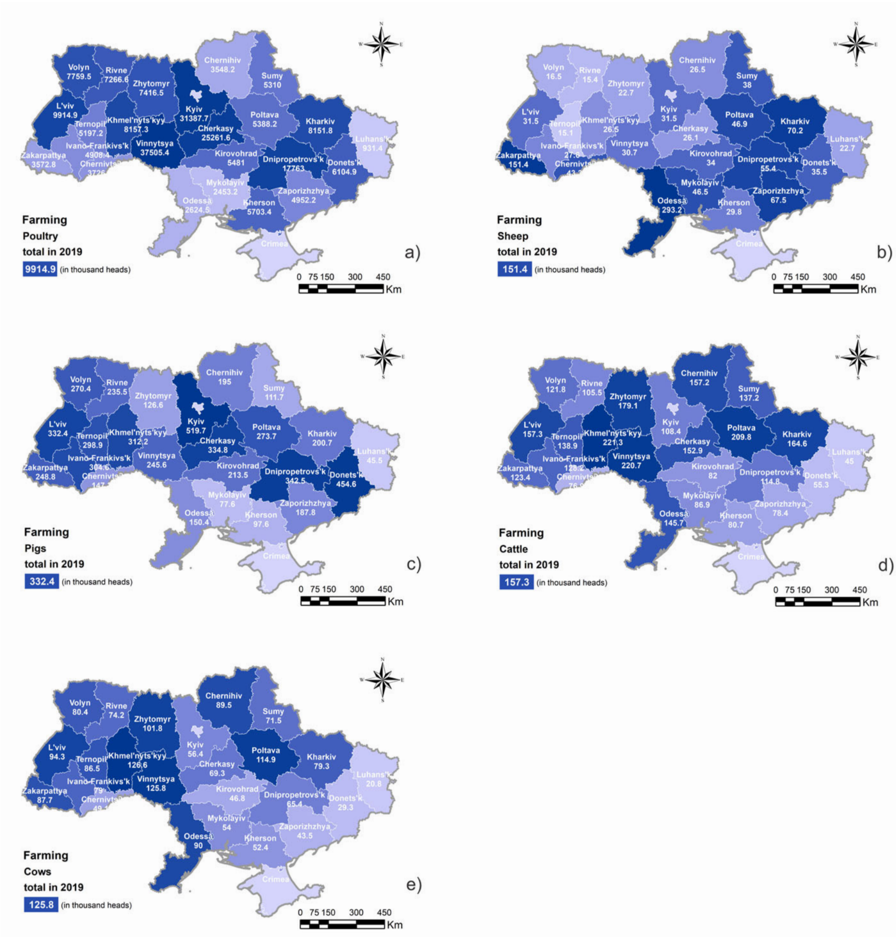

Fig. 5. Spatial distribution of the number of, poultry (a), sheep (b), pigs (c), cattle (d) and cows (e) reared in 2019 in Ukraine (source: authors' study based on (State Statistics Service of Ukraine 2016))

4. Identification of factors determining emissions of odour-active pollutants and their sources in livestock farming

The operation of livestock farming facilities often entails the generation of odorous pollutants, including ammonia – most commonly associated with livestock farming. The total number of odorants emitted as a result of farming is still unknown. However, the data available in the literature on the subject suggests that formation of as many as 168 different compounds of odorous nature (O'Neill & Phillips 1992). In the case of agricultural and livestock activities, the formation of odorous compounds is mainly the result of enzymatic and microbial decomposition of organic matter contained in litter and animal faeces. Odorous compounds are also formed due to reactions occurring in the digestive systems of livestock and as part of processes of respiration and evaporation through the surface of their skin (Grzelka et al. 2018, Korczyński et al. 2010, Saba et al. 2003).

The amount and type of odorous compounds produced by animal farming are contingent on many factors. The basic parameters are the environmental and technical conditions prevailing in animal farming facilities. The environmental conditions outside livestock buildings also play an important role in the case of odour and ammonia emissions, according to research (Gang et al. 2010), seasonal changes in emissions have been found. Other authors suggests that as the temperature outside increases, there is a noticeable increase in daily NH_3 emissions from dairy barns (Ngwabie et al. 2011). The emission of odorants depends on the prevailing temperature, humidity, animal density, type and frequency of changing the litter used, type of flooring and frequency of removing animal faeces (Grzelka et al. 2018, Sówka et al. 2020). Table 7 summarises the main factors determining the amount of odorous compounds emissions from animal farming activities (Úbeda et al. 2013, Sówka et al. 2020).

Another factor determining the formation of gaseous pollutants, including odorants, is the optimisation of animal nutrition. Adequate feed balancing makes it possible to reduce the amount of protein in the faeces and to ensure optimal pH (Jugowar et al. 2010, Sówka et al. 2020, Grela et al. 2010). Animal feeds are formulated in a way that provides the right amount of carbohydrates for the species and life stage of the animal to meet its energy needs. Therefore, animal feed is usually produced from grasses or soya, often containing excess protein which results in an increased excretion of nitrogen, mainly in the form of urea which is the main source of NH_3 emissions from animal faeces (Webb et al. 2005). In addition, with appropriate animal nutrition resulting in a reduction in faecal pH, the potential for NH_3 emissions may also be relatively reduced (Misselbrook et al. 1998). The Nitrogen content in the faeces of non-ruminants may be reduced by adjusting the protein concentration in the feed to meet the needs of the animal at different stages of its life cycle. Protein intake can be further reduced through optimising the essential amino acid content by adding synthetic amino acids to the feed to reduce total protein intake (Kay & Lee 1997).

Table 7. Factors determining the amount and type of odorants formed in animal facilities (Grzelka et al. 2018, Herbut et al. 2010, Jugowar et al. 2010, Sówka et al. 2020, Úbeda et al. 2013, State Statistics Service of Ukraine 2020, Gang et al. 2010, Ngwabie et al. 2011)

	Environmental conditions	Animal feeding	Animal characteristics	Animal faeces/manure
Factors	– particulate matter concentration – temperature – humidity – air flow speed – air exchange rate – weather conditions outside the livestock buildings	Feed composition: – protein content – quantity and type of amino acids – content of non-starch polysaccharides	– animal species – animal age – animal number – animal genotype – animal health status – animal behaviour – male:female ratio	– frequency of manure removal – emission area – manure collection system – type of litter – physical and chemical properties

As yet, no reliable and effective techniques have been worked out for reducing emissions from naturally ventilated buildings – i.e., among others, those commonly used for cattle rearing – where manure is discharged as slurry. However, in the case of a litter system, increasing the amount of straw used for litter purposes may have a beneficial effect on NH_3 emissions (Webb et al. 2005, Balsdon et al. 2002). It is also possible to curb emissions from buildings by reducing the area available to animals and thus reducing the floor area contaminated by faeces; this, however, entails a deterioration in animal welfare (Webb et al. 2005). Moreover, keeping litter moisture as low as possible on the floors of buildings housing broilers by minimising water leakage (e.g. by installing special nipple drinkers) also helps to minimise NH_3 emissions (Elwinger & Svensson 1996). Research has also been conducted in the context of using special additives for litter. It is believed that polyphenols contained in tea extracts can absorb ammonia and hydrogen sulphide particles by a chemical reaction. Tan et al. (Tan et al. 2019) havedemonstrated experimentally that the addition of tea leaves, sawdust, rice husks and straw to chicken faeces effectively inhibited ammonia emissions. Compared with pure chicken manure without litter, the inhibitory effect of addition of tea leaves, straw, rice husk and sawdust on NH_3 emission after 72 hours reached 94.58%, 88.85%, 84.00% and 80.40%, respectively. A significant difference was recorded as regards the inhibition ability of the four types of litter where tea leaves proved the most effective.

In order to reduce odour emissions from livestock farming, it is also necessary to ensure adequate frequency of faeces removal and, in the case of slatted system, to ensure that the slatted floor scrapers operate smoothly enough to continuously discharge the faeces produced. Currently, increasingly popular solutions to reduce emissions include the use of special bacterial inoculations of litter, which, according to literature reports, allows for nitrogen compound emissions reduction by up to 50%. Herbut et al. (Herbut et al. 2010) conducted research aimed at recognising the scope and scale of emission of zoonotic odorants from livestock housing facilities with the most commonly used systems of keeping pigs and cattle. The research was conducted in special climate chambers in which similar microclimatic conditions were maintained for each group of animals and each type of litter used. The highest level of total odorant emission for pigs was recorded for the slatted system, followed by the deep litter system (Table 8). Ammonia was found to constitute the highest share in the total emissions. Also in the case of studies with cows, significant differences in emissions were recorded depending on the housing system. The highest emission values of all groups of compounds were recorded in the litter-free rearing and in the deep sawdust litter system. The lowest emission factors were recorded for shallow straw litter. The research showed that the decisive factor for the emission of odorants is the share of anaerobic conditions. Straw is characterised by its pore structure allowing natural aeration and a higher share of aerobic processes, which explains why the lowest values were recorded for shallow straw litter.

According to the studies presented in the paper up to 30 different gases may be formed during litter-free rearing of pigs, with hydrogen sulphide and ammonia being the most prevalent ones. Gases (mainly methane and carbon dioxide) are formed in animal facilities as a result of animals breathing and fermentation. According to the study on a complex of pig houses, given the capacity of 54 thousand pigs/year, during one hour there may be formed: 83.4 billion microorganisms, 0.6 kg/m^2 of dust and 14.4 kg/m^2 of ammonia. Increasing the number of animals to 108 thousand head/year using outdated rearing technologies led to air pollution and the spread of odours over a distance of up to 5,000 m, and at a capacity of 10 thousand head/year – over a distance of up to 3,000 m (Report on research work 2019, Annotated report of research work 2019).

Table 8. Emission of main groups of odorants from rearing of fattening pigs and lactating cows depending on rearing system used (kg/animal place/year) (Herbut et al. 2010)

Group of compounds	Fattening pigs			Lactating cows			
	Shallow litter	Deep litter	Slatted	Shallow litter	Deep straw litter	Deep saw-dust litter	Litter-free
	kg/animal place/year						
Ammonia	2.31	3.67	5.24	72.5	47.1	63.7	90.9
Hydrogen sulphide	0.084	0.108	0.322	0.379	0.019	0.351	0.473
Sulphur dioxide	0.043	0.071	0.048	24.1	19.3	28.4	56.1
Aldehydes	0.02102	0.02656	0.03489	0.2973	0.1902	0.2456	0.3723
Alcohols	0.0072	0.00983	0.01564	0.1240	0.072	0.0983	0.176
Ketones	0.01401	0.01585	0.01962	0.1696	0.1401	0.1585	0.2380
Organic acids	0.00586	0.00673	0.008407	0.782	0.58867	0.67363	1.0352
Thiols	0.05606	0.06423	0.07789	0.07142	0.05606	0.06423	0.08190
Phenols	0.2053	0.22342	0.3891	0.2984	0.2053	0.22342	0.40924
Amines	0.0724	0.07792	0.1292	1.0001	0.724.	0.7792	1.4708
Esters	0.00694	0.00716	0.00978	0.0823	0.0694	0.0716	0.1230

The BAT Reference Document for Intensive Rearing of Poultry or Pigs (Commission Implementing Decision 2017) describes an innovative litter-free rearing system (called AFS – AviHome Flooring System) developed by Avi-Home LLC, a US company, in collaboration with the University of Maryland. The system consists of two layers of pH-neutral polymer flooring with an air plenum in between. The top layer is perforated to allow the downward wicking of moisture from the liquid part of the faeces and evaporating, thus producing dry manure with low ammonia content. The AviHome Floor System (AFS) was developed to reduce ammonia production and emissions by accelerating the evaporation of water from the manure, thereby removing it from the uric acid breakdown process. Curbing the nitrification process reduces the number of bacteria in manure, resulting in improved animal welfare and meat production (Commission Implementing Decision 2017, Boggia et al. 2019).

A study conducted on a farm with 20,000 broilers showed a drastic reduction in ammonia due to this method (Harter-Dennis 2010).

Manure storage is recognised as a significant element in total farm emissions. Ammonia emissions from livestock buildings as a result of the deposition on manure onto cultivated fields are considered to be the most significant sources of odour from the operation of livestock farming facilities. Ammonia emissions are considered dangerous because ammonia can cause soil acidification and eutrophication (Marcinkiewicz & Kolomiets 2015).

Furthermore, NH_3 emissions attributed to the storage of animal manure are also an important element. Typically, once removed from livestock facilities, slurry is stored in concrete, steel or wooden tanks, or in earth-banked lagoons. In the case of storing in open lagoons orlarge-quantity field usage, local communities living near industrial farms suffer from a distinctive unpleasant odour (Marcinkiewicz & Kolomiets 2015). Reducing the concentration of odorous emissions and their spread contributes to alleviating the social tensions of the population living in the vicinity of livestock facilities and manure-fertilised cultivated fields. Lagoons, due to their large surface-to-volume ratio, have a significantly higher potential for NH_3 emissions. Table 9 juxtaposes techniques for reducing NH_3 emissions from faeces storage along with their estimated effectiveness (Webb 2005).

Table 9. The effectiveness of techniques for reducing NH_3 emissions from animal faeces storage (Webb 2005)

Technology	Effectiveness (%)
Maintaining low surface to tank volume ratio	20-50
Permanent roofing/tent structure over the tank	80
Formation of a natural crust	35-50
Flexible, floating covers made of plastic	60
Use of LECA (expanded clay aggregate) for insulation	40

Reducing the volume-to-surface ratio of a manure storage tank may significantly curb NH_3 emissions. For example, for a slurry volume of 1000 m^3, increasing the tank wall height from 3 to 5 m may reduce NH_3 emissions by 1/3 (Webb 2005). The most effective way to reduce NH_3 emissions is to install covers (Webb 2005, Sommer et al 1993). The cover prevents the volatilisation of odorous compounds from above the slurry surface. Said covers are used for above-ground, usually circular tanks made of steel sheets or concrete. However, unsealing of the cover must be ensured to prevent the accumulation of methane gas inside, hence this solution will not eliminate the emission of odorous compounds completely (Webb 2005, Sommer et al 1993). Other methods, such as maintaining a natural or artificial crust on the surface of the stored slurry, give poorer results and are more difficult in terms of management – yet they are also cheaper. Cattle slurry usually forms a natural crust if DM is > 7% and mixing is minimised. With a view to avoiding damage to the crust, tanks must be filled with manure from below. Frequent mixing and emptying should be avoided if possible, as these operations increase NH_3 emissions from slurry (Webb 2005).

5. Methods used in health impact assessments

Individual branches of the animal breeding/husbandry industry create a spectrum of environmental impacts, including odour nuisance, which can bring about health effects due to the emission of odorous compounds. Studies on the health effects of odours are especially difficult to conduct because odours have an individual and discretionary nature. Excessive levels of odour nuisance may cause significant impairment in the quality of life of those exposed to it. Odour-active compounds can be immunosuppressive, e.g. in the case of respiratory diseases (Mitloehner & Schenker 2007). Previous studies (Schulze et al. 2011) demonstrate that odorous substances including ammonia, hydrogen sulphide and others can cause ailments and diseases among people exposedStimulation of the trigeminal nerve, which may occur during exposure to odorants, causes irritation of the mucous membranes of the nose (rhinitis), throat (pain or scratching in the throat), eyes (tearing) and may trigger defensive reactions from the respiratory tract (coughing, shortness of breath, shallow breathing). On the other hand, psychosomatic symptoms such as insomnia, panic attacks, photophobia, and decreased psychophysical performance are largely determined by one's personality traits, and may be caused by general everyday problems or the stress resulting, for example, from exposure to unpleasant odours. These symptoms are not, however, an effect of the toxicity of a particular chemical compound (Michalak et al. 2014). Another effect of exposure to odorous compounds may also be an increased risk of aggravated cardiovascular ailments for people suffering from cardiovascular diseases such as ischemic heart disease (EPA 2000 2001, Pohl et al. 2017).

Schiffmann et al. (Schiffman et al. 2004) describe three possible paths for the emergence of ailments as a result of exposure to odours:

- the emergence of health effects once toxicity thresholds for the emitted odorous substances are exceeded;
- the appearance of health ailments once the olfactory threshold is exceeded;
- the appearance of health problems following exposure to a mixture of odours, one of which is responsible for the indicated ailments.

Intensive livestock farming contributes to high concentrations of NH_3 inside livestock housing. Both, NH_3 concentration and exposure time determine negative health effects on farm workers and livestock. According to the recommendations of the US National Institute for Occupational Safety and Health, it is estimated that the maximum level of ammonia concentration in the air safe for human health is 25 ppm for the exposure time of 8-10 h. Furthermore, according to the American Conference of Governmental Industrial Hygienists, the maximum safe time of staying in the concentration of 35 ppm is only 15 minutes.

The concentration of NH_3 in the air causing an immediate risk to health and life even at momentary exposure is 300 ppm (Ritz et al. 2004, ACoGIH 2001) Numerous studies also suggest the ammonia is harmful for animals. Exposure to ammonia in poultry houses can increase the risk of disease among birds (Carlile 1984, Beker 2004, Miles et al. 2002, Anderson 1964). Studies (Miles et al. 2002) indicate that – for animal health reasons – ammonia concentrations inside poultry houses should not exceed 25 ppm. However symptoms of reduced health and growth, including increased susceptibility to Newcastle disease, may already be seen at 20 ppm. It has also been demonstrated that broilers reared in 25 ppm ammonia conditions gain noticeably lower body weights, partly due to lower feed intake. Exposure to 46-102 ppm caused eye damage in the form of keratoconjunctivitis (Carr & Nicholson 1980). Other symptoms of ammonia toxicity in poultry include tracheal irritation, air sac inflammation, conjunctivitis and dyspnoea (Carlile 1984).

One of the methodologies most commonly used to assess the health effects of emitted odorous substances is the risk assessment proposed by the US Environmental Protection Agency (US EPA) using the so-called Hazard Index (HI) (EPA 1986, EPA 2000). This method consists in estimating the level of human exposure to a given agent (pollutant) scaled according to a certain threshold level of exposure, so-called acceptable or safe for health. In the event of HI > 1 there is a potential health hazard. The formula by which HI is calculated is shown below.

$$HI = CE_1/DR_1 + CE_2/DR_2 + \dots + CE_n/DR_n \qquad (1)$$

where:
CE1 is defined as the exposure level to the first chemical substance in the mixture,
DR1 is the acceptable exposure level to the first chemical substance,
CE2 and DR2 are the respective levels for chemical substance 2.
Each specific factor is called a hazard quotient (HQ).

Pohl et al. (Pohl et al. 2017) conducted a study to estimate local community exposure and assess the potential health hazard to the population living near 10 large poultry farms (concentrated animal feeding operation: CAFOs) located in Poland. The AERMOD model and hazard index (HI) estimation were used for the purpose of risk assessment. HI calculations were performed for a group of air pollutants characteristic of CAFO-type facilities, including ammonia, followed by a simulation of pollutant dispersion in the AERMOD model. The data obtained suggest that odour-causing pollutants emitted from CAFOs, such as hydrogen sulphide and ammonia, can exceed background concentrations by more than an order of magnitude in residential areas within a kilometre radius of the surveyed farms, eventually falling to background levels several kilometres from the source. However, studies have not identified significant health hazards from the analysed substances.

In studies conducted in the Lower Saxony region (Schulze et al. 2011), researchers carried out stationary grid measurements of NH_3 concentrations to assesst exposure to high ammonia concentrations in concentrated animal feeding operations (CAFOs). The collected data was then interpolated with GIS (Geographic Information System) tools using the IDW (Inverse Distance Weighting) method. Additionally, a survey was carried out among the resident population in the area to estimate the prevalence of respiratory health problems. Furthermore, a randomly selected group of residents were invited for lung function and blood tests. The results showed that ammonia emissions from CAFOs can contribute to respiratory ailments as well as increase the risk of allergic reactions.

The survey method was also used in a study on the relationship between odour exposure and somatic effects conducted in North Rhineland-Westphalia (Steinheider 1990) where field studies of odour nuisance in accordance with the methodology in VDI-3940 were also applied. Here, the field studies were carried out to assess the incidence of odour nuisance, the so-called odour hours. The survey concerned people living in the vicinity of two facilities, specialising in pig farming and producing substrate for mushroom growing, respectively. The study showed that excessive exposure to odours can cause (apart from irritation symptoms) somatic complaints, especially those related to the digestive system, such as nausea, vomiting, loss of appetite, and sleep disturbances.

6. Solutions to curb the impact of odour-active compounds emitted by animal farming facilities

The basic principles for reducing odour emissions in livestock farming include (EPA 2001): reducing the formation of odorous substances in slurry, reducing the rate of spread from surface sources, reducing the exposed surface area of slurry, including stored slurry, soiled surfaces, grids, etc., as well as utilizing feed additives, slurry additives and ventilation air extraction and treatment (secondary methods). Indirect methods affecting the reduction of pollutant emissions to air include bedding-related techniques such as aeration and drying of litter, underfloor heating, as well as the use of chemical and microbiological preparations disinfecting the litter and binding ammonia (Korczyński et al. 2010). Ammonia emissions can also be curbed during storing, warehousing and applying slurry and manure in the field (air-tight sealing of tanks, lowering the temperature, soil application (Lisowska-Mieszkowska 2014). An important aspect of avoiding the negative environmental impact of animal farming is proper spatial planning. Proper location of livestock facilities can prove effective in preventing odour nuisance. The use of buffer zones and protective green belts (VEB – Vegetative Environmental Buffers) can also limit the spread of pollutants in the air and thus reduce the range of negative impacts (Kunowska-Ślósarz et al. 2016).

Within the framework of the general BAT conclusions (Commission Implementing Decision 2017), for intensive poultry or pig farming, the implementation of an odour management plan is includedfor facilities demonstrating a potential or identified issue with odour nuisance. Such an odour management plan is a part of an environmental management system aimed at improving the overall environmental performance of the farms. Said an odour management plan should include: a protocol containing appropriate actions and timelines, a protocol for conducting odour monitoring, a protocol respondnig to identified odour nuisance, an odour prevention and elimination programme, a review of historical odour incidents and remedies and the dissemination of odour incident knowledge. The odour prevention programme aims to identify sources of odorous substances, monitor odour emissions, determine the contribution of individual sources and introduce measures to prevent or reduce odour emissions. In addition, the document identifies techniques to prevent or reduce odour emissions, such as:

- ensuring an adequate distance between the farm/plant and the sensitive receptors;
- one of foolowing: keeping the animals and surfaces dry and clean or reducing the emitting surface of manure or removing manure frequently to an external (covered) manure store or reducing the temperature of the manure and of the indoor environment or decreasing the air flow and velocity over the manure surface or keeping the litter dry and under aerobic conditions (for litter-based systems);
- optimising the discharge conditions of exhaust air by: increasing the outlet height or increasing the outlet ventilation velocity, or placing barriers (e.g. planting vegetation) to reduce the dispersion of odours in the air over longer distances, or using deflector covers in order to divert exhaust air towards the ground, or directing odour emissions in parts of the farm further away from the sensitive receptor, or aligning the ridge axis of a naturally ventilated building transversally to the prevailing wind direction;
- using air cleaning systems, such as bioscrubbers/biotrickling filters or biofilters, or a two-stage or three-stage air cleaning system;
- covering slurry or solid manure during storage or locating the store taking into account the general wind direction and adopting measures to reduce odour spread, such as natural barriers or minimising the stirring of slurry;
- processing manure with aerobic digestion (aeration) of slurry or composting solid manure or with anaerobic digestion;
- manure landspreading using a band spreader, shallow/deep injector to incorporate manure as soon as possible.

BAT also provides the following methods for reducing emissions of ammonia – one of the key odorants emitted in livestock farming – from solid manure storage: reducing the ratio between the emitting surface area and volume of the solid manure heap; covering solid manure heaps; storing dried solid manure in a barn. For farms where manure processing is used, in order to reduce (i.a.), odour emissions, the following techniques are recommended: mechanical separation of slurry (e.g. by using screw press or decanter-centrifuge separators, coagulation-flocculation, separation by sieves, using filter pressing); anaerobic digestion of manure in a biogas installation; use of an external tunnel for manure drying; aerobic digestion (aeration) of manure; composting solid manure.

Monitoring odour emissions regularly is recommended as part of an odour management plan. To this end, it is possible to apply EN standards (e.g. EN 13725: Air quality. Determination of odour concentration by dynamic olfactometry) (PN-EN 13725, 2007) or alternative methods for which there are no EN standards, ISO standards, national or international standards that ensure the acquisition of data of equivalent scientific quality In addition, ammonia emissions should be monitored by mean of estimation through a mass balance based on excretion and the total (or total ammoniacal) nitrogen content at each manure management stage,calculation by means of measurement of ammonia concentration and the ventilation rate using ISO, national or international standard methods or other methods ensuring the data is of equivalent scientific quality or estimation by using emission factors. It is also necessary to carry out a one-time verification of the air cleaning system by measuring ammonia, odour and/or dust under practical farm conditions according to a prescribed measurement protocol and using EN or other standard methods (ISO, national or international) ensuring data of an equivalent scientific quality and a daily control of the effective function of the air cleaning system (e.g. by continuously recording operational parameters or using alarm systems).

Methods of reducing emissions from livestock facilities through gas treatment mainly include (Economic Commission for Europe 2014) sorption techniques and biological methods. Sorption techniques include absorption and adsorption, which are highly effective in controlling organic odours, including volatile organic compounds and may also be used to reduce emissions of inorganic compounds such as ammonia (Kwaśny & Balcerzak 2014]). On the other hand biological methods allow for elimination of both odours and other pollutants found in the treated gases, such as: aliphatic, aromatic, aerobic, sulphur, nitrogen, and chlorine compounds. Biological gas treatment is most commonly implemented in installations such as : bioscrubbers, biotricklers, and biofilters.

7. Conclusions

Intensive livestock farming is, doubtlessly, a source of odorous emissions. Individual odorous substances and their mixtures present in the air/environment may cause discomfort, irritation and annoyance among residents living in the vicinity of livestock farming facilities, and in extreme cases even trigger a disease – especially if the chemical compound concentrations are elevated, the exposure time is long, andif the frequency of episodes is high. The elderly, children and people from high-risk groups are particularly vulnerable to such negative effects. Therefore, actions such as monitoring and control of odour-active compounds by reference to certain standards, application of good practices and preventive measures to mitigate the risk of odour emissions are crucial. Said actions have been recommended and described in scientific studies, by environmental agencies including the Environmental Protection Agency, and in BAT reference documents. Proper location of farming facilities in relation to residential buildings is a key factor in preventing odour nuisance. There are many factors determining the amount and type of pollutants generated during farming and keeping of animals, including the followingenvironmental and technical conditions in livestock farming facilities: the prevailing temperature, humidity, care for the welfare of animals, including their proper density, appropriate way of air exchange in the interior of the facility, type and frequency of litter replacement, type of flooring, method of feeding and type of food, frequency of animal faeces removal, the method of their storage, disposal or use as agricultural products. The application of appropriate standards and solutions available in Europe and worldwide allows – and in the case of countries outside the European community such as e.g. Ukraine may allow – to minimise the negative impact of livestock farming facilities, including the exposure of humans and animals to abnormal concentrations of odorous compounds. A holistic approach to analyses and evaluations of odorous air quality or odour nuisance, and thus the impact on the comfort of human life and health, should include, inter alia, standards (emission as well as immission) expressed in ou_E/m^3 and opinions (in line with the current or proposed standards for sociological studies) of residents living in the vicinity of livestock farming facilities.

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References

ACoGIH 2001 American Conference of Governmental Industrial Hygienists. (2001). in 2001 Threshold Limit Values (TLVs) and Biological and Exposure Indices (BEIs). ACGIH, Cincinnati, OH. 72-75

Anderson, D., Peard, C. W. & Hanson, R. P. (1964). Adverse effects of ammonia on chickens including resistance to infection with Newcastle disease virus. Avian Dis., *8*, 369-378.

Annotated report of research work on scientific and hygienic support of the object "Construction of a pig farm № 11 JV LLC" Niva Pereyaslavshchyna "within the administrative boundaries of Gostrolutsk village council of Baryshiv district of Kyiv region (outside the settlement)" in terms of determining the carcinogenic and non-carcinogenic risk. Marzeeva O.M. (2019).

Balsdon, S.L., Chadwick, D.R., Webb, J. & Day, J. (2002). Evaluation of increased straw use as a means of reducing ammonia emission from housed cattle and pigs. In: Venglovsky, J., Gre´serova, G. (Eds.), *Proceedings of the 10th International Conference of the RAMIRAN Network*, Srbske Pleso, Slovak Republic, 291-292.

Beker, A., Vanhooser, S. L., Swartzlander, J. H. & Teeter, R. G. (2004). Atmospheric ammonia concentration effects on broiler growth and performance. J. Appl. Poult. Res., *13*, 5-9.

Boggia, A., Paolotti, L., Antegiovanni, P., Fagioli, F. F., & Rocchi, L. (2019). Managing ammonia emissions using no-litter flooring system for broilers: Environmental and economic analysis. *Environmental Science & Policy*, *101*, 331-340.

Carlile, F. S. (1984). Ammonia in poultry houses: a literature review. Worlds Poult. Sci. J., *40*, 99-113.

Carr, L. E. & Nicholson, J. L. (1980). Broiler response to three ventilation rates. Trans. ASAE, *23*, 414-418.

Chen, B., Koziel, J.A., Lee, M., O'Brien, S.C., Li, P. & Brown, R.C. (2021). Mitigation of Acute Hydrogen Sulfide and Ammonia Emissions from Swine Manure during Three-Hour Agitation Using Pelletized Biochar. *Atmosphere*, *12*(825). DOI:/10.3390/atmos12070825.

Commission Implementing Decision (EU) 2017/302 of 15 February 2017 establishing best available techniques (BAT) conclusions, under Directive 2010/75/EU of the European Parliament and of the Council, for the intensive rearing of poultry or pigs.

Conti, C. (2020). Measurement techniques and models to assess odor annoyance: A review, *Environmental International*, *134*,105-261.

Czurejno, M. (2005). Municipal waste landfills as a source of odorant emissions, *Communal Review (Przegląd Komunalny)*, *11*, 108-110 [in Polish].

Devos, M., Patte, E., Rouault, I., Laffort, P. & Van Gernert, L.l. (1990). (Eds.). Standardized Human Olfactory Thresholds. Oxford University Press, New York.

Draft act on the minimum distance for planned projects of the agricultural sector, the functioning of which may be associated with the risk of odour nuisance, 28 March 2019. https://legislacja.rcl.gov.pl/docs//2/12321413/12579301/12579302/dokument387162.pdf (access: 28.02.2021).

Economic Commission for Europe. (2014). Guidance document on preventing and abating ammonia emissions from agricultural sources.

Elwinger, K. & Svensson, L. (1996). Effect of dietary protein content, litter and drinker type on ammonia emission from broiler houses. *Journal of Agricultural Engineering Research*, *64*, 197-208.
Environmental Protection Agency. (2001). Odour Impacts and Odour Emission Control Measures for Intensive Agriculture. Final Report. R&D Report Series, 14.
European Environment Agency. (2019). EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019 – *Technical Guidance to Prepare National Emission Inventories*. EEA Report No 13/2019.
EPA 2000. (2001). Environmental Protection Agency, Odour Impacts and Odour Emission Control Measures for Intensive Agriculture. Final Report. R&D Report Series, 14.
Glindemann, D., Novak, J., Witherspoon, J. (2006). Dimethyl sulfoxide (DMSO) waste residues and municipal waste water odor by dimethyl sulfide (DMS): the northeast WPCP plant of Philadelphia. *Environ. Sci. Technol*., *40*(1), 202-207.
Grela, E. R., Czech, A., Semeniuk, W. (2010). Żywieniowe metody ograniczania wydalania azotu do środowiska podczas chowu trzody chlewnej, w: *Współczesna problematyka odorów*, Warszawa: Wydawnictwo Naukowo-Techniczne. 383-407.
Grzelka, A., Sówka, I., Miller, U. (2018). Methods of evaluation of odor emissions from livestock management facilities. *Ecological Engineering*. *19(2),* 56-64 (in Polish).
GUS, Agriculture in 2003. (2004). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2003-r-,3,1.html, (access: 1.03.2021) (in Polish).
GUS, Agriculture in 2004. (2005). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2004-r-,3,2.html, ([access: 1.03.2021) (in Polish).
GUS, Agriculture in 2005. (2006). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2005-r-,3,3.html, (access: 1.03.2021) (in Polish).
GUS, Agriculture in 2006. (2007). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2006-r-,3,4.html, (access: 1.03.2021) (in Polish).
GUS, Agriculture in 2007. (2008). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2007-r-,3,5.html, (access: 1.03.2021) (in Polish).
GUS, Agriculture in 2008. (2009). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2008-r-,3,6.html, (access: 1.03.2021) (in Polish).
GUS, Agriculture in 2009. (2011).Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2009-r-,3,7.html, (access: 1.03.2021) (in Polish).
GUS, Agriculture in 2011 (2012). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2011-r-,3,8.html, (access: 1.03.2021) (in Polish).
GUS, Agriculture in 2012. (2013). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2012-r-,3,9.html, (access: 1.03.2021) (in Polish).
GUS, Agriculture in 2013. (2014). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2013-r-,3,10.html, (access: 1.03.2021) (in Polish).
GUS, Agriculture in 2014. (2015). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2014-r-,3,11.html, (access: 1.03.2021) (in Polish).
GUS, Agriculture in 2015. (2016). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2015-roku,3,12.html, (access: 1.03.2021) (in Polish).
GUS, Agriculture in 2016. (2017). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2016-roku,3,13.html, (access: 1.03.2021) (in Polish).

GUS, Environmental economic accounts – Annex 1. Air emission accounts. Warsaw, 2017, https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/rachunki-ekonomiczne-srodowiska,7,3.html, (access: 1.03.2021) (in Polish).

GUS, Agriculture in 2017. (2018). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2017-roku,3,14.html, (access: 1.03.2021) (in Polish).

GUS, Agriculture in 2018. (2019). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2018-roku,3,15.html, (access: 1.03.2021) (in Polish).

GUS, Agriculture in 2019. (2020). Warsaw, https://stat.gov.pl/obszary-tematyczne/ rolnictwo-lesnictwo/rolnictwo/rolnictwo-w-2019-roku,3,16.html, (access: 1.03.2021) (in Polish).

GUS, Concise Statistical Yearbook of Poland. (2020). Warsaw (in Polish).

Harter-Dennis, J. (2010). Summary of Research UMES/AviHome Flooring System. University of Maryland Eastern Shore.

Herbut, E., Waczak, J., Krawczyk, W., Szewczyk, A. & Pająk, T. (2010). Research on odorant emissions from livestock keeping, [in:] *Contemporary problem of odors*, Eds. Szynkowska, M.I., Zwoździak, J., Scientific and Technical Publishing House (Wydawnictwo Naukowo-Techniczne), Warsaw, 1-12 (in Polish).

Institute of Agricultural and Food Economics – National Research Institute. (2018). Analysis of the agri-food market in Poland with recommendations for products that can be traded on the Food Platform – thematic report no.1, Warsaw (in Polish).

Jugowar, J.L., Kołodziejczyk, T., Myczko, R. & Graczyk, A. Evaluation of the effectiveness of nanopreparations for hygienizing livestock premises [in:] *Contemporary problem of odors*, Eds. Szynkowka, M.I., Zwoździak, J., Scientific and Technical Publishing House. (2010). Warsaw: Wydawnictwo Naukowo-Techniczne. 310-326 (in Polish).

Kay, R.M. & Lee, P.A. (1997). Ammonia emissions from pig buildings and characteristics of slurry produced by pigs offered low crude protein diets. In: Voermans, J.A.M., Monteny, G.J. (Eds.), *Ammonia and Odour Emission from Animal Production Facilities*. Vinkeloord, The Netherlands, 253-259.

Korczyński, M., Opaliński, S., Kołacz, R., Dobrzański Z., Gbiorczyk, W. & Szołtysik, M. (2010). Chemical and biotechnological preparations for bedding, manure and slurry reducing the emission of odors and toxic gases "at source", [in:] *Contemporary problem of odors*, Eds. Szynkowka, M.I., Zwoździak, J., Scientific and Technical Publishing House. Warszawa. 452-478 (in Polish).

Kunowska-Ślósarz, M., Gurdała, J., Gołebiewski, M. & Przysucha, T. (2016). Methods of reducing odor emissions in livestock buildings and their surroundings, *Zootechnical news* (Wiadomości Zootechniczne). 118-126 (in Polish).

Kwaśny, J. & Balcerzak, W. (2014). Characteristics of selected indirect methods of reducing the emission of odors, *Archives of Waste Management and Environmental Protection*. *16*(4).

Legislation of Ukraine. Ministry of Health of Ukraine (1997). Kyiv. N 201 of 09.07.97. State Sanitary Rules for the Protection of Ambient Air of the Settlements (from the Contamination with Chemical and Biological Substances): DSP-201-97. 57 p., https://zakon.rada.gov.ua/rada/show/en/v0201282-97/conv#Text (access: 19.03.2021) (in Ukrainian).

Lisowska-Mieszkowska, E. (2014). Control and reduction of ammonia emissions from agricultural sources. Actions taken on the international forum. *Economics and Environment* (Ekonomia i Środowisko), *3*(50).

Nagata, Y. (2003). Measurement of Odor Threshold by Triangle Odor Bag Method In Odor Measurement Review. Japan: Office of Odor, Noise and Vibration Environmental Management Bureau, Ministry of the Environment, Government of Japan. 118-12.

Ngwabie, N. M., Jeppsson, K. H., Gustafsson, G. & Nimmermark, S. (2011). Effects of animal activity and air temperature on methane and ammonia emissions from a naturally ventilated building for dairy cows. *Atmospheric Environment*. *45*(37), 6760-6768.

Mannebeck, D. & Mannebeck, H. (2002). Hazardous substances. Keeping the air clean. *62*, 135-40 (in German).

Marcinkiewicz, V. & Kolomiets, N. (2015). National Ecological Center of Ukraine. Livestock waste management: advantages of anaerobic digestion technology. Kyiv, Access: (https://necu.org.ua/wp-content/uploads/Biogaz_A4_web-2.pdf) (in Ukrainian).

McGinley, M. A. & McGinley, C. M. (2004). Comparison of field olfactometers in a controlled chamber using hydrogen sulfide as the test odorant, *Water Sci. Technol*. *50*(4), 75-82. DOI:10.2166/wst.2004.0225

Michalak, A., Krzeszowiak, J. & Pawlas, K. (2014). Does exposure to unpleasant odors (odors) harm human health. *Environmental Medicine 17*, 76-81 (in Polish).

Miles, D. M., Branton, S. L., Lott, B. D. & Simmons, J. D. (2002). Quantified detriment of ammonia to broilers. *Poult. Sci. (Abstr.), 81*, 54-55.

Ministry of Climate. (2020). Warsaw. National emission balance of SO_2, NO_x, CO, NH_3, NMVOC, dust, heavy metals and POPs for the years 1990-2018 (in Polish).

Misselbrook, T. H., Chadwick, D. R., Pain, B. F. & Headon, D. M. (1998). Dietary manipulation as a means of decreasing N losses and methane emissions and improving herbage N uptake following application of pig slurry to grassland. *The Journal of Agricultural Science*, *130*(2), 183-191.

Mitloehner Frank M. & Schenker, Marc B. (2007). Environmental Exposure and Health Effects From Concentrated Animal Feeding Operations, *Epidemiology*, *18*, 309-311.

O'Neill, D. H. & Phillips, V. R. (1992). Review of the control of odour nuisance from livestock buildings: Part 3, properties of the odorous substances which have been identified in livestock wastes or in the air around them. *Journal of Agricultural Engineering Research*, *53*, 23-50.

Pinchuk, V.O. & Borodai, V.P. (2019). Efficiency of nitrogen use in industrial livestock of Ukraine. *Agroecological Journal*. No. 4. DOI: 10.33730/2077-4893.4.2019. 189462 (access: 22.01.2021).

PN-EN 13725. (2007). Standard Air quality Determination of odor concentration by dynamic olfactometry (in Polish).

Pohl, H. R., Citra, M., Abadin, H. A., Szadkowska-Stańczyk, I., Kozajda, A., Ingerman, L. & Murray, H. E. (2017). Modeling emissions from CAFO poultry farms in Poland and evaluating potential risk to surrounding populations. *Regulatory Toxicology and Pharmacology*, *84*, 18-25.

Regulation of the Minister of Infrastructure of 12 April 2002 on the technical conditions to be met by buildings and their location, *Journal of Laws of 2015*, item 1422.

Regulation of the Minister of Agriculture and Food Economy of 7 October 1997 on technical conditions to be met by agricultural structures and their location *Journal of Laws of 2014*, 81, as amended.

Regulation of the Minister of the Environment of 26 January 2010 on reference values for certain substances in the air *Journal of Laws of 2010*, *16*(87).

Report on research work in the field of scientific and hygienic support for the facility "Construction of a pig farm № 11 JV Sp. z o. o. "Niva Pereyaslavshchyna" within the administrative boundaries of the Gostrolutsk commune of the Baryshovsky district of the Kiev region "(outside the settlement) in the determination of carcinogenic and non-carcinogenic risks to public health. National Academy of Medical Sciences of Ukraine. State institution "Institute of Public Health". OM Marzeeva (access: 30.05.2019).

Ritz, C. W., Fairchild, B. D. & Lacy, M. P. (2004). Implications of ammonia production and emissions from commercial poultry facilities: A review. *Journal of applied poultry research*, *13*(4), 684-692.

Ruth, J.H. (1986). Odor thresholds and irritation levels of several chemical substances: a review. *Am. Ind. Hyg. Assoc. J. 47*, A142-A151.

Saba, I., Nowakiewicz-Dębek, B., Zarębska, A., Bis-Wencel, H. & Wnuk, W. (2003). Air pollution with alcohols, aldehydes and ketones from a cattle farm, *Yearbook of Animal Science* (Rocznik Nauk Zootechnicznych), *30*, 381-388 (in Polish).

Schauberger, G., Piringer, M., Mikovits, C., Zollitsch, W., Hörtenhuber, S. J., Baumgartner, J. & Schönhart, M. (2018). Impact of global warming on the odour and ammonia emissions of livestock buildings used for fattening pigs. *Biosystems Engineering*, *175*, 106-114.

Schiffman, S.S., Walker, J.M. & Dalton, P. (2004). Potential health effects of odor from animal operations, wastewater treatment, and recycling of byproducts. J *Agromedicine*. *9*(2), 397-403.

Schulze, A., Römmelt, H., Ehrenstein, V., van Strien, R., Praml, G., Küchenhoff, H. & Radon, K. (2011). Effects on pulmonary health of neighboring residents of concentrated animal feeding operations: exposure assessed using optimized estimation technique. *Archives of environmental & occupational health*, *66*(3), 146-154.

Sommer, S. G., Christensen, B. T., Nielsen, N. E. & Schjφrring, J. K. (1993). Ammonia volatilization during storage of cattle and pig slurry: effect of surface cover. *The Journal of Agricultural Science*, *121*(1), 63-71.

Sówka, I. (2011). Publishing House of the Wrocław University of Technology Wroclaw. Methods of identifying odorogenic gases emitted from industrial facilities (in Polish).

Sówka, I., Grzelka, A. & Miller, U. (2020). Bydgoszcz: Regionalna Dyrekcja Ochrony Środowiska w Bydgoszczy. Chów i hodowla zwierząt jako źródło emisji zanieczyszczeń powietrza atmosferycznego. W: *Środowiskowe uwarunkowania realizacji przedsięwzięć w krajobrazie rolniczym województwa kujawsko-pomorskiego* / Regionalna Dyrekcja Ochrony Środowiska w Bydgoszczy. 55-67.

State Statistics Service of Ukraine. (2016). Kyiv. Industry of Ukraine. 2011-2015. *Statistical Publication*.

State Statistics Service of Ukraine. (2020). Kyiv. The Statistical Yearbook "Agriculture of Ukraine" for 2019. *Statistical Yearbook*.

Steinheider, B. (1999). Environmental Odours and Somatic Complaints. *202*(2-4), DOI:10.1016/s0934-8859(99)80011-x

Sun, G., Gu, H. & Peterson, J. (2010). Seasonal Odor, Ammonia, Hydrogen Sulfide, and Carbon Dioxide Concentrations and Emissions from Swine Grower-Finisher Rooms*, Journal of the Air & Waste Management Association*, *60*(4), 471-480, DOI: https://doi.org/10.3155/1047-3289.60.4.471

Sutton, M.A., Reis, S., Riddick, S.N., Dragosits, U., Nemitz, E. & Theobald, M.R. (2013). Toewards a climate-dependent paradigm of ammonia emission and depositon. Philosophical Transactions of the Royal Society. *Biological Sciences*, *368*.Talaiekhozani, A., M. Bagheri, M., Goli, A., & Khoozani, M. R. T. (2016). An overview of principles of odor production, emission, and control methods in wastewater collection and treatment system. *Environ J. Manage*, *170*, 186-206. DOI: 10.1016/j.jenvman.2016.01.021.

Tan, H. Q., Li, M., Jie, D. F., Zhou, Y. F. & Li, X. A. (2019). Effects of different litters on ammonia emissions from chicken manure. *Int J Agric & Biol Eng*, *12*(4), 27-33.

Tymczyna, L., Chmielowiec-Korzeniowska, A., Drabik, A. & Raczyńska, J. (2010). Warsaw: Wydawnictwo Naukowo-Techniczne. Reduction of microbiological air pollutants emitted from a litterless piggery with the use of various biofiltration beds, [in:] *Contemporary problem of odors*, Eds. Szynkowska, M.I., Zwoździak, J., Scientific and Technical Publishing House 255-268 (in Polish).

Úbeda, S. Y., López, J.J., P. A, Nicolas, J. & Calvet S. S. (2013). Strategies to control odours in livestock facilities: a critical review. *Spanish Journal of Agricultural Research*, *11*(4), 1004-1015.

Webb, J., Menzi, H., Pain, B. F., Misselbrook, T. H., Dämmgen, U., Hendriks, H., & Döhler, H. (2005). Managing ammonia emissions from livestock production in Europe. *Environmental pollution*. *135(3*), 399-406.

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Analysis of the Physicochemical Quality of Water Within the Hydropower Plant on the Ślęza River in Wrocław, Poland

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Abstract: The aim of the article was the analysis of the physicochemical quality of water within the hydropower plant on the Ślęza River in Wrocław (south-west Poland) in the context of the European Union's classification of water quality, as well as an assessment of the potential impact of hydropower plants on this quality. The study uses the results of monthly tests from three measurement points within the hydropower plant on the Ślęza River in the city of Wrocław (points upstream and downstream the hydropower plant and the reference point), from the period June 2018 to May 2020. The analyses covered 10 physicochemical parameters, i.e.: pH, electrical conductivity (EC), water temperature, turbidity, NH_4-N, NO_3-N, NO_2-N, total phosphorus, dissolved oxygen and BOD_5. The conducted analysis showed that the hydropower plant has no clear influence on the physicochemical quality of the water in the Ślęza River, other interactions present in the catchment area are more important. From the effects visible in the results, a decrease in the amplitudes of water temperature downstream the hydropower plant compared to the other points was noted, as well as a lower median of its value (statistically significant changes). An additional noticeable effect was the increase in water oxygenation below the damming, but it was not statistically significant. It has been shown that the physicochemical condition of water at the tested points does not meet the assumed standards for 8 out of 9 parameters (except for water temperature). The largest exceedances of the limit values concerned NO_2-N (up to 923% of the norm), and the most consistent, almost constantly occurring – EC (23 out of 24 months). The reason for the high NO_2-N content was most probably surface runoff from the fields and the re-suspension of sediments rich in nutrients, while in the case of EC, its high values result from the specificity of the catchment area.

Keywords: water quality, hydropower plants, environmental impacts, renewable energy sources, Water Framework Directive

1. Introduction

Hydropower plants are a renewable energy source, the use of which is associated with a number of benefits, but it is also not without its drawbacks (Operacz 2021, Kasperek & Wiatkowski 2014). The literature describes the impact of hydropower on society, economy and the environment (Kuriqi et al. 2021, Tomczyk & Wiatkowski 2020). In the context of environmental research, particular attention is paid to the impact of hydropower plants on the conditions for the migration of aquatic organisms (Puzdrowska & Heese 2019, Virbickas et al. 2021), on the accumulation and erosion processes below the damming (Soininen et al. 2018, Kibler & Tullos 2013), but mainly on the hydrological conditions not only within hydropower facilities, but also at longer distances (Bejarano et al. 2017, Chiogna et al. 2016, Fantin-Cruz et al. 2015).

In the context of the physicochemical quality of water, this influence concerns the modification of oxygen, thermal and trophic conditions (Tomczyk & Wiatkowski 2021a). In the first case, due to the formation of whirling motion due to the phenomenon of hydraulic recoil downstream hydropower plants (Wu et al. 2018), an increase in water saturation with oxygen is visible (Da Cruz et al. 2021). In the second, in water reservoirs located downstream the dams, there may be disturbances in seasonal thermal stratification (Preece & Jones 2002, Magadza 2010), as well as reduction of temperature amplitudes within hydropower plants (Pimenta et al. 2012). The trophic changes concern the possible remobilization of phosphorus accumulated in bottom sediments below hydropower facilities (Winton et al. 2019), which may contribute to the intensification of the eutrophication phenomenon (Smith et al. 1999, Zbierska et al. 2015). On the other hand, the accumulation of bottom sediments above damming levels favors the accumulation of biogenic compounds in them (Bogen & Bønsnes 2001) – e.g. it is estimated that 15% of the river's phosphorus load is upstream dams (Maavara et al. 2015). This accumulation is associated with changes in the transport of suspended sediment, which is also a carrier of trace elements (e.g. heavy metals) (Sojka et al. 2018, Sojka et al. 2009, Obolewski & Glińska-Lewczuk 2013, Wdowczyk & Szymańska-Pulikowska 2021). Mentioned changes in access to the food base have further consequences, including with changes in the functioning of water-related ecosystems and in the living conditions of aquatic organisms (Wiatkowski et al. 2017, Kjaerstad et al. 2018, Camargo 2018, Česonienė et al. 2021).

The aim of the article is to analyze the physicochemical quality of water in the Ślęza hydropower plant in the city of Wrocław in the context of the current water quality classification, as well as to estimate the potential impact of hydropower plants on this quality. It should be added that the full assessment of the quality of surface water in the light of the applicable provisions of the European Union law (Water Framework Directive) includes the assessment of the chemical status and the ecological status (or ecological potential) of water bodies (state – natural waters, potential – artificial or heavily modified) (EPC 2000, MMEIN 2019). The article focuses on the state of physicochemical elements that complement the assessment of the ecological status (potential) (biological elements are considered leading in the assessment, while physicochemistry and hydromorphology support this assessment; in the assessment of the chemical status, priority substances are taken into account, i.e. especially hazardous to the aquatic environment).

2. Materials and Methods

2.1. Study area

The research area covers the lower section of the Ślęza River in the city of Wrocław (the left tributary of the Odra River, south-western Poland), near the "Sobolewski" hydropower plant. It is located at km 3.014 from the mouth of the watercourse, it was built in 1992. It is classified as a small hydropower plant (0.024 MW) with a low damming height (4.0 m). It is equipped with one Kaplan-type turbine, it does not have a fish pass (Wiatkowski & Tomczyk 2018). There are three sampling points: 50 m upstream (point 1) and 50 m downstream the hydropower plant (point 2), as well as a reference point (comparative; point 3, 500 m upstream the hydropower plant). Figure 1 shows the location of the research area.

2.2. Field studies and laboratory analyzes

Field studies were carried out monthly, from June 2018 to May 2020. Water samples were scooped from the subsurface layer, then transferred to bottles and transported in a refrigerator to the Environmental Research Laboratory of the University of Life Sciences in Wrocław. The analyzes were performed within 24 hours from the time of collection (Szymańska-Pulikowska & Wdowczyk 2021). The scope of determinations concerned 10 physicochemical parameters, the characteristics of which are presented in Table 1.

Fig. 1. Location of the research area

Table 1. Methods for determining the physicochemical parameters of water

No.	Parameter	Unit	Name of the method
1.	Temperature of water	°C	Temperature sensor
2.	pH	–	Potentiometric method
3.	Electrolytic conductivity (EC)	μS/cm	Conductometric method
4.	Turbidity	NTU	Nephelometric method
5.	Ammonium nitrogen (NH_4-N)	mg/L	Spectrophotometric method
6.	Nitrate nitrogen (NO_3-N)		
7.	Nitrite nitrogen (NO_2-N)		
8.	Total phosphorus (TP)		
9.	Dissolved oxygen (DO)		Electrochemical sensor
10.	Biochemical oxygen demand (BOD_5)		Dilution method

2.3. Analysis of the results

The results of the above-described physicochemical analyzes were further analyzed. It was based on checking the statistical significance for individual parameters between the analyzed points using the ANOVA test for repeated measurements for $p < 0.05$ (SPSS Statistics 26, IBM), performing basic statistical analyzes (Statistica 13, Dell), characterizing the variability in parameter values (Excel 2013, Microsoft) and classifying the results in in the context of the current quality requirements for surface waters (in this case, their physicochemical status) in water bodies, in accordance with the implementation of the requirements of the Water Framework Directive to Polish conditions. The studied points are located in a heavily modified surface water body – Ślęza from Mała Ślęza to Odra (PLRW60001913369), which is classified as a lowland sandy loam river (abiotic type 19). The information about the classification of the physicochemical quality of water in the analyzed points is shown in Table 2.

Table 2. Information for the classification of the physicochemical quality of water at the tested measuring points on the Ślęza River, belonging to the abiotic type 19 (MMEIN 2019)

Classification / Parameter (unit)	Limit values		
	1st class (very good status)	2nd class (good status)	Below good status
Temperature (°C)	≤ 22.0	22.1-24.0	> 24.0
pH (-)	7.4-8.0	6.7-8.1	< 6.7, > 8.1
EC (μS/cm)	≤ 411	412-553	> 553
NH_4-N (mg/L)	≤ 0.170	0.171-0.553	> 0.553
NO_3-N (mg/L)	≤ 1.6	1.7-2.5	> 2.5
NO_2-N (mg/L)	≤ 0.01	0.02-0.03	> 0.03
TP (mg/L)	≤ 0.20	0.21-0.30	> 0.30
DO (mg/L)	≥ 7.0	6.6-6.9	< 6.6
BOD_5 (mg/L)	≤ 2.6	2.7-3.7	> 3.7

For a more complete comparison of the results, an analysis was also performed using the Universal Water Quality Index – UWQI (Boyacioglu 2007, Tomczyk & Wiatkowski 2021b). It is calculated based on each parameter's equations and the weights assigned to them (Table 3). The 90th percentile of parameter values is used for the calculation (for dissolved oxygen, the 10th percentile due to the inversely proportional relationship between its concentration and water quality), which takes into account possible measurement errors.

After calculating mentioned elements, the final index value is determined from the formula (1):

$$\mathrm{UWQI} = \sum_{i=1}^{n} I_i W_i$$

where UWQI is the final index value, I_i is the sub-index value for each parameter (in the range from 0 to 100), W_i is the weight value for each parameter, and n is the number of parameters considered in the calculations.

The final classification consists of five classes ranging from excellent to poor, based on the index's final value on a scale of 0 to 100. The point scale is as follows: 95-100 – excellent water quality, 75-94.9 – good, 50-74.9 – moderate, 25-49.9 – poor, 0-24.9 – bad.

Spatial analyzes concern the comparison of the results between the examined points, located within the hydroelectric power plant, and the temporal – the variability in the analyzed two-year research period.

Table 3. Determination of sub-indices values for Universal Water Quality Index – UWQI (Boyacioglu 2007, Tomczyk & Wiatkowski 2021b)

Parameter	Weightage	Value range	Equation
pH	$W_{pH} = 0.085$	6.6-8.5	$I_{pH} = 100$
		5.5-6.4 and 8.6-9.0	$I_{pH} = 50$
		< 5.5 and > 9.0	$I_{pH} = 0$
NO_3[1]	$W_{NO3} = 0.251$	≤ 5.0 mg/L	$I_{NO3} = 100$
		5.1-10.0 mg/L	$I_{NO3} = -10(NO_3) + 150$
		10.1-20.0 mg/L	$I_{NO3} = -4.5(NO_3) + 95$
		> 20.0 mg/L	$I_{NO3} = 0$
TP	$W_{TP} = 0.166$	≤ 0.02 mg/L	$I_{TP} = 100$
		0.021-0.16 mg/L	$I_{TP} = -357.14(TP) + 107.14$
		0.161-0.65 mg/L	$I_{TP} = -91.837(TP) + 64.964$
		> 0.65 mg/L	$I_{TP} = 0$

Table 3. cont.

Parameter	Weightage	Value range	Equation
DO	$W_{DO} = 0.332$	≥ 8.0 mg/L	$I_{DO} = 100$
		6.0-7.9 mg/L	$I_{DO} = 25(DO) – 100$
		3.0-5.9 mg/L	$I_{DO} = 15(DO) – 40$
		< 3.0 mg/L	$I_{DO} = 0$
BOD_5	$W_{BOD} = 0.166$	< 3.0 mg/L	$I_{BOD} = 100$
		3.0-4.9 mg/L	$I_{BOD} = -25(BOD) + 175$
		5.0-6.9 mg/L	$I_{BOD} = -22.5(BOD) + 162.5$
		≥ 7.0 mg/L	$I_{BOD} = 0$

Designations in the table: [1] – NO_3 = 4.43 NO_3-N

3. Results and discussion

3.1. Basic statistics

Table 4 presents the basic results of the physicochemical analyzes performed. The greatest differences in the values between the points concerned temperature and DO. In the case of temperature, it can be seen that below the hydropower plant it fluctuated in a narrower range than in the other points (respectively: point 2 – from 0 to 21.5°C, point 1 and 3: 0-22°C and 0-21.9°C; standard deviation: 7.58, 7.78 and 7.76°C), which is also reflected in the lower median. In the case of dissolved oxygen, there is an increase in its amount below the damming, as a result of the aforementioned hydraulic bounce (median values: point above the hydropower plant – 7.6 mg/L, point below the hydropower plant – 8.15 mg/L, reference point – 7.3 mg/L). Other parameters did not show as much variability as the above – in the context of the convergence of the amplitudes of the values and the median values (e.g. for EC, despite the greater range of results in points 2 and 3 compared to 1, no large differences were found between the median of its value; similar relationships can be seen for turbidity or NO_3-N).

Table 4. Basic results of the conducted physicochemical analyzes

Points	Statistics	Parameters (unit)									
		Temperature (°C)	pH (-)	EC (µS/cm)	Turbidity (NTU)	NH_4-N (mg/L)	NO_3-N (mg/L)	NO_2-N (mg/L)	TP (mg/L)	DO (mg/L)	BOD_5 (mg/L)
1 – upstream Ślęza HP	min	0.0	7.0	466	1.30	0.090	0.5	0.015	0.060	4.8	0.8
	max	22.2	8.8	1680	18.50	1.030	10.5	0.304	0.460	12.0	10.8
	med.	10.7	8.2	1104	4.10	0.205	1.7	0.030	0.285	7.6	2.3
	x̄	11.9	8.1	1119	5.02	0.267	2.5	0.049	0.271	7.9	3.4
	SD	7.8	0.5	272	3.95	0.204	2.3	0.061	0.098	2.3	2.6
2 – downstream Ślęza HP	min	0.0	7.0	466	1.20	0.030	0.5	0.015	0.170	5.8	1.0
	max	21.5	8.8	1772	20.80	1.030	10.6	0.307	0.500	12.6	12.8
	Med.	10.5	8.2	1104	3.80	0.205	1.5	0.029	0.285	8.2	2.5
	x̄	11.7	8.1	1121	5.09	0.268	2.5	0.054	0.300	8.3	3.4
	SD	7.6	0.5	287	4.79	0.205	2.5	0.066	0.080	1.9	2.8
3 – reference point	min	0.0	6.9	468	1.10	0.010	0.6	0.012	0.160	4.6	0.9
	max	21.9	8.8	1770	25.60	1.040	8.6	0.289	0.510	10.9	9.3
	med.	10.7	8.2	1113	3.99	0.195	1.6	0.027	0.295	7.3	2.4
	x̄	11.9	8.1	1123	5.49	0.249	2.5	0.047	0.295	7.8	3.2
	SD	7.7	0.5	284	5.56	0.219	2.3	0.059	0.083	2.0	2.2

Designations in the table: med. – median, x̄ – mean, SD – standard deviation

3.2. Temporal and spatial variability of parameter values at the analyzed points – ANOVA for repeated measures

In order to reliably determine whether the values of the considered physicochemical parameters actually change in a specific, ordered way over time, the ANOVA analysis was performed (Table 5). It shows that only for temperature statistically significant variability is visible, which is reflected in the pairwise comparison, in which the results were found to be significant between points 1 and 2 and 2 and 3, and also in the highest effect size of all analyzed parameters (η_p^2 = 0.169). Moreover, in the pairwise comparison for DO and NH_4-N between points 2 and 3 as well as 1 and 3 showed statistically significant relationships. However, they will be omitted from the analysis as they do not relate to the assessment of the impact of a hydropower plant.

Table 5. Summary of the results of the within-group analysis of variance for repeated measures (ANOVA)

Parameter	d*f*	Error d*f*	F	p (< 0.05)	η_p^2
Temperature	1.801	41.426	4.666	0.018* (1/2, 2/3)	0.169
TP	1.157	26.619	3.249	0.078	0.124
DO	1.447	33.280	2.895	0.084 (2/3)	0.112
NH_4-N	1.382	31.783	1.569	0.224 (1/3)	0.064
Turbidity	1.141	26.248	1.370	0.258	0.056
pH	1.895	43.578	1.183	0.314	0.049
NO_2-N	1.061	24.395	0.972	0.339	0.041
EC	1.288	29.622	0.171	0.745	0.007
BOD_5	1.841	42.337	0.161	0.835	0.007
NO_3-N	1.164	26.764	0.035	0.885	0.002

Designations in the table: d*f* – degrees of freedom, F – F-value (variance of the group means / mean of the within group variances), p – statistical significance, ηp^2 – effect size for the parameter (comparison between the sum of squares of an effect for one parameter and the sum of squares error in the ANOVA), * – statistically significant value ($p < 0.05$), the numbers in parentheses – statistical significance between the points in the pairwise comparison

Checking the temporal variability of the water temperature between the points above and below the hydropower plant on the Ślęza River showed that in 14 out of 24 months below the damming structure, the water cooled, and in the next 10 months – warmed or its temperature did not change any changes were found in 5 months). The scope of these changes ranged from -0.95°C to +0.4°C at the lower stand of the hydropower plant. If there was a heating of water below a hydropower facility, it usually took place in the winter half-year (November 2018, January, November and December 2019, February 2020), while cooling – in the summer half-year (especially from June to September). These dependencies are shown in Figure 2.

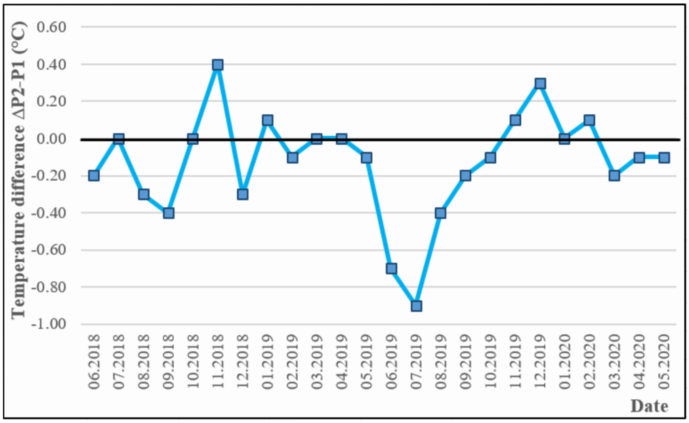

Fig. 2. The temperature difference variability between the points downstream (P2) and upstream the hydropower plant (P1) on the Ślęza River in Wrocław, June 2018 – May 2020

3.3. Assessment of the physicochemical quality of water within a hydropower plant based on WFD classification

The physicochemical quality of water in the area of the Ślęza hydropower plant does not meet the assumed standards (Table 6). Exceedances of the limit values were recorded for 8 out of 9 assessed parameters (except for temperature). The factor deteriorating the physicochemical condition of water is primarily the constantly high conductivity values, which remained outside the assumed standards in 23 out of 24 months (the maximum value of exceedances was 220% of the standard). As for the amount of exceedances, the most outlier parameter is NO_2-N – depending on the point, the amount of exceedances ranged from 865% to 923% in relation to the limit value; the standards were not met in 11 of the 24 surveyed months. In the case of other parameters, the scale of exceedances of the limit values was not so large (in terms of the size, NO_3-N can also be mentioned – from 245% to 319%, as well as BOD_5 – from 151% to 246% of exceedances compared to the norm; in terms of the number of exceeded pH – 12 or 13 out of 24 months with exceedances of the limit value).

The presented results are consistent with the results obtained from the water quality monitoring data for the measuring point Ślęza – estuary to the Odra River, belonging to the same body of surface water as the analyzed points (PIEP 2017). In relation to 2016, the most exceedances were recorded for EC – 100% (maximum exceedance by 130% compared to the standard), while the maximum exceedances against the standard – for NO_2-N (1593% compared to the limit value, 66.7% exceedances per year). The remaining parameters reached intermediate values - in relation to the percentage of exceedances, it was as follows: NO_3-N = TP > pH > DO > BOD_5 > NH_4-N > temperature of water (respectively: 58.3% > 37.5% > 25.0% > 12.5% > 8.33% > 0.00%).

Table 6. Classification of the physicochemical quality of water at points within the hydropower plant on the Ślęza River in Wrocław, June 2018 – May 2020

Parameter (unit)	Limit value for 2nd class	Point numer	Number of exceedances	The maximum value of the parameter	The maximum amount of exceeding the limit values
Temperature (°C)	≤ 24.0	1	0	22.2	0
		2	0	21.5	0
		3	0	21.9	0
pH (-)	6.7 – 8.1	1	12 (50.0%)	8.8	8.64%
		2	13 (54.2%)	8.8	8.64%
		3	12 (50.0%)	8.8	8.64%
EC (µS/cm)	**≤ 553**	**1**	**23 (95.8%)**	**1680**	**204%**
		2	**23 (95.8%)**	**1772**	**220%**
		3	**23 (95.8%)**	**1770**	**220%**
NH_4-N (mg/L)	≤ 0.553	1	2 (8.33%)	1.03	86.3%
		2	2 (8.33%)	1.03	86.3%
		3	2 (8.33%)	1.04	88.1%
NO_3-N (mg/L)	≤ 2.5	1	9 (37.5%)	10.47	319%
		2	9 (37.5%)	10.57	323%
		3	9 (37.5%)	8.64	245%
NO_2-N (mg/L)	**≤ 0.03**	**1**	**11 (45.8%)**	**0.304**	**913%**
		2	**11 (45.8%)**	**0.307**	**923%**
		3	**11 (45.8%)**	**0.289**	**865%**
TP (mg/L)	≤ 0.30	1	8 (33.3%)	0.46	53.3%
		2	10 (41.7%)	0.50	66.7%
		3	10 (41.7%)	0.51	70.0%
DO (mg/L)	≥ 6.6	1	7 (29.2%)	4.8*	27.2%
		2	4 (16.7%)	5.8*	12.1%
		3	7 (29.2%)	4.6*	30.3%
BOD_5 (mg/L)	≤ 3.7	1	8 (33.3%)	10.8	192%
		2	6 (25.0%)	12.8	246%
		3	8 (33.3%)	9.3	151%

Designations in the table: * – the minimum value of the parameter, bold font – parameters analyzed later in the article

As can be seen in Figure 3, except for April 2020, exceedances in the EC values occurred constantly. Comparing the results in similar catchments (e.g. the Bystrzyca river, which is also the left tributary of the Odra River, with similar size and characteristics - in the lower section, EC values ranged between 312 and 961 µS/cm, with a median of 495 µS/cm; Tomczyk & Wiatkowski 2021), it can be concluded that this is a feature of this catchment, which is the result of its use, geological structure, anthropogenic interactions (for example, the presence of levees on both sides of the river and reinforcements of the riverbanks and riverbed in the vicinity of the hydropower plant) and its other features. The presence of a hydropower plant has no major impact on the variability of the value of this parameter (the median difference between the upper and lower stands in the analyzed period was 0.25%).

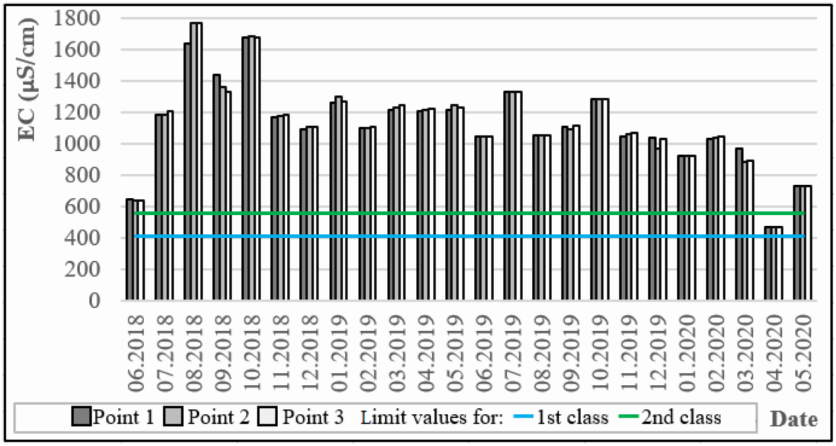

Fig. 3. Electrical conductivity values within the hydropower plant on the Ślęza River according to the classification of physicochemical water quality, June 2018 – May 2020

With regard to NO_2-N, the exceedances were less frequent, but much more pronounced (Figure 4) – they were especially visible in April and May 2020. The reason for the high values of NO_2-N in that period was primarily intense rainfall, carrying large loads pollution from the entire catchment area of the Ślęza River flowing down the watercourse. The catchment area of the Ślęza River in its upper and middle reaches is of an agricultural nature, therefore in these areas more fertilizers and plant protection products are used, which contain higher levels of nitrogen compounds, and along with surface runoff, these compounds can get into the river water. In addition to April and May 2020, in July 2019, a water pollution incident of NO_2-N also occurred downstream the hydropower plant – the reason could be the release of sediments accumulated on the damming of the damming structure, and then their resuspension as a result of the vortex movement at the bottom site, and finally the release of the stored in them NO_2-N. These types of sediment resuspension phenomena have been studied, for example, within a reservoir hydropower plant in the French Alps (Monnin et al. 2018) or on hydraulic models imitating individual technical elements of hydropower plants (e.g. pressure sand traps, Richter et al. 2021).

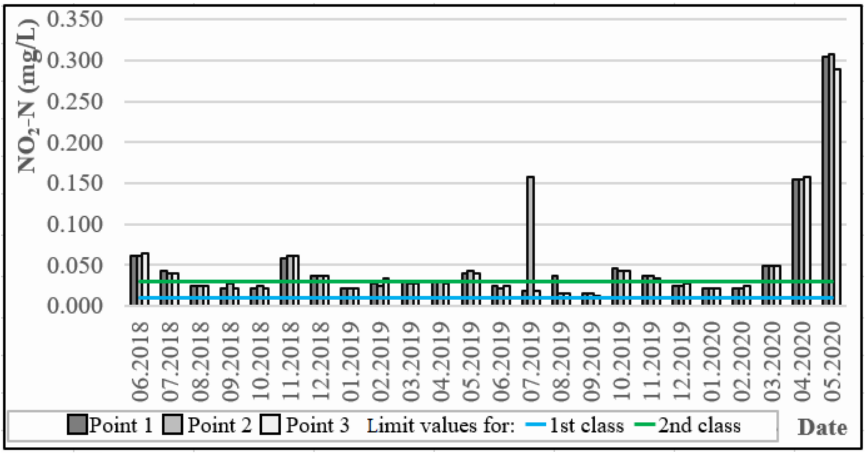

Fig. 4. Concentrations of NO_2-N within the hydropower plant on the Ślęza River in the context of the classification of physicochemical water quality, June 2018 – May 2020

3.4. Universal Water Quality Index (UWQI)

The results of the calculated water quality index indicate that in each of the analyzed points, the water quality was moderate (the third class out of five possible; Table 7). The best quality was achieved at the point below the hydroelectric power plant on the Ślęza River (point 2), while the weakest – at the reference point (point 3). The parameter significantly improving the result for point 2 were the higher values of dissolved oxygen in the research period. In the context of other results, there is a noticeable difference between the BOD_5 values between points 1, 2 and 3, and also between NO_3 concentrations (in the first case, less favorable values in points 1 and 2, in the second – in point 3, compared to the rest of the points). The overall results of water quality expressed by UWQI do not differ significantly (they are around 7%).

The presented results for UWQI are consistent with the results for reservoir hydropower plants: Michalice in Poland (Tomczyk et al., 2021), Bakun in Malaysia (Ling et al. 2016) and Gongguoqiao in China (Luo et al. 2019). In these cases, better water quality was noted, expressed by the water quality index below the hydrotechnical structures. A different result was achieved for the Irapė hydroelectric power plant in Brazil, where the calculated result was the weakest below the damming structure (De Oliveira et al. 2021). With regard to run-of-river hydroelectric power plants, such analyzes have hardly been carried out (however, physicochemical studies have been performed, e.g. Álvarez et al. 2020, Fantin-Cruz et al. 2015, Česonienė et al. 2021).

Table 7. Universal Water Quality Index (UWQI) calculated for at points within the hydropower plant on the Ślęza River in Wrocław, June 2018 – May 2020

Para-meter	Research points		
	1 – upstream Ślęza HP	2 – downstream Ślęza HP	3 – reference point
pH	8.50	8.50	8.50
NO_3	25.10	25.10	22.59
TP	4.88	4.82	4.82
DO	12.22	15.75	12.96
BOD_5	5.61	5.42	6.69
UWQI	**56.31**	**59.60**	**55.57**

4. Conclusions

As a result of the research, the following conclusions can be drawn:

1. The Ślęza hydropower plant significantly influences changes in temperature and dissolved oxygen.
2. Water temperature amplitudes below the hydropower plant have decreased compared to other points, and the median value is lower. An additional noticeable effect is the increase in water oxygenation below the damming.
3. Statistically significant changes for the examined points were shown for the water temperature – in most months (in 14 out of 24) the hydropower plant caused its decrease (especially in the summer half-year). Changes in temperature differences in the lower station compared to the upper one ranged from –0.95°C to +0.4°C.
4. The physicochemical status of water in the tested points does not meet the standards for 8 out of 9 parameters (except the water temperature).
5. The highest exceedances of the limit values concerned NO_2-N (up to 923% of the norm), and the most consistent, almost constantly occurring – EC (23 out of 24 months). The reason for the high NO_2-N content was most probably the surface runoff from the fields and the resuspension of sediments rich in nutrients, and in the case of EC, its high values result from the specificity of the catchment area.
6. The calculated Universal Water Quality Index indicated moderate water quality at each point (the most favorable below the hydropower plant, the least – at the reference point).
7. This research is a pilot study on the impact of hydropower plants on changes in water quality.

References

Álvarez, X., Valero, E., Torre-Rodríguez, N. D. L., & Acuña-Alonso, C. (2020). Influence of small hydroelectric power stations on river water quality. *Water, 12*(2), 312.

Bejarano, M.D., Sordo-Ward, Á., Alonso, C., Nilsson, C. (2017). Characterizing effects of hydropower plants on sub-daily flow regimes. *J. Hydrol., 550*, 186-200.

Bogen, J., Bønsnes, T.E. (2001). The impact of a hydroelectric power plant on the sediment load in downstream water bodies, Svartisen, northern Norway. *Science of the Total Environment, 266*, 273-280.

Boyacioglu, H. (2007). Development of a water quality index based on a European classification scheme. *Water SA, 33*(1), 101-106.

Camargo, J.A. (2018). Responses of aquatic macrophytes to anthropogenic pressures: Comparison between macrophyte metrics and indices. *Environmental Monitoring and Assessment, 190*, 173.

Česonienė, L., Dapkienė, M., Punys, P. (2021). Assessment of the Impact of Small Hydropower Plants on the Ecological Status Indicators of Water Bodies: A Case Study in Lithuania. *Water, 13*, 433.

Chiogna, G., Majone, B., Paoli, K.C., Diamantini, E., Stella, E., Mallucci, S., Lencioni, V., Zandonai, F., Bellin, A. (2016). A review of hydrological and chemical stressors in the Adige catchment and its ecological status. *Science of the Total Environment, 540*, 429-443.

da Cruz, R.F., Hamilton, S.K., Tritico, H.M., Fantin-Cruz, I., de Figueiredo, D.M., Zeilhofer, P. (2021). Water quality impacts of small hydroelectric power plants in a tributary to the Pantanal floodplain, Brazil. *River Res Appl, 37*, 448-461.

De Oliveira, K.L., Ramos, R.L., Oliveira, S.C., Christofaro, C. (2021). Water quality index and spatio-temporal perspective of a large Brazilian water reservoir. *Water Supply, 21*(3), 971-982.

Fantin-Cruz, I., Pedrollo, O., Girard, P., Zeilhofer, P., Hamilton, S.K. (2015). Effects of a diversion hydropower facility on the hydrological regime of the Correntes River, a tributary to the Pantanal floodplain, Brazil. *Journal of Hydrology, 531*, 810-820.

Kasperek, R., Wiatkowski, M. (2014). Hydropower Generation on The Nysa Klodzka River. *Ecological Chemistry and Engineering S, 2*1(2), 327-336.

Kibler, K.M., Tullos, D.D. (2013). Cumulative biophysical impact of small and large hydropower development in Nu River, China. *Water Resour Res 49*(6), 3104-3118.

Kjaerstad, G., Arnekleiv, J.V., Speed, J.D.M., Herland, A.K. (2018). Effects of hydropeaking on benthic invertebrate community composition in two central Norwegian rivers. *River Research and Applications, 34*, 218-231.

Kuriqi, A., Pinheiro, A.N., Sordo-Ward, A., Bejarano, M.D., Garrote, L. (2021). Ecological impacts of run-of-river hydropower plants – Current status and future prospects on the brink of energy transition. *Renew. Sust. Energy Rev. 142*, 110833.

Ling, T.Y., Soo, C.L., Heng, T.L.E., Nyanti, L., Sim, S.F., Grinang, J. (2016). Physicochemical Characteristics of River Water Downstream of a Large Tropical Hydroelectric Dam. *Journal of Chemistry*, *7895234*.

Luo, X., Xiang, X., Huang, G., Song, X., Wang, P., & Fu, K. (2019). Bacterial abundance and physicochemical characteristics of water and sediment associated with hydroelectric dam on the Lancang River China. *International Journal of Environmental Research and Public Health, 16*(11), 2031.

Maavara, T., Parsons, C.T., Ridenour, C., Stojanovic, S., Dürr, H.H., Powley, H.R., Van Cappellen, P. (2015). Global phosphorus retention by river damming. *Proceedings of the National Academy of Sciences of the United States of America, 112*, 15603-15608.

Magadza, C.H.D. (2010). Environmental state of Lake Kariba and Zambezi River Valley: Lessons learned and not learned. *Lake Reserv. Manag. 15*, 167-192.

Minister of Maritime Economy and Inland Navigation (MMEIN 2019). Regulation of the Minister of Maritime Economy and Inland Navigation of 11 October 2019 on the Classification of Ecological Status, Ecological Potential and Chemical Status and the Method of Classifying the Status of Surface Water Bodies… (OJ 2019 item 2149, in Polish), Prime Minister of Poland: Warsaw, Poland, 2019.

Monnin, L., Ciffroy, P., Garnier, J.M., Ambrosi, J.P., Radakovitch, O. (2018). Remobilization of trace metals during laboratory resuspension of contaminated sediments from a dam reservoir. *Journal of Soils Sediments 18*, 2596-2613.

Obolewski, K., Glińska-Lewczuk, K. (2013). Distribution of heavy metals in bottom sediments of floodplain lakes and their partent river – a case study of the Słupia. *Journal of Elementology, 18*(4), 673-682.

Operacz, A. (2021). Possibility of Hydropower Development: A Simple-to-Use Index. *Energies, 14*, 2764.

Pimenta, A.M., Albertoni, E.F., Palma-Silva, C. (2012). Characterization of water quality in a small hydropower plant reservoir in southern Brazil. *Lakes & Reservoirs Research & Management, 17*, 243-251.

Preece, R.M., Jones, H.A. (2002). The effect of Keepit Dam on the temperature regime of the Namoi River, Australia. *River Research and Applications, 18*, 397-414.

Provincial Inspectorate for Environmental Protection in Wrocław (PIEP) (2017). Results of surface water quality tests: Ślęza from Mała Ślęza to Odra at the control point of Ślęza – estuary to the Oder.

Puzdrowska, M., Heese, T. (2019). Experimental Studies on the Spatial Structure and Distribution of Flow Velocities in Bolt Fishways. *J. Ecol. Eng., 20*, 82-99.

Richter, W., Vereide, K., Mauko, G., Havrevoll, O.H., Schneider, J., Zenz, G. (2021). Retrofitting of Pressurized Sand Traps in Hydropower Plants. *Water, 13*, 2515.

Smith, V., Tilman, G., Nekola, J. (1999). Eutrophication: Impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution, 100*, 179-196.

Soininen, N., Belinskij, A., Vainikka, A., Huuskonen, H. (2018). Bringing back ecological flows: Migratory fish, hydropower and legal maladaptivity in the governance of Finnish rivers. *Water International, 44*, 321-336.

Sojka, M., Siepak, M., Jaskuła, J., & Wicher-Dysarz, J. (2018). Heavy Metal Transport in a River-Reservoir System: a Case Study from Central Poland. *Polish Journal of Environmental Studies, 27*(4).

Sojka, M., Zioła-Frankowska, A., Siepak, M., & Murat-Błażejewska, S. (2009). Distribution of heavy metals in the Mała Wełna River system (western Poland). *Oceanological and Hydrobiological Studies, 38*(2), 51-61.

Szymańska-Pulikowska, A., Wdowczyk, A. (2021). Changes of a Landfill Leachate Toxicity as a Result of Treatment With Phragmites australis and Ceratophyllum demersum – A Case Study. *Frontiers in Environmental Science, 9*.

The European Parliament and the Council (EPC). Directive 2000/60/EC of the European Parliament and of the Council Establishing a Framework for Community Action in the Field of Water Policy, Brussels, Belgium, 2000.

Tomczyk, P., Wiatkowski, M. (2020). Shaping changes in the ecological status of watercourses within barrages with hydropower schemes – Literature review. *Archives of Environmental Protection, 46*, 78-94.

Tomczyk, P., Wiatkowski, M. (2021a). The Effects of Hydropower Plants on the Physicochemical Parameters of the Bystrzyca River in Poland. *Energies, 14*, 2075.

Tomczyk, P., Wiatkowski, M. (2021b). Impact of a small hydropower plant on water quality dynamics in a diversion and natural river channel. *Journal of Environmental Quality, 50*(5), 1156-1170.

Tomczyk, P., Wiatkowski, M., Gruss, Ł., Buta, B., Kasperek, R., Głowski, R., Rembielak, K. (2021). Hydropower impact on water quality: a case study on the Michalice Reservoir, Poland. *Environmental Engineering and Management Journal 5*(5), 725-738.

Virbickas, T., Vezza, P., Kriaučiūnienė, J., Akstinas, V., Šarauskienė, D., Steponėnas, D. (2021). Impacts of low-head hydropower plants on cyprinid-dominated fish assemblages in Lithuanian rivers. *Scientific Reports, 10*, 21687.

Wdowczyk, A., Szymańska-Pulikowska, A. (2021). Analysis of the possibility of conducting a comprehensive assessment of landfill leachate contamination using physicochemical indicators and toxicity test. *Ecotoxicol. Environm. Saf. 221*, 112434.

Wiatkowski, M., Rosik-Dulewska, C., Tomczyk, P. (2017). Hydropower Structures in the Natura 2000 Site on the River Radew: An Analysis in the Context of Sustainable Water Development. *Annual Set the Environment Protection, 19*, 65-80.

Wiatkowski, M., Tomczyk, P. (2018). Comparative Assessment of the Hydromorphological Status of the Rivers Odra, Bystrzyca, and Ślęza Using the RHS, LAWA, QBR, and HEM Methods above and below the Hydropower Plants. *Water, 10*, 855.

Winton, R.S., Calamita, E., Wehrli, B. (2019). Reviews and syntheses: Dams, water quality and tropical reservoir stratification. *Biogeosciences, 16*, 1657-1671.

Wu, J.-H., Zhou, Y., Ma, F. (2018). Air entrainment of hydraulic jump aeration basin. *Journal of Hydrodynamics, 30*, 962-965.

Zbierska, J., Ławniczak, A.E., Zbierska, A. (2015). Changes in the trophic status of Lake Niepruszewskie (Poland). *Journal of Ecological Engineering, 16*, 65-73.

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Model of a Sustainable Transport System on the Example of Olsztyn

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Abstract: The main aim of the article is to present a theoretical model of a sustainable urban transport system and to indicate the need for changes in the approach to it. The issues of sustainable development and functioning of the municipal transport system in Olsztyn discussed in the article evoke vivid social and political interests of the city's inhabitants. This is mainly due to the impact of transport operation on quality of life, the correlation of its development with the economic development of the city, and the strong impact of transport on the natural environment. Today, it is already known that a coherent and modern transport system is an indispensable element of a competitive city. Connecting the city into a functional system, it presents it as a system of interdependencies between its elements.

Keywords: urban transport, sustainable transport, transport model

1. Introduction

The ongoing urbanization processes in the world, the increase in the share of the urban population in relation to the total population, the formation of agglomerations of great importance for economic and social life, places more and more demands on urban transport systems (Kłos et al. 2020) and transport safety (Woźniak et al. 2018). It is related to the increasing number of trips (Zochowska 2012), limitations of land that can be used for transport purposes, problems related to the impact on the natural environment, as well as congestion and inefficiency of the urban transport system. Of course, the invention of a mass-produced and increasingly accessible car had a huge impact on this.

Currently, passenger cars are the second type of ubiquitous objects after buildings, and only the lack of space means that there are not more of them. Moreover, there is an increasingly visible contradiction between the desire to have a car by the inhabitants and the technical possibilities of using it in densely built-up streets and neighborhoods (Burnewicz 2005). In this situation, it becomes necessary to rationally plan the transport system in which urban transport would be treated as a priority and the possibilities to own and use a passenger car would be limited. However, this is a difficult measurement and requires considerable time and financial resources. It is also important to identify problems and dysfunctions in urban transport, which can significantly contribute to increasing its functionality (Tundys 2008). Generally, it can be said that these are problems with social, economic and ecological implications (Szołtysek 2008).

Consequently, it should be added that the period in which buses were the only available means of transport for urban travel has definitely passed. City transport has irretrievably lost a huge number of passengers traveling from home to work every day. In this sense, the urban transport market has not only been affected by the outflow of passengers, but also by the loss of state patronage, which has not been replaced by anything. The state has completely withdrawn from the care of public transport and the self-government in charge of it has not received adequate resources for the new tasks. We did not have to wait long for the effects of this state of affairs: ticket prices increased, there were not enough financial resources for the replacement of rolling stock and the development of infrastructure. This largely contributed to the decline in the attractiveness of urban transport. Also congestion and increased individual motorisation have contributed to the deterioration of transport conditions (Igliński 2008, Altshuler 1979, Zomkowska 2008, Ciesielski & Szudrowicz 2001, Kosacka-Olejnik 2021).

This hard-to-stop urban transport degradation process bears the hallmarks of a downward spiral. The decreasing number of passengers traveling by bus leads to an increase in ticket costs and a lower frequency of their rate, which entails a further decrease in the number of passengers transported. In such situation, the number of passenger cars in the city is increasing. Traffic, noise, and emissions are increasing. As a long-term effect, urban space and the natural environment are degraded and the quality of life of inhabitants decreases (Rudnicki & Starowicz 2007).

The main aim of this article is to present the theoretical model of a sustainable urban transport system and to indicate the need to change the approach to it. In particular, this concerns the ways of analysing and diagnosing its problems, regardless of whether we are dealing with a transport system in a metropolitan area or a small town. The aspect of mobility in urban areas is also important (Chamier-Gliszczyński & Bohdal 2016, Chamier-Gliszczyński & Bohdal 2016a).

However, the premises for taking up the topic should be found in the fact that modern cities are subject to constant processes of evolution. Thus, urban transport systems, which are the pillars of their functioning, are not free from change. However, it is important that the necessity of these changes is recognized at the right time and subjected to a proper analysis, which will result in a modified approach to the programming of sustainable development not only of the urban transport system, mobility (Chamier-Gliszczyński 2015), but also of the entire city. Rationality and urban sustainability can be achieved by using effective instruments to reduce the intensity of urban transport, as well as by stimulating technological and organizational changes in urban transport that reduce its intensity of resources, intensity of energy, nuisance to the environment (Jacyna et al. 2021) and existing traffic conditions (Prasolenko et al. 2019).

2. The idea of sustainable development and its specification in transport

In its basic interpretation, the concept, or rather the feature of the state of development referred to as sustainability, reflects a concern with the consequences arising from various indirect and long term effects and impacts (Borys 2005). In short, sustainability is a fundamental human aspiration to protect and improve the quality of life. Without going into detail, sustainability is an intuitively understandable concept, but as Litman and Burwell point out, it is a category fraught with many complex implications (Litman & Burwell 2003). The general outline of the concept of sustainable development forms the basis of assumptions made in sectoral applications (Borys 2005, Nicolas et al. 2003). Of course, there are some difficulties in distinguishing between the concepts of sustainable transport and sustainable transport development. Sustainable transport is considered in a broad and narrow sense. Sustainable transport, strictly speaking, raises three issues. Firstly, it only refers to environmental aspects related to rational human activity (for example, minimizing the consumption of environmental components, minimizing the emission of pollutants, maximizing the use of waste products (Kryk 1993), therefore, it is called environmentally sustainable transport. Second, sustainable transport is considered in terms of two factors: resource scarcity and climate change. In this sense, sustainable planning is a specialised enterprise. Thirdly, sustainable transport is environmentally sustainable mobility (Chamier-Gliszczyński 2012), which includes changes in behaviour and an unusual approach in all sectors of the economy. On the other hand, sustainable transport in the broad sense is not limited only to the environmental dimension, but to the whole triad of aspects. In general, it is a system that reduces the negative effects of any transport activity, is characterized by features such as mobility and accessibility and, above all, is beneficial for the economy and the user.

Although there is no uniform definition and uniform perception of the content, form and meaning of this concept, most definitions refer to the concept of sustainable transport, which from generation to generation can fully function, carrying out the processes of moving people and cargo without including materials, energy, and other environmental resources due to each next generation (OECD 1991). This approach to the problem is presented in the classic definition adopted in 2004 by the European Conference of Transport Ministers and in 2005 by the Centre for Sustainable Transport. This is the classic definition adopted by the European Conference of Ministers of Transport in 2004 and by the Centre for Sustainable Transport in 2005. From this definition it follows that a sustainable transport system is one that (Borys 2005):

- it enables the basic need for access by individuals and society to be met in a safe and consistent manner with the needs of human health and ecosystems and meets the capital value requirements within a given generation and on an intergenerational scale;
- it is affordable, functions efficiently, offers a choice of means of transport, and supports a thriving economy;
- reduces emissions and waste, taking into account the absorption capacity of the planet, minimizes the use of nonrenewable resources, reduces the consumption of renewable resources to a sustainable level, recycles and reuses their components, minimizes land use, and reduces noise levels.

According to this definition, the sustainable transport system takes into account the criterion of accessibility to transport services in accordance with the requirement of health and environmental safety, taking into account the principle of intergenerational justice, then the criterion of economic efficiency and the criterion of limiting the environmental impact (Chamier-Gliszczyński 2011, Jacyna 2018) and use of space. This definition can be considered the most comprehensive and unambiguous and is preferred by many experts in the transport industry.

Today, the concept of sustainable transport is at the heart of many policies, strategies, and actions. However, despite four decades of discussion, it can be said that it still remains more of a debatable concept than a guideline for real action (Dobrzańska 2007). In order to make this concept real in urban transport, operational principles for sustainable transport have been identified. These are:

- The principle of adequate funding for infrastructure necessary to eliminate bottlenecks.
- The principle of political determination to implement the measures proposed in the White Paper.
- The principle of a new local authority approach to urban transport.
- The principle of meeting the needs of users, in return for increasing mobility costs, has the right to expect high-quality services.

Undoubtedly, the concept of sustainable transport under current social and economic conditions is an idea that is difficult to implement, as there is little chance that the transition from declared ecological values to specific actions will take place in a short time. This is because the positive attitude of society toward the issues of environmental protection often loses when confronted with the economic conditions of functioning. Hence, sustainable transport is still the future as too many transport needs are met with a private car. It will be possible to talk about real sustainable urban transport when most of society will abandon cars in favour of urban transport, walking, or cycling. However, we should remember that only sustainable urban transport is the only one that can prove itself in our modern cities.

3. Towards a sustainable urban transport system

The road to sustainable urban transport has been outlined. The Lisbon Strategy set a new strategic goal for the European Union – to become the most dynamic and competitive economy in the world, capable of sustainable economic growth accompanied by qualitative and quantitative improvements in employment and greater social cohesion. The basic strategy for achieving it is the transition from the growth promotion model to a model in which environmental protection and rational management of natural resources will become components of development patterns (Kozłowski 1994). Urban transport has a significant role to play in this process. Every day it faces contradictions between the community demanding more mobility and the public criticizing the delays and congestion of transport modes. Reconciling them always seems to be a difficult, even impossible task. After all, no one has managed to reconcile the interests of all people or to satisfy everyone at once.

The new path to sustainable urban transport involves the need to break away from traditional and dominant patterns, taking into account the civilization and cultural megatrends (Stacewicz 1996) that shape the society of the future. Sustainable development is currently the only fully crystallized alternative development concept. It is a multifaceted concept that covers the basic aspects of development (Pyć 2006): social, economic, ecological, spatial and cultural.

In light of the above arguments, there is no doubt that the development of the transport system is a continuous process. There is no end state to which it aspires. Each condition achieved is a transitional state that forms the basis of the next stage of development. Development understood in this way makes it possible to achieve better conditions of functioning by making positive changes. Certainly, the process of developing sustainable transport systems must be a conscious, purposeful and prospective activity conducted in the interest of local communities. Only then, at least from a purely theoretical point of view, will the conditions of sustainable development be created, i. e. the development that will bring the maximum social effects, satisfying the participants of this development, appropriate and expected individual effects, and will proceed with the minimum risk of failure (Parysek 2001).

The above premises indicate that one of the main goals of each city should be to create conditions for efficient, safe, and effective movement of people while limiting the harmful impact on the natural environment. In this context, adopting a sustainable approach to the city's transport system seems appropriate and satisfactory – Figure 1.

This is indicated by the opinions of the scientific community and the activities of local communities associated with various types of associations that promote the idea of sustainable development. What is missing are only specific, often drastic, and politically unpopular measures that could actually contribute to the simultaneous improvement of the quality of life of the inhabitants and the natural environment. Without it, the sustainable transport system can only become a fiction.

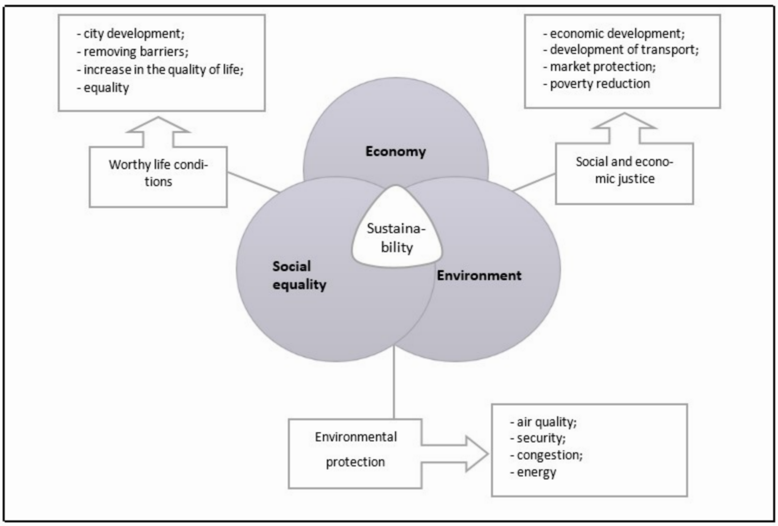

Fig. 1. Sustainable solutions in transport
Own study based on Urban Mobility in Developing Countries, UITP, Brussels 2007

Continuing the thought, it is obvious that the development of the transport system should take place in an orderly manner, based on a mosaic of plans with a different spatial scale and a different time horizon. On the other hand, the vision of future sustainable transport should present its shape and features desired for the region and local communities, differing from its present state by a large set of implemented innovative solutions (Burnewicz 2005). Naturally, a vision is not a forecast, a plan, or a program, but only the starting ideas for its creation. It is a look at the future of transport through the lens of innovation trends around the world that can be transferred to it. Hence, on a strictly theoretical basis, it can be imagined that this is an optimistic vision, showing a sustainable urban transport system as:

- efficient, to be able to handle a huge number of passengers at the highest possible level;
- flexible, so that local communities can move according to their preferences and expectations, using various forms and means of transport;
- efficient, so that the financing of transport does not limit investment activity in new technologies and its development;
- integrated not only within the regional transport system itself, but also with urban and superregional transport;
- modern and ecological, so that it attracts crowds of stakeholders and is a positive element of the city's image, as well as ensuring sustainable development of the urban area.

The above list shows that the development of urban transport should stimulate economic development and spatial order, improve the image of the city, and reduce the differences in development and quality of life in individual areas of the city. What is referred to as 'quality of life' depends to a large extent on the transport solutions adopted. Not surprisingly, the choice of a particular transport option translates into issues such as pollution, noise levels, commuting times to work and school, etc. All this, in turn, contributes to the character of the city and how it is lived in - pleasant and nice or the opposite.

4. Determinants of a sustainable model of the Olsztyn urban transport system

Olsztyn's public transport, like similar systems in other Polish cities, is an integral part of the complex organism that is the city. Hence, it is subject to numerous limitations and development stimuli, appropriate for an urbanized area. A properly organized and efficient operating system is of key importance for the proper functioning of the city and the lives of its inhabitants. And its formation is closely related to the constant need to move around, which determines the possibility of satisfying human needs (Jacyna 2009). This thesis is still relevant today. What changes are the requirements and the means by which these challenges can be met.

This view supports a comprehensive view of transport in Olsztyn, so that, as in other Polish or European cities, the passenger can be transported in one travel chain upon presentation of one ticket. Therefore, it is necessary to organize urban transport in such a way that the competences and scope of action of all transport operators are strictly defined and delimited. By its very nature, this leads to the conclusion that an institution is needed to manage and coordinate the entire public transport system, which should set common transport goals for the city. In addition, it should cooperate with the authorities of neighboring communes in order to ensure the possibility of satisfying the basic mobility needs of individual communities, limiting the sources of congestion, and ensuring environmental protection. In this context, under the circumstances of the existence of numerous operators on the local urban transport market, it is most appropriate for the public transport organiser to manage it on the basis of regulated competition, which is in line with European Union guidelines and Polish legislation.

And if so, improving the efficiency of urban transport operation requires structuring of the functions and competences of the participants in the transport process. The model presented in Figure 2 is characteristic of a market corresponding to the conditions of regulated competition. It assumes separation of the sphere of organisation from the realisation of transport. In addition, it takes into account the functioning of the public regulator and the operation of more than one entity in the field of transport with different forms of ownership. The designed model considers four levels of functionality:

- regulation of the market and transport policy;
- managing the transport offer;
- provision of transport services;
- consumption by consumers.

The model presented assumes that integration is a desirable state and a way to organize the urban transport system that should be pursued. It is recognized that the integration of urban transport will be both a factor determining the quality of life of local communities and influencing the development in the entire area of which it is part. As an efficient city transport system attracts new residents, tourists, and investors, it contributes to the economic growth of the area and contributes to its image.

Of course, fulfilling public service objectives does not necessarily mean that transport services will be available and consumed by all. The model assumes that the organization and financing of services of general interest will concern the part of services available on the market that meet certain criteria of general interest. Thus, the correct solution should be considered to directly link the volume of journeys made on the basis of free and concessionary travel entitlements with financial support for municipal transport from municipal budgets in the form of reimbursement of lost revenues on this account.

The proposed concept of the model aims to improve the functioning of public transport and change the current state of the transport system in the city. The project postulates based on the public transport system on two subsystems, tram and bus transport. At the same time, the designed tram line takes the form of a transport spine, supplemented by bus lines with assigned delivery functions. This results in the creation of a clear transport system, an increase in the quality standard of the provided services and, consequently, an increase in demand for public transport services.

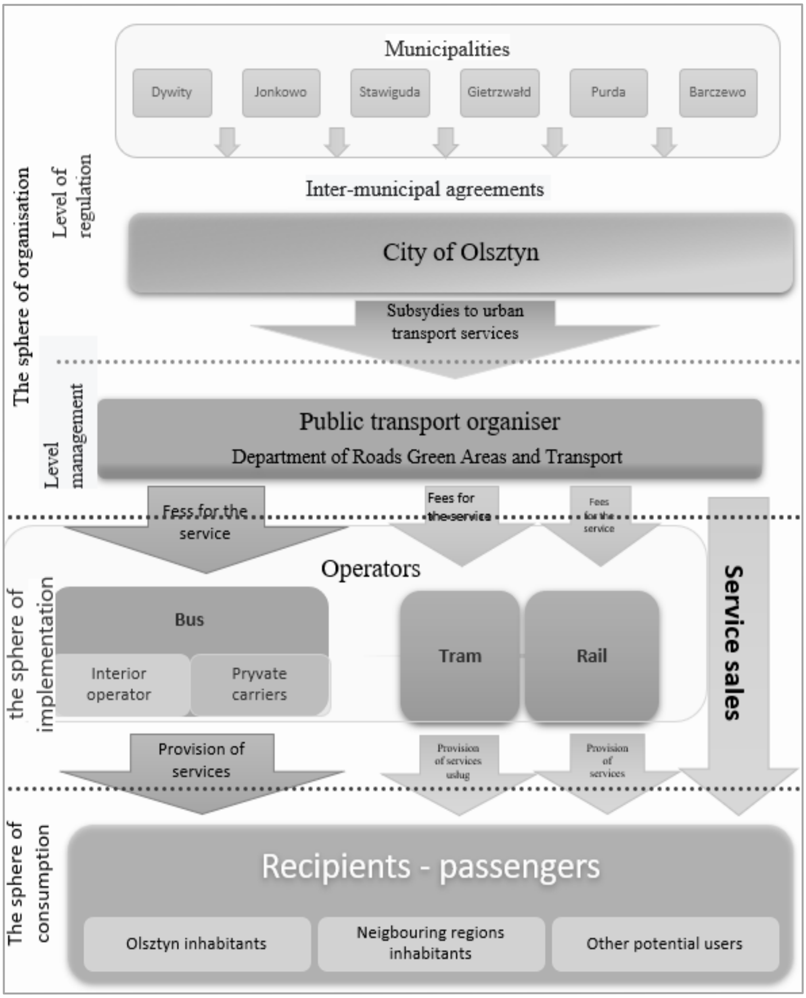

Fig. 2. Model of the urban transport system of Olsztyn

It should be emphasized that the presented model is also an attempt to synthesize the most important elements of the concept of sustainable transport development. In particular, strengthening the benefits and reducing the costs of transport, including its external costs. It is formulated to meet both the present and future needs of the inhabitants of Olsztyn. Therefore, it is not an utopian theory to say that Olsztyn can have a public transport system which would allow efficient travel in a spatially integrated and environmentally balanced way. It is enough that the current subjective barriers and prejudices of all its stakeholders will be eliminated.

5. Conclusions

1. The issues of the sustainable model of the urban transport system in Olsztyn evoke vivid social and political interests of the city's inhabitants. This is mainly due to the impact of the functioning of transport on the quality of life, the correlation of its development with the economic development of the city, and the strong impact of transport on the natural environment.
2. The condition for the efficient and effective functioning of public transport is the provision of appropriate organizational solutions. It turns out that the way of organization and management translates into appropriate quality and size of the transport offer.
3. Properly organized and managed urban transport, ensuring the implementation of transport demands at the appropriate level, is also a condition for rationalizing the costs of providing transport services and increasing its attractiveness.
4. A sustainable urban transport system is an essential element of a competitive city. It connects the area in a functional system and presents the city as a system of interdependencies between its elements.

References

Altshuler, A. (1979). *The Urban Transportation Problem*. MIT.

Borys, T. (2005). *Wąskie i szerokie interpretacje zrównoważonego rozwoju oraz konsekwencje wyboru*, W: A. Papuziński, (red.), Zrównoważony rozwój. Od utopii do praw człowieka. Bydgoszcz: Oficyna Wydawnicza Branta (In Polish).

Burnewicz, J. (2005). *Sektor samochodowy Unii Europejskiej*. Warszawa: WKŁ (In Polish).

Chamier-Gliszczynski, N. (2011). Sustainable operation of a transport system in cities. *Key Engineering Materials*, 486, 175-178. DOI: 10.4028/www.scientific.net/KEM.486.175

Chamier-Gliszczyński, N. (2012). *Modeling system mobility in urban areas*. Congress Proceedings – CLC 2012, Carpathian Logistics Congress, Jesenik, Czech Republic, 07-09 November 2012, 501-508, Code 111467. ISBN 978-808729436-9.

Chamier-Gliszczynski, N. (2015). *City logistics – sustainable urban mobility*. CLC 2015, Carpathian Logistics Congress, Congress Proceedings, Tanger Ltd, Jesenik, Czech Republic, 04-06 November 2015, 263-268.

Chamier-Gliszczynski, N., Bohdal, T. (2016). Mobility in Urban Areas in Environment Protection. *Rocznik Ochrona Srodowiska*, *18*(1), 387-399.

Chamier-Gliszczynski, N., Bohdal, T. (2016a), Urban Mobility Assessment Indicators in the Perspective of the Environment Protection. *Rocznik Ochrona Srodowiska*, *18*(1), 670-681.

Ciesielski, M. Szudrowicz, A. (2001). *Ekonomika transportu*. Poznań: Wydawnictwo Akademii Ekonomicznej w Poznaniu (In Polish).

Ciesielski, M. (1986). *Koszty kongestii transportowej w miastach*. Zeszyty Naukowe – Seria II, nr 87, Poznań. Wydawnictwo Akademii Ekonomicznej w Poznaniu (In Polish).

Dobrzańska, B.M. (2007). *Planowanie strategiczne zrównoważonego rozwoju obszarów przyrodniczo cennych.* Białystok: Wydawnictwo Uniwersytetu w Białymstoku (In Polish).

Ejdys, S. (2009). *Zrównoważony rozwój jako perspektywa funkcjonowania transportu miejskiego*. W: D. Kiełczewski, B. Dobrzańska, (red.) Ekologiczne problemy zrównoważonego rozwoju. Białystok: Wydawnictwo Wyższej Szkoły Ekonomicznej w Białymstoku (In Polish).

Igliński, H. (2008). *Koszty kongestii transportowej w Poznaniu*. W: Współczesne wyzwania transportu w logistyce. Prace Naukowe Politechniki Warszawskiej. 64, Transport, Warszawa (In Polish).

Jacyna, M. (2009). *Modelowanie i ocena systemów transportowych*. Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej (In Polish).

Jacyna, M., Wasiak, M., Lewczuk, K., Chamier-Gliszczynski, N., Dabrowski, T. (2018), Decision Problems in Developing Proecological Transport System. *Rocznik Ochrona Srodowiska*, *20*(2), 1007-1025.

Jacyna, M., Żochowska, R., Sobota, W., Wasiak, M. (2021), Scenario analyses of exhaust emissions reduction through the introduction of electric vehicles into the city. *Energies*, *14*(7), 2030. DOI: 10.3390/pl14072030

Kłos, M.J., Sobota, A., Żochowska, R., Soczówka, P. (2020), Traffic measurements for development a transport model. *Advances in Intelligent Systems and Computing*, *1091*, 265-278. DOI: 10.1007/978-3-030-35543-2_21

Komitet Ekonomiczny Rady Ministrów. Polityka transportowa państwa na lata 2001-2015 dla zrównoważonego rozwoju kraju oraz Założenia polityki transportowej państwa na lata 2000-2015 dla realizacji zrównoważonego rozwoju kraju. Kraków: Zeszyty Naukowo-Techniczne Oddziału Stowarzyszenia Inżynierów i Techników Komunikacji w Krakowie (In Polish).

Kosacka-Olejnik, M., Kostrzewski, M., Marczewska, M., Mrówczyńska, B., Pawelski, P. (2021), How digital twin concept supports internal transport system? – Literature review. *Energies*, *14*(16), 4919. DOI: 10.3390/en14164919

Kozłowski, S. (1994). *Droga do ekorozwoju.* Warszawa: PWN.

Kryk, B. (1993). *Wycena strat ekologicznych wynikających z działalności energetyki w regionie szczecińskim*. Rozprawa doktorska. Szczecin: Wydział Ekonomiczny US (In Polish).

Litman, T. Burwell, B. (2003). Issues in sustainable transportation. *International Journal of Global Environmental. 6*(4), 331-347.

Nicolas, J., Pochet, P., Poimboeuf, H. (2003), Towards Sustainable Mobility Indicators: Application To The Lyons Conurbation, *Transport Policy*, *10*.

OECD. (1991). Integrating transport and enviromental policies: perspectives for a sustainable mobility. Berlin.

Parysek, J.J. (2001). *Podstawy gospodarki lokalnej*. Wydawnictwo Naukowe UAM, Poznań 2001 (In Polish).

Prasolenko, O., Łobaszow, O., Bugajow, I. Gyulyev, N., Filina-Dawidowicz, L. (2019), *Designing the conditions of road traffic in the cities taking into account the human factor*. MT-ITS 2019, 6th International Conference on Models and Technologies for Intelligent Transportation Systems. DOI: 10.1109/MTITS.2019.8883381

Pearce, D.W., Barbier, E.W., Markandya, A., (1990). *Sustainable Development*. Earthscan, London.

Pyć, D. (2006). *Prawo zrównoważonego rozwoju*. Wydawnictwo Uniwersytetu Gdańskiego (In Polish).

Rudnicki, A. Starowicz, W. (2007). *Transport miejski. Uwarunkowania rozwoju systemu transportowego Polski*. Wydawnictwo Instytutu Technologii Eksploatacji-PIB, 421 (In Polish).

Stacewicz, M. (1996). *Megatrendy a strategia i polityka rozwoju*. Warszawa: Dom Wydawniczy Elipsa (In Polish).

Szołtysek, J. (2011). Kreowanie mobilności mieszkańców miast. Warszawa: Wolters Kluwer Polska (In Polish).

Tundys, B. (2008). Logistyka miejska, koncepcje, systemy, rozwiązania. Warszawa: Difin (In Polish).

Woźniak, W., Walkowiak, J., Sąsiadek, M., Stryjski, R. (2018). *Organisation of the research proces into an innovative, anti-clogging assembly for heavy vehicles in the interests of increased road safety*. Proceedings of the 32nd International Business Information Management Association Conference, IBIMA 2018, Seville, 15-16 November 2018, 4772-4784.

Zamkowska, S. (2008). Przeciwdziałanie kongestii w miastach. *Transport Miejski i Regionalny*, 11 (In Polish).

Zochowska, R. (2012), Dynamic approach to the Origin-destination matrix estimation in dense street networks. *Archives of Transport. 24*(3), 389-413. DOI: 10.2478/v 10174-012-0025-1

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The Use of Algae in the Process of Cadmium and Lead Ions Removal from Wastewater

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Abstract: The study presents the possibility of using chlorophyta in the removal of cadmium and lead ions from industrial wastewater produced after the washing of equipment used in the manufacture of battery and batteries. The process was conducted with the use of two algal cultures: *Raphidocelis subcapitata* produced in laboratory conditions, and a mixed chlorophyta population collected from a natural, eutrophicated water reservoir with heavy metal ions present in the water and sludge. The study showed that the effectiveness of a pure algal culture is comparable to that of a mixed chlorophyta population, characterized by greater diversity of functional groups at binding sites and higher resistance to stress that may occur in the wastewater environment. The maximum effectiveness of ions sorption was 64% for cadmium (mixed algal population) and 60% for lead (*Raphidocelis subcapitata*).

Keywords: algae, heavy metals, cadmium, lead, biosorption, *Raphidocelis subcapitata*

1. Introduction

Currently, there is growing interest in biological methods of removing heavy metal ions from wastewater. The most popular methods are biosorption and bioaccumulation. Biosorption takes place on the surface of a cell and involves the exchange of substances diffusing into the cell and metabolites transferred out of it. Dynamic exchange of substances present within the cell with the ones around it determines constant regeneration of the cell surface and the ability to sorb new molecules. This process may be equally efficient with live and dead matter (Romera et al. 2007, Jayakumar & Govindaradjane 2017).

Bioaccumulation involves the accumulation of ions or chemical compounds, such as chlorinated hydrocarbons or heavy metal salts, inside a cell. It often has a detrimental effect on the cell organelles, e.g., leading to chlorophyll loss, lower enzymatic activity, or prolonged regeneration time. As a result of gradual degradation, the cell decomposes and releases the accumulated substances to the environment (Filipiuk et al. 2006). Bioaccumulation requires the supply of metabolic energy, so it only occurs with the participation of living organisms.

The most commonly used biological method of wastewater treatment is biosorption. For many years, this process has been subject to many laboratory studies, which have proved beyond doubt that some groups of microorganisms, such as fungi, yeast, bacteria and algae, may sorb various dangerous substances, i.a., heavy metal ions, from the environment (Tab. 1) (Wang & Chen 2009).

Table 1. Effectiveness of different groups of organisms removing ions of selected heavy metals

Metal	Biosorbent	Organism	Metal content [μmol/g $_{d.m.}$]
Cd^{2+}	Brown algae	*Ascophyllum nodosum*	1900
	Aquatic plants	*Potamogeton luceus*	1100
	Bacteria	*Bacillus sp.*	900
	Yeast	*Candida tropicalis*	530
	Fungi	*Rhizopus arrhizus*	240
Cu^{2+}	Aquatic plants	*Potamogeton luceus*	1280
	Bacteria	*Bacillus sp.*	2400
	Yeast	*Candida tropicalis*	1270
	Fungi	*Rhizopus arrhizus*	253
Ni^{2+}	Brown algae	*Ascophyllum nodosum*	680
	Yeast	*Candida tropicalis*	340
	Fungi	*Rhizopus arrhizus*	305
Pb^{2+}	Brown algae	*Saragassum natans*	1300
	Aquatic plants	*Potamogeton luceus*	1360
	Bacteria	*Bacillus sp.*	2110
	Fungi	*Absidia orchidis*	1700
Zn^{2+}	Aquatic plants	*Potamogeton luceus*	1000
	Bacteria	*Bacillus sp.*	2110
	Yeast	*Candida tropicalis*	460
	Fungi	*Rhizopus arrhizus*	310

(Filipiuk et al. 2006)

The phenomenon of biosorption can be compared to the process of ion exchange. The sorption of metals occurs thanks to the presence of i.a., various polysaccharides containing functional groups (carboxyl, phenol, hydroxyl, etc.) on the cell surface (Ramrakhiani et al. 2011). Other mechanisms that may stimulate this process are complexation, microprecipitation or oxidation – reduction reactions, and physical adsorption. (Jayakumar & Govindaradjane 2017, Mata et al. 2008).

The main advantages of biosorption used in removing metal ions from wastewater are the ease of separating the biomass from the solution, and the possibility to regenerate and use the same biomass several times. As for disadvantages, the mechanical strength of microorganisms is rather poor.

The process of biosorption of heavy metals from wastewater is based on the contact between the solid body and the liquid, which can be static or dynamic. In both methods, biomass is mixed with the solution to be purified, and after a specific incubation time, it is separated from the purified solution and regenerated via the desorption of metal ions. If the process is carried out in several steps, its effectiveness is greatly improved (Filipiuk et al. 2006).

The sorption capacity of freshwater and seawater algae is one of the highest out of all microorganisms used in biosorption. Their high effectiveness in the removal of heavy metal ions has been proved by many researchers (Bădescu et al. 2017, Flouty & Estephane 2012). The doubtless advantages of most kinds of algae are their common occurrence, easy culture, and high affinity for various metal ions. The biosorption process with the use of algae allows for the recovery of the sorbed metal ions and easy disposal (Ibrahim et al. 2018, He & Chen 2014).

Algae are effective as biosorbents, especially in removing low concentrations of heavy metal ions. The removal of concentrations higher than several mg/dm^3 is less effective. The aim of the work is to present the possibility of using chlorophyta in the removal of cadmium and lead ions from industrial wastewater produced after the washing of equipment used in the manufacture of batteries. The research was conducted with the use of a model solution and wastewater.

2. Methodology and course of the study

2.1. The origin of algae

The experiments were carried out with the use of algae from two cultures: *Raphidocelis subcapitata* proliferated in laboratory conditions from a lyophilized pure culture, and a mixed chlorophyta population from a natural water reservoir.

In culture 1, i.e., a pure *Raphidocelis subcapitata* culture, there were few cells of *Scenedesmus quadricauda* (< 0.1%), which got to the environment despite the sterilization of the medium. *Raphidocelis subcapitata* algae are commonly found in natural surface standing waters, mostly in temperate climate conditions.

Culture 2 was obtained from the highly eutrophicated Poraj dam reservoir, located at 763.3 km of the Warta River in the southern part of Poland. Each year, there are algal blooms in that reservoir, mainly including chlorophyta, whose abundant development causes water alkalization in the process of photosynthesis. High pH fosters the precipitation of metal ions. Tests of water and sludge from the reservoir confirmed the presence of metals such as nickel (15-59 mg Ni/kg), cadmium (1.5-2.3 mg Cd/kg), and copper (3.3-7.5 mg Cu/kg)

(Rosińska & Dąbrowska 2008). Culture 2 is a mixed population of chlorophyta, mostly made up of *Tetrasporales*, *Chlorosarcinales*, *Chlorococcales*, and *Volvocales* obtained from the water of the reservoir.

2.2. The culture medium

The culture medium used in the culture process was prepared in accordance with the applicable regulation (Commission Directive No. 92/69/EEC of 31.07.1992). The stock solutions contained the following salts:

- Solution I: 1.5 g NH_4Cl, 1.2 g $MgCl_2 \times 6H_2O$, 1.8 g $CaCl_2 \times 2H_2O$, 1.5 g $MgSO_4 \times 7H_2O$ and 0.16 g KH_2PO_4,
- Solution II: $FeCl_3 \times 6H_2O$, 0.08 g and disodium edetate (Na_2EDTA) $\times 2H_2O$, 0.1 g,
- Solution III: 0.185 g H_3BO_3, 0.415 g $MnCl_2 \times 4H_2O$, 0.003 g $ZnCl_2$, 0.0015 g $CoCl_2 \times 6H_2O$, 0.00001 g $CuCl_2 \times 2H_2O$ and 0.007 g $Na_2MoO_4 \times 2H_2O$,
- Solution IV: 50 g $NaHCO_3$.

Four stock solutions were prepared by entering weighted amounts of the selected salts and complementing them with distilled water up to the volume of 1 dm^3. The solutions were sterilized and then kept in dark bottles at 4°C.

The stock solutions were used to prepare the culture medium for the culture of algae. 10 cm^3 of stock solution I was entered into a 1 dm^3 volumetric flask, and then 1 cm^3 samples of the remaining stock solutions (II, III and IV) were added; finally, it was complemented with deionized water up to the volume of 1 dm^3.

2.3. Origin of wastewater

The wastewater used in the experiment had a weakly acidic reaction (pH = 6.1) and contained the following concentrations of heavy metal ions: Cd – 21.7 mg/dm^3, Ni – 72.4 mg/dm^3, Zn – 84.1 mg/dm^3, Cu – 36.2 mg/dm^3, Pb – 58.4 mg/dm^3. The wastewater came from battery production industry, in particular, from the washing of equipment used in manufacture technology. Samples of wastewater were collected to plastic containers and kept at the temperature of 4°C. The sampling took place just after the process of washing of the equipment, directly from the outlet to the treatment plant.

2.4. Model study: determination of metal ions in algae and in the culture medium

Before the sampling of algae, the cultures were mixed, and algae samples were entered into a number of bioreactors with 50 cm^3 culture medium. Then, specific amounts of heavy metal ions were entered so as to achieve the desired concentration. After the assumed exposure time, the samples were centrifuged for 5 minutes at 5,000 rpm. Finally, the culture medium and the biomass were separated.

2.4.1. Determination of metal ions in the model solution

The model solution was the centrifuged culture medium (section 2.4.). 30 cm^3 of medium was taken from each centrifuged sample and filtered through a qualitative filter; afterwards, each sample of the filtrate was placed in a tight, sterile plastic container. Next, each sample was acidified with concentrated HNO_3 up to pH of approx. 2 and kept at 4°C until the assay with the flame atomic absorption spectroscopy method (AAS) in accordance with the standard PN-81/C-04570/01.

2.4.2. Preparation of biomass

The biomass obtained after centrifugation (section 2.4.) was placed in a quartz vaporizer and then dried up to dry matter at 105°C, ground in a mortar and weighed. Then, the samples were subject to mineralization in accordance with PN – EN 14084:2004 in a VELP DK20 mineralizer. The samples were transferred to the mineralizer reaction vessels and flooded with 12.5 cm^3 of aqua regis (HCl 38% and HNO_3 65% at the ratio of 3:1). The procedure was carried out in three successive temperature ranges (I – 20 minutes at 70°C, II – 40 minutes at 100°C, III – 30 minutes at 140°C). After the procedure, the hot samples were filtered through qualitative filters to measuring cylinders and complemented with distilled water up to 50 cm^3. Then, the samples were placed in sterile plastic containers and kept at 4°C until the determination of heavy metal ions content with the atomic absorption spectroscopy method (AAS). The experiment was performed in three iterations.

2.5. Experiment using wastewater: determination of metal ions in algae and wastewater

The experiment was carried out with the use of the same algae that were used in the model study. A number of samples containing algae and culture medium (50 cm^3) were collected and then centrifuged to separate the medium from the biomass. The culture medium was removed and the remaining biomass (approx. 7 cm^3) was washed several times with redistilled water and then entered into reactors containing wastewater (43 cm^3). After the assumed exposure time, the samples were centrifuged and the wastewater and biomass were separated.

In the subsequent stages of the study, the procedure was the same as in the case of preparing the model solution (section 2.4.1) and biomass (section 2.4.2) in the model study.

2.6. Algal culture

Both cultures had similar conditions of development. They were kept at the temperature of 25°C (±2°C) and continuously lit with fluorescent lamps. The number of algal specimens developing in the culture medium was determined with the use of a microscope and a Sedgwick-Rafter Counting Cell. The experiment began after obtaining the culture with the density of 2,500,000 specimens in 1 cm^3 of the medium.

2.7. Procedure of the experiments

2.7.1. Model study

The concentrations of metal ions used in the model study were adjusted to the contents of heavy metal ions in the wastewater. Thus, it was possible to compare the results of the experiment done with the model solution and the experiment using wastewater. For the same reason, the pH of the culture medium was adjusted to 6.1, i.e., the pH of the wastewater. In order to maintain the same conditions of procedures with the use of wastewater and the model solution, all five heavy metal ions present in the wastewater were entered into the model solution, although this study only focuses on the assessment of effectiveness of biosorption of ions of cadmium and lead.

Solutions of metal compounds in the amounts corresponding to their concentrations in the wastewater were entered into 50 cm^3 of culture medium containing the algae *Raphidocelis subcapitata* (culture 1). Cadmium was entered in the form of salt $Cd(NO_3)_2 \times 4H_2O$ in the amount corresponding to 21,7 mg/dm^3, and lead – in the form of $Pb(NO_3)_2$ – in the amount of 58,4 mg/dm^3. The control solution contained the culture medium and *Raphidocelis subcapitata* algae without the added metals.

The experiments were carried out for six exposure times: 1, 10, 30, 60, 120 minutes and 24 hours. After the lapse of the each time of contact between metals and the algal biomass, the contents of cadmium and lead ions were determined in the model solution and in the algal biomass (section 2.4).

A similar experiment was carried out for culture 2, containing a mixed chlorophyta population. The experiment was performed in three iterations.

2.7.2. Experiment using wastewater

Algae *Raphidocelis subcapitata* were entered into the samples of wastewater containing metals (culture 1). The time of contact of metals in the wastewater with the algae was 1, 10, 30, 60, 120 minutes or 24 hours, and after the lapse of each time, the contents of cadmium and lead ions in the biomass were determined. A similar experiment was carried out for culture 2, containing a mixed chlorophyta population. The experiment was performed in three iterations.

3. Results and discussion

Before the study, the contents of cadmium and lead in both cultures were determined. The population of *Raphidocelis subcapitata* did not contain any Cd or Pb ions. Cadmium ions (< 0.01 mg Cd/$g_{d.m.}$) and lead ions (0.01mg Pb/$g_{d.m.}$) were observed in the mixed algal population collected from a natural water reservoir. After specific times of contact between algae and metals, the process was controlled by determining the concentrations of metal ions in the algal biomass and in the model solution or wastewater. The effectiveness of the process was assessed with reference to the control samples.

3.1. Model study

The model study of cadmium ions showed an increase in the content of this element in the algal biomass of both cultures (Fig. 1). The degree of cadmium ions removal by *Raphidocelis subcapitata* (culture 1) was higher and achieved much more quickly than in the case of a mixed chlorophyta population (culture 2). Even in the first minute, the sorption of cadmium in the biomass amounted to 6.33 mg/$g_{d.m.}$, while the mixed population sorbed 1.38 mg/$g_{d.m.}$ after one minute of exposure. The maximum saturation for culture 1 was achieved after 60 minutes of contact (8.26 mg/$g_{d.m.}$), and retained at least for 60 minutes thereafter. After 24 hours, cadmium ions were partially desorbed (6.42 mg/$g_{d.m.}$). For culture 2, maximum saturation was never achieved. The sorption of Cd ions by a mixed chlorophyta population was growing for the whole duration of the experiment. After 24 hours, it was 8.16 mg/$g_{d.m}$.

In the initial stages of the process, the effectiveness of cadmium ions removal from the model solution was several times higher with the use of *Raphidocelis subcapitata*. After 24 hours, the situation changed and the effectiveness of Cd ions removal by the mixed chlorophyta population did increase, but the time needed for this to occur was much shorter in the case of culture 1.

The dynamics of lead ions removal shows an increase in the content of that element in biomass for both cultures (Fig. 1). From the 10th minute to the end of the experiment, the culture of *Raphidocelis subcapitata* (culture 1) displayed relatively unchanged, high effectiveness of sorption of Pb ions (10.0-10.8 mg/$g_{d.m.}$). This proves that doing the experiment for longer than 10 minutes is useless and ineffective. The mixed chlorophyta population (culture 2) displayed much lower effectiveness of lead ions removal than did *Raphidocelis subcapitata* after shorter exposure times (up to 30 minutes). However, from the 60th minute on, it was approx. 15% more effective (12.5-12.9 mg/$g_{d.m.}$).

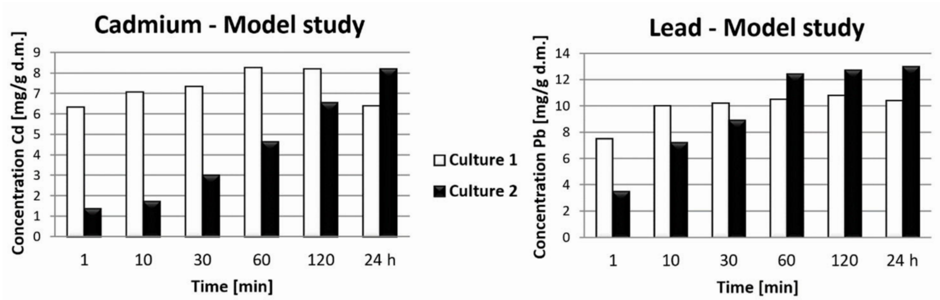

Fig. 1. Changes in cadmium and lead concentrations in the algae biomass depending on the time of exposure

To conclude, for shorter exposure times, *Raphidocelis subcapitata* (culture 1) displayed much better affinity for cadmium and lead ions removal than a mixed chlorophyta population with greater diversity of binding sites.

3.2. Experiment using wastewater

The experiment using wastewater proved the higher effectiveness of cadmium ions sorption by the mixed algal population than by *Raphidocelis subcapitata* (culture 1) (Fig. 2). The effectiveness of a mixed population (culture 2) was on average two times higher for nearly all the times of contact between the biomass and Cd ions. After 24 hours, it was more than 4.5 times higher, because cadmium ions in culture 1 were desorbed. The best effect of cadmium ions removal for the mixed algal population was achieved in the 60th minute (8.02 mg/$g_{d.m.}$), and for *Raphidocelis subcapitata* in the 120th minute (4.07 mg/$g_{d.m.}$).

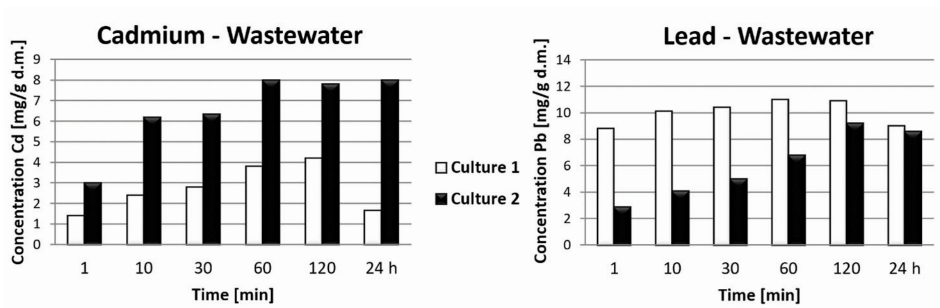

Fig. 2. Changes in cadmium and lead concentrations in the algae biomass depending on the time of exposure

In the case of *Raphidocelis subcapitata*, the effectiveness of lead ions removal from the wastewater was comparable to the effectiveness of sorption in the model study. Culture 1 achieved the maximum saturation (Fig. 2) after 60 minutes (11.05 mg/$g_{d.m.}$). For shorter exposure times, the mixed algal population displayed almost 3 times lower effectiveness of removing lead ions from the wastewater. It only achieved the maximum effectiveness after two hours (9.22 mg/$g_{d.m.}$).

On the basis of the results of cadmium and lead ions removal from wastewater, it was proved that the use of a mixed algal culture makes it possible to achieve a higher level of sorbing ions of both elements in the biomass than the use of *Raphidocelis subcapitata*. The mixed algal population displays high effectiveness of removing cadmium ions from wastewater and is only 15% less effective in removing lead ions (after 120 minutes).

The experiment showed a varied degree of removal of cadmium ions, depending on the medium, exposure time, and the used algal culture (Fig. 3). Cadmium was most effectively removed from the model solution by*Raphidocelis subcapitata* (67%). A similar degree of removal was achieved with the use of the mixed algal population but only after 24 hours of exposure. An opposite trend was observed in the wastewater, where the mixed algal population displayed at least two times higher effectiveness of sorbing cadmium ions than did *Raphidocelis subcapitata* for all exposure times (after 120 minutes, culture 1: 34%, culture 2: 64%).

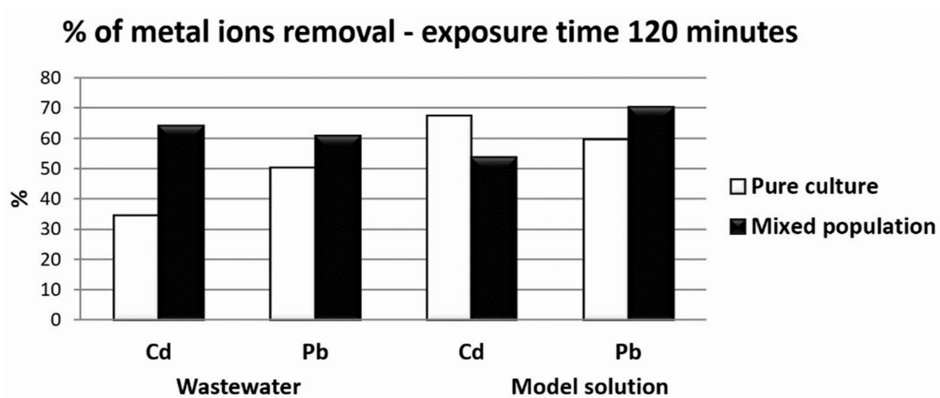

Fig. 3. Percentage removal of cadmium and lead ions after 120 min.

The obtained results proved that the effectiveness of removing lead ions is relatively high in the case of culture 1 and around 57-61% in the model study and in the wastewater. *Raphidocelis subcapitata* displayed high affinity for lead ions removal in the selected pH conditions (6.1) and resistance to various substances present in the wastewater.

In the model study, the process of lead ions removal with the use of a mixed chlorophyta population was slower. Finally, the mixed population proved to be a 16% more efficient biosorbent of lead, but only after 60 minutes of exposure (71% removal). In the case of culture 2, lead ions were removed less efficiently from the wastewater than from the model solution. The mixed population achieved the maximum saturation after 120 minutes of contact, which corresponded to 50% effectiveness of lead ions removal.

Raphidocelis subcapitata are microorganisms used in toxicity tests. They are the subject of very few scientific works concerning the issue of biosorption, although they are common in the temperate climate. The procedure with the use of a mixed chlorophyta population from a natural water reservoir is not popular with many researchers, either, because microorganisms occur in waters quite randomly and it is difficult to reconstruct the culture. However, if metal ions need to be removed from wastewater with diverse composition, a mixed population may be more effective than a pure culture.

Before the experiment, it was assumed that a mixed algal population collected from a natural, highly eutrophicated water reservoir with the content of heavy metal ions (several or over a dozen of mg/dm^3) would be a much more effective biosorbent than the culture of *Raphidocelis subcapitata* produced in laboratory conditions. Greater diversity of functional groups at binding sites and the necessity to develop and adapt in a more toxic environment were in favor of the mixed algal population. Hence, better effects of biosorption in the mixed chlorophyta population were expected, especially when the process involved natural wastewater.

However, *Raphidocelis subcapitata* proved to be much more resistant to additional substances present in the wastewater (e.g., surfactants), which were not taken into consideration in the model solution (it included the elements of the culture medium, section 2.2.). They displayed better effectiveness of removing lead from the wastewater and cadmium from the model solution than did the mixed population, and their effectiveness was only slightly lower (by 15%) when sorbing lead from the model solution. In all these cases, *Raphidocelis subcapitata* worked much more quickly than the mixed population. They achieved 70% of the maximum saturation even in the first minute of the experiment. The mixed chlorophyta population needed much more time (at least 60 minutes) to achieve the results comparable to those achieved by *Raphidocelis subcapitata.* The only case in which the mixed population was more effective (2 times and more) was the removal of cadmium ions from the wastewater.

4. Conclusions

The aim of the study was to present the possibility of using chlorophyta in the removal of cadmium and lead ions from industrial wastewater produced after the washing of equipment used in the manufacture of batteries. The experiment proved that *Raphidocelis subcapitata* and a mixed chlorophyta population can be effectively used to remove heavy metal ions from wastewater. The process of biosorption had different intensities, mostly depending on the time of exposure and the used biomass. The maximum effectiveness of the process was 64% for cadmium and 60% for lead. The effect of purification is not sufficient to safely channel the wastewater to waters or to the ground (providing the content of Cd and Pb ions). Still, the effects are promising, and conducting the procedure in several steps would probably lead to much better effects.

References

Bădescu, I.S., Bulgariu, D. & Bulgariu, L. (2017). Alternative utilization of algal biomass (Ulva sp.) loaded with Zn(II) ions for improving of soil quality. *Journal of Applied Phycology, 29*(2), 1069-1079. DOI: 10.1007/s10811-016-0997-y

Filipiuk, D., Fuks, L. & Majdan, M. (2006). Biosorption as a new method for sequestering heavy metals in industrial aqueous effluents. *Chemical industry 85*(6), 417-422. Retrieved from: http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-AGH4-0005-0053 (in Polish)

Flouty, R., Estephane, G. (2012). Bioaccumulation and biosorption of copper and lead by a unicellular algae Chlamydomonas reinhardtii in single and binary metal systems: A comparative study. *Journal of Environmental Management, 111*, 106-114. DOI: 10.1016/j.jenvman.2012.06.042

He, J., Chen, J.P. (2014). A comprehensive review on biosorption of heavy metals by algal biomass: materials, performances, chemistry and modeling simulation tools. *Bioresource Technology, 160,* 67-78. DOI: 10.1016/j.biortech.2014.01.068

Ibrahim, W.M., Yasmeen, S.A., Soha, M.H. & Nahed, S.G. (2018). Comparative Study for Biosorption of Heavy Metals from Synthetic Wastewater by Different Types of Marine Algae. *Journal of Bioremediation & Biodegradation 9*(1) 425. DOI: 10.4172/2155-6199.1000425

Jayakumar, V., Govindaradjane, S. (2017). Biosorption of Cadmium by Green Algae – A Review. *Journal of Advanced Chemical Sciences, 3*(2), 480-484. Retrieved from: https://www.jacsdirectory.com/journal-of-advanced-chemical-sciences/articleview.php?id=151

Mata, Y.N., Blázquez, M.L., Ballester, A., González, F. & Muñoz, J.A. (2008). Characterization of the biosorption of cadmium, lead and copper with the brown alga Fucus vesiculosus. *Journal of Hazardous Materials, 158*, 316-323. DOI: 10.1016/j.jhazmat.2008.01.084

Ramrakhiani, L., Majumder, R. & Khowala, S. (2011). Removal of hexavalent chromium by heat inactivated fungal biomass of Termitomyces clypeatus: surface characterization and mechanism of biosorption. *Chemical Engineering Journal, 171*, 1060-1068. DOI: 10.1016/j.cej.2011.05.002

Romera, E., González, F., Ballester, A., Blazquez, M.L. & Muñoz, J.A. (2007). Comparative study of biosorption of heavy metals using different types of algae. *Bioresource Technology, 98*(17), 3344-3353. DOI: 10.1016/j.biortech.2006.09.026

Rosińska, A., Dąbrowska, L. (2008). PCBs and heavy metals in bottom sediments of the dam reservoir Poraj. *Engineering and Environmental Protection, 11*(4), 455-469. Retrieved from: https://ios.is.pcz.pl/index.php/tom-11/numer-4-2008 (in Polish).

Wang, J., Chen, C. (2009). Biosorbents for heavy metals removal and their future. *Biotechnology Advances, 27*, 195-226. DOI: 10.1016/j.biotechadv.2008.11.002

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Kohonen Artificial Networks for the Verification of the Diameters of Water-pipes

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Abstract: The design of the water distribution system is inherently linked to the execution of calculations, which aim, among other things, to determine the flow rate through individual pipes and the selection of diameters at the appropriate speed. Each step in the calculations is followed by an evaluation of the results and, if necessary, a correction of the data and further calculations. It is up to the designer to analyse the accuracy of the calculation results and is time-consuming for large systems. In this article, a diagnostic method for the results of hydraulic calculations, based on Kohonen Network, which classifies nominal diameters [DN] on the basis of data, in the form of flows, has been proposed. After calculating the new variant of the water distribution system, the individual calculation sections are assigned to the neurons of the topological map of Kohonen Network drawn up for nominal diameters. By comparing the diameter used for the calculation, with the diameter obtained on the topological map, the accuracy of the chosen diameter can be assessed. The topological map, created as a result of labelling the neurons of the output layer of the Kohonen Network, graphically shows the position of the classified diameter, relative to those diameters with similar input values. The position of a given diameter, relative to other diameters, may suggest the need to change the diameter of the pipe.

Keywords: water distribution system, hydraulic calculations, diameter selection, Kohonen Network, evaluation of calculation results

1. Introduction

The design of the water distribution system is inherently linked to the execution of calculations, the purpose of which is, among other things, determination of the flow rate through the individual pipes, the selection of diameters for maintaining appropriate speeds, the calculation of pressure losses and pressure levels at the nodes. It seems that classical algorithms with a formalised course, can be supplemented with much more advanced computational techniques derived from the field known as artificial intelligence (Konar 2005, Bishop 1995). The scope of this approach includes such methods as artificial, neural networks, expert systems and genetic algorithms. In this paper, an attempt is made to supplement classical methodology by calculating water distribution systems using elements of artificial neural networks. A uni-directional artificial neural network, the so-called "neural network" was used in this paper, the Kohonen Network (Kohonen 2001, Kangas & Kohonen 1996).

An important challenge in the operation of water supply systems is the effective detection of leaks. In the article, by (Aksela et al. 2009) a method based on a self-organising map for the detection of leaks, in the water supply network, was presented. The data used for network training and validation consists of flowmeter readings and reported leak locations. The most important factor facilitating the self-organising, map-based modelling of leakages is the developed leakage function. The experimental results, presented, show that a model, trained on flow data, can detect leaks in a specific area of the water supply network. In the article by (Brentan et al. 2018) presented a grouping method based on self-organising maps, in combination with k-mean algorithms, in order to obtain groups that can be easily identified and used to make decisions supporting the design, operation and management of water distribution systems. In the article by (Blokker et al. 2016) the application of the self-organising, map technique of the SOM was analysed, in order to determine how this method could be used in the numerical analysis of water quality, in water distribution systems. An overview of the methods of artificial intelligence, including SOM, for water supply issues, is given in the work by (Czapczuk et al. 2015). The problem of assessing the accuracy of the selection of diameters of water supply pipes was also addressed in the work by (Dawidowicz et al. 2018) using the K-Nearest Neighbours method, and in the work also by (Dawidowicz 2012), where the method of inducing the rules of the expert system was used. A comparison of two artificial intelligence methods for predicting water supply failure is included in the paper (Kutylowska 2016).

2. Introduction to Kohonen Network

In the 1950's, the idea of a self-organising system, *i.e.,* one that changes its structure on the basis of information coming to it from the environment, the so-called

SOM - Self Organizing Map, was used for the first time. Kohonen used the concept of self-organisation for artificial neural networks and proposed a network called 'Self-organising mapping'.

This, today, but with various modifications, is the most popular type of self-organising network and is named after its inventor- Kohonen.

2.1. The Kohonen Network structure

Kohonen nets are used for a non-model classification. Their aim is to select from a certain population, described by a multi-dimensional data vector $\boldsymbol{X} = [x_1,x_2,...,x_i,...,x_N]^T$, possibly homogeneous groups (clusters) in terms of considered features (input variables). They consist of two layers: input and output. Figure 1 shows a two-dimensional network, while Figure 2 shows a two-dimensional network. The neurons of the input layer (i = 1,..., N), are only used for entering data into the network, without performing any processing. In the output layer of the network, there are radial neurons, hence it is called a *radial layer*. Individual radial neurons are connected to all inputs and a weight is assigned to each connection. The collection of all connection weights, for each radial neuron, creates a vector of weights $\mathbf{W}=[w_1, w_2,...,w_i,..., w_N]^T$, the so-called *prototype or code-book vector*. The number of neurons in the output layer is determined by the network designer. Neurons in the output layer are not connected to each other and do not transmit information to each other but are connected by a neighbourhood relationship that affects the way neurons learn.

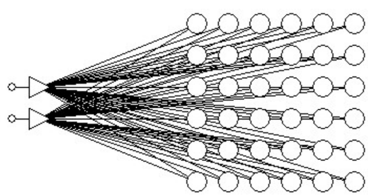

Fig. 1. Diagram of an example of the two-dimensional Kohonen Network for N = 2 (source: own study)

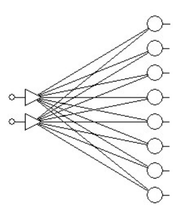

Fig. 2. Diagram of an example of the one-dimensional Kohonen Network for N = 2 (source: own study)

2.2. Learning the Kohonen network

Kohonen Networks are taught using an unsupervised learning algorithm (*self-organising learning*, *unsupervised learning*) where no *'d output values'* of the teaching data are used. In the case of Kohonen Network, we are dealing with *competitive learning,* so-called. Network learning is done by repeatedly showing examples of learning data, in the vector form X**,** along with modifications of the output neuron scales 'W**'**. The network is presented with additional input data, without information on the output signal which the network is to generate for a particular learning vector. The input signal is assumed to belong to one of several classes, but the classes sought are not known and the network seeks to detect them on its own. Similar input signals should be recognised as belonging to the same class. In this way, Kohonen Network tries to determine the structure of the data and the clusters of learning examples present in them.

After training the Kohonen Network, individual neurons should be assigned appropriate class labels, if known. Only then can the radial neurons act as classifiers. Each input signal is assumed to belong to one of several classes and the network output value identifies the class to which the signal belongs. After the learning process, each radial neuron of the output layer, or more precisely the vector of its weights (the so-called master /pattern vector), becomes the pattern or *"centre"* of a group of closely related input signals. After assigning the corresponding labels (names) of the individual classes to the individual neurons of the output layer, a so-called topological map is created. Class assignment is performed using the K-L Nearest Neighbours algorithm, in which a given neuron is assigned a label, based on the labels of the K-Nearest teaching cases. However, the condition is that at least L of K Neighbours has the same class, otherwise the label of the neuron will be "unknown".

The topological map graphically determines the position in the output layer of neurons, describing individual classes, their neighbourhood and the presence of clusters. In the case of a trained network, it is expected that similar input signals should elicit similar network responses, hence the arrangement of neurons, representing similar classes, should be similar on a topological map, forming certain groups.

3. Kohonen Network in the assessment of the diameters of water pipes

Numerical experiments were carried out to test the applicability of Kohonen's Network in assessing the diameters of the water distribution system. Sequential learning is used, i.e., learning examples are repeatedly presented to the network.

In order to compile a data set for the teaching neural networks, information on 33 existing medium -*and small-sized*- water supply systems was collected. Hydraulic calculations were performed for the above water distribution systems for different variants of water uptake from nodes, so as to obtain the widest possible range of data for teaching neural networks. Due to the large amount of data, a procedure was developed to convert the calculations' results for individual sections of the calculation wires to the appropriate format and save them in a set of training examples. Calculations were performed for different values of the absolute roughness coefficient. Based on the results of the hydraulic calculations, for the maximum water intake hour Q_{hmax}, 13,923 teaching examples were obtained. The calculation uses a methodology that takes into account nodal and sectional expenditure (Mielcarzewicz 2000). In this case, the teaching dataset was divided into two subsets: teaching and testing, covering 70% and 30% of the examples, respectively.

3.1. An overview of Kohonen Network solutions tested, in the assessment of the diameters of water pipes

Firstly, the network was trained in the form of a chain, consisting of 10 neurons in the output layer. In this case, at the learning stage, it is not possible to assign appropriate diameters to individual neurons, since the 'without a teacher' method was used. The purpose of this training was to verify whether the network automatically assigns input vectors corresponding to individual pipe diameters.

The set of input variables L, Q_p, q_{odc}., Q_k, k was assumed. The above network is shown schematically in Fig. 3.

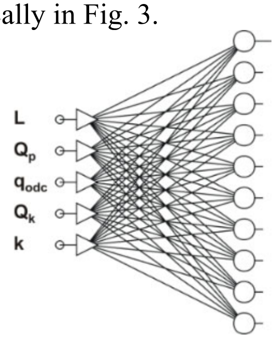

Fig. 3. Diagram of Kohonen one-dimensional network for assessing cable diameters (source: own study)

Kohonen Networks, with a square grid. The same set of input variables was used as for a one-dimensional network. The learning outcomes for these networks are presented in Table 1. The sensitivity analysis of the input variables for the Kohonen Network is presented in Table 2. The results indicate that two variables are relevant for this type of network Q_p and Q_k.

Network learning with two input variables: Q_p and Q_k described in Table 3. Sensitivity analysis for the above variables, showed that they are very important in the functioning of the network.

Table 1. Kohonen neural networks, for assessing wire diameters (5 input variables) (source: own study)

Basic data of neural networks:

Number of entries: 5
Input variables: L, Q_p, q_{odc}, Q_k, k
Output variable: none
Output layer function: Euclidean measure
Error function: Kohonen

Net no.	Network type	Number of neurons in the input layer	Number of neurons in the output layer	Error in the training set	Error in the test set	Accuracy of classification in the learning set	Accuracy of classification in the test set
1	Kohonen	5	10 (10x1)	0.210393	0.2090614	0.001436	0.001675
2	Kohonen	5	100 (10x10)	0.0857	0.08404	0.1953846	0.1809478
3	Kohonen	5	225 (15x15)	0.06057	0.05871	0.3802051	0.362853
4	Kohonen	5	400 (20x20)	0.04815	0.04718	0.4781538	0.4511728
5	Kohonen	5	900 (30 x 30)	0.06177	0.0641	0.4339118	0.4079371
6	Kohonen	5	1600 (40 x 40)	0.04854	0.05161	0.6235863	0.5745367
7	Kohonen	5	2500 (50 x 50)	0.03795	0.04232	0.7567988	0.6865344

Table 2. Sensitivity analysis of neural network input variables from Table 1 (source: own study)

Net no. from Table 7.19	Type of data subset	Assessment parameter of variable sensitivity	Kohonen's input variable				
			LD	Q_p	q_{odc}	Q_k	K
1	Learning set	Rank	5	2	3	1	4
		Error E_i	0.1910124	0.3235362	0.2023955	0.3239577	0.2002289
		Quotient	0.9078833	1.53777	0.9619873	1.539773	0.9516893
2	Learning set	Rank	4	2	5	1	3
		Error E_i	0.07702	0.2705157	0.06907	0.2708085	0.08325
		Quotient	0.8987833	3.156711	0.8059887	3.160128	0.9715154
3	Learning set	Rank	3	2	5	1	4
		Error E_i	0.05226	0.264514	0.04887	0.2646739	0.04952
		Quotient	0.8628372	4.36696	0.8067703	4.3696	0.8175303
4	Learning set	Rank	3	2	4	1	5
		Error E_i	0.04266	0.2625269	0.04186	0.262776	0.04051
		Quotient	0.8860484	5.452492	0.8694931	5.457665	0.8413751
5	Learning set	Rank	4	5	2	1	3
		Error E_i	0,06524	0,05822	0,188856	0,18910	0,06774
		Quotient	1,056091	0,9424292	3,057326	3,061276	1,096599
6	Learning set	Rank	4	5	2	1	3
		Error E_i	0,05317	0,04498	0,1844805	0,1848024	0,05361
		Quotient	1,095457	0,9268248	3,80085	3,807482	1,104571
7	Learning set	Rank	3	5	2	1	4
		Error E_i	0,0474278	0,03446	0,1831879	0,1834781	0,04701
		Quotient	1,249718	0,9081402	4,826982	4,834629	1,238826

A diagram of Kohonen net, in the form of a 10x10 rectangular grid is shown in Fig. 4.

Table 3. Kohonen neural networks for assessing wire diameters (2 input variables) (source: own elaboration)

Net no.	Network type	Neurons in the input layer	Neurons in the output layer	Error in the training set	Error in the test set	Accuracy of classification in the learning set	Accuracy of classification in the test set
Basic data of neural networks: Number of entries: 2 Input variables: Q_p, Q_k Output variable: none Output layer function: Euclidean measure Error function: Kohonen							
1	Kohonen	2	100 (10x10)	0.01997	0.0222	0.8285128	0.831738
2	Kohonen	2	225 (15x15)	0.01161	0.01303	0.8953846	0.898277
3	Kohonen	2	400 (20x20)	0.004524	0.005345	0.9368205	0.94136
4	Kohonen	2	625 (25x25)	0.003046	0.003473	0.9365128	0.935376
5	Kohonen	2	900 (30x30)	0.002189	0.002556	0.9758974	0.971757
6	Kohonen	2	1225(35x35)	0.001694	0.001897	0.9775385	0.969603

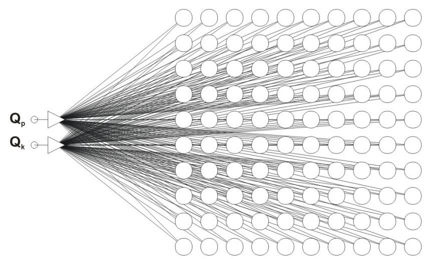

Fig. 4. Kohonen Network diagram in the assessment of cable diameters (source: own elaboration)

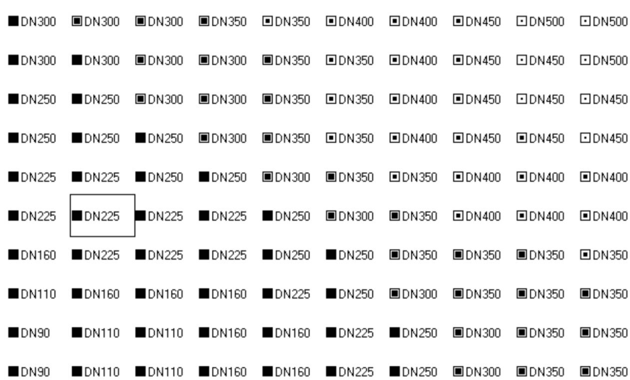

Fig. 5. An example of a topological map for the classification of pipe diameters (source: own elaboration)

Labels of individual pipe diameters were assigned to the neurons of the output layer of the Kohonen Network, thus determining their significance. In Kohonen Network, there is a regularity that says that the proximity of signals in the input space of the network equals the similarity of neighbouring objects on the topological map, described by these signals. Therefore, neurons describing the same diameters lie side by side in groups and gradually pass into diameters adjacent to the typeset.

3.2. A detailed description of *Kohonen Network* in the assessment of the diameters of water pipes

As a result of Kohonen neural networks learning, a structure with 2 neurons in the input layer and 900 neurons in the output layer was selected, arranged on a square grid with a width of 30 by 30 neurons (Table 3, item 5). The initial flow values $_p$ [l/s] in the Q branch are given at the network input together with the final flow Q_k [l/s]. In the case of the Kohonen Network, the effect of the remaining variables on the learning error was so insignificant that it was decided to abandon it.

Activation of Kohonen Network for the entire data set, after assigning labels describing the diameters of the wires to individual neurons, made it possible to evaluate the accuracy of the classifications obtained. The results presented in Table 4 indicate a certain number of incorrect classifications, which, however, represent a small percentage of all data. The accuracy of the classification for the learning set is 0.9758974, while, for the test set, it is 0.9717568.

Table 4. Results of the classification of water pipe diameters, using Kohonen Network for the test subset (source: own study)

	DN 90	DN 110	DN 160	DN 225	DN 250	DN 300	DN 350	DN 400	DN 450	DN 500
Total	568	598	535	457	299	428	462	419	248	164
Correct	558	555	510	448	293	424	457	409	247	159
Incorrect	10	43	25	9	4	3	2	9	0	3
Unspecified	0	0	0	0	2	1	3	1	1	2
DN90	558	39	0	0	0	0	0	0	0	0
DN110	10	555	22	0	0	0	0	0	0	0
DN160	0	4	510	9	0	0	0	0	0	0
DN225	0	0	3	448	1	0	0	0	0	0
DN250	0	0	0	0	293	2	0	0	0	0
DN300	0	0	0	0	3	424	2	0	0	0
DN350	0	0	0	0	0	1	457	9	0	0
DN400	0	0	0	0	0	0	0	409	0	0
DN450	0	0	0	0	0	0	0	0	247	3
DN500	0	0	0	0	0	0	0	0	0	159

3.3. Application of *Kohonen Network* in assessing the selected water pipe diameters of a water distribution system

Each calculation procedure is followed by an evaluation of the results and, if necessary, correction of the data and subsequent calculations.

The diagnostic method of Kohonen Network, classifies nominal diameters DN based on input data in the form of Q_p and Q_k. After the calculation of the new variant of the water distribution system, the individual sections of the calculation are assigned to the neurons of the topological map, drawn up for the nominal diameters. By comparing the diameter used for the calculation, with the diameter obtained on the topological map, the accuracy of the chosen diameter can be assessed.

A topological map, created as a result of the labelling neurons of the output layer, graphically shows the position of the classified diameter, relative to those diameters with similar input values. The position of a given diameter relative to other diameters may, for example, suggest the need to change the diameter of the duct, when the neuron describing the diameter, on a given section, is surrounded by neurons corresponding to other diameters.

4. Summary and conclusions

Various Kohonen Network structures, *viz*., the number and type of inputs and the size of the output layer were analysed. A sensitivity analysis was carried out to determine the impact of individual inputs on the way the network operates. A series of numerical experiments allowed a set of neural networks with different structures to be created and networks with the best parameters to then be selected.

Kohonen Networks can be used to assess the diameters of water supply lines. The advantage of this solution is the topological map, which graphically shows the position of a given diameter, relative to other diameters, depending on the parameters describing the computational section.

References

Aksela, K., Aksela, M., & Vahala, R. (2009). Leakage detection in a real distribution network using a SOM. *Urban Water Journal, 6*(4), 279-289.

Bishop, C. M. (1995). *Neural Networks for Pattern Recognition.* Oxford: Oxford Univ. Press.

Blokker, E. J. M., Furnass, W. R., Machell, J., Mounce, S. R., Schaap, P. G., & Boxall, J. B. (2016). Relating Water Quality and Age in Drinking Water Distribution Systems Using Self-Organising Maps. *Environments, 3*(2).

Brentan, B., Meirelles, G., Luvizotto, E., & Izquierdo, J. (2018). Hybrid SOM plus k-Means clustering to improve planning, operation and management in water distribution systems. *Environmental Modelling & Software, 106*, 77-88.

Czapczuk, A., Dawidowicz, J., & Piekarski, J. (2015). Artificial Intelligence Methods in the Design and Operation of Water Supply Systems. *Rocznik Ochrona Srodowiska, 17*, 1527-1544.

Dawidowicz, J. (2012). Expert System for Evaluation of Water Distribution System Created with an Inductive Inference. *Rocznik Ochrona Srodowiska, 14*, 650-659.

Dawidowicz, J., Kruszynski, W., Andraka, D., & Czapczuk, A. (2018). Assessing the Diameters of Water Pipes Using the k-Nearest Neighbours Method in the Calculations of Water Distribution Systems. *Rocznik Ochrona Srodowiska, 20*, 528-537.

Kangas, J., Kohonen, T. (1996). Developments and applications of the self-organizing map and related algorithms. *Mathematics and Computers in Simulation*, *41*, 3-12.

Kohonen, T. (2001). Self-Organizing Maps. *Springer Series in Information Sciences*, *30*, Springer-Verlag.

Konar, A. (2005). *Computational Intelligence: Principles, Techniques and Applications.* Springer-Verlag.

Kutylowska, M. (2016). Prediction of Water Conduits Failure Rate – Comparison of Support Vector machine and Neural Network. *Ecological Chemistry and Engineering a-Chemia i Inzynieria Ekologiczna A, 23*(2), 147-160.

Mielcarzewicz, W.E. (2000). *Calculation of water supply systems.* Warszawa: Arkady (in Polish).

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Diversity of Fish and Zoobenthic Communities in Lowland River Related to the Factors of Hydromorphological, River Continuum and Pollution Disturbances

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Abstract: The response of zoobenthos and ichthyofauna to different levels of habitat degradation was estimated on a small lowland river. The level of fragmentation, the hydromorphological modifications of the watercourse bed, and the water quality of different river stretches were assessed as proxies of the degree of anthropogenic transformation of habitats. The degree of fauna similarity between the study sites, as well as the relationships between habitat quality and biotic indexes were estimated. A strong response of both assemblages to changes in environmental conditions was demonstrated, however, reaction to individual pressures differs. This confirms that these organisms are excellent, universal bioindicators and both groups should be used together. The key role of a well developed riparian zone in shaping the diversity of freshwater biota has also been demonstrated.

Keywords: lowland stream, anthropopressure, fish fauna, benthic macroinvertebrates, biodiversity

1. Introduction

Surface waters in Poland are still subject to strong anthropogenic pressures despite measures to reduce the impacts required by the implementation of the European Directive have been undertaken. Running waters are subject to hydromorphometric modifications that profoundly alter their natural course and hydrological regime, and to the impact of pollutants that alter water quality. These main drivers of anthropogenic alteration lead to a loss of habitat heterogeneity and to a consequent impoverishment of biocoenoses (Allan 1998, Golski et al. 2010, Mueller et al. 2020, Pytka et al. 2013). According to the concept of river continuum, the longitudinal variation of the characteristics of the river ecosystem is the result of a gradient of physical conditions (width and depth, velocity and volume of flow, temperature, bottom substrate) and of resources along which the biota and ecosystem processes are gradually adjusted. According to the concept, the effects of processes in the head course of the river affect the dynamics of processes occurring in the down section (Allan 1998, Branco et al. 2014, Vannote et al. 1980). Even the smallest hydro-technical building or other interference in the river channel disrupts the continuity of the river system. Currently, most rivers in Europe suffer to a greater or lesser extent from river continuum disturbances (Mazurkiewicz-Boroń & Starmach 2009, Prus et al. 2016, Przybylski et al. 2020). In addition to the direct modifications of the river channel, the use of the surrounding land also has an impact on the characteristics of the river ecosystem, for example by modifying the type of sedimentation and the load of material of terrestrial origin that enters the river. Commonly carried out maintenance works – consisting of profiling and strengthening the banks, straightening and deepening of the channels, removing the bottom substrate and macrophytes – lead to a loss of heterogeneity of the micro-habitats and, consequently, to drastic changes in the structure of the assemblages (Golski et al. 2010, Kalny et al. 2017, Przybylski et al. 2020). Habitat fragmentation is also a major driver of diversity loss. As an example, river sections within larger cities were an insurmountable barrier for many species (Czerniawska-Kusza 2001, Penczak et al. 2010, Przybylski et al. 2020).

Until the end of the 1980s, flowing water pollution was the most important factor limiting the abundance and composition of biotic assemblages. After the political transformation, and especially after the enlargement of the European Union, the approach to environmental protection in Central and Eastern Europe has changed significantly. The quality of water began to gradually improve, which enabled the reconstruction of biocenoses, although still not enough to bring most of the running waters to a good ecological state, according to the requirements of the Water Framework Directive (Kruk et al. 2016, Marszał et al. 2014). Currently, phosphorus and nitrogen pollution continues to be one of the major problems (Pytka et al. 2013).

Macroinvertebrates and fish are particularly sensitive to river fragmentation, profiling and pollution (Bis & Mikulec 2013, Branco et al. 2014, Pietraszewski et al. 2008, Prus et al. 2016). Fish, due to their high mobility, are particularly associated with the disruption of the watercourse, and their species composition reflects the effects of anthropogenic disturbances over many years (Branco et al. 2014, Prus et al. 2016, Rechulicz & Płaska 2016). Unlike fish, the species richness of benthic macroinvertebrates depends more closely on the heterogeneity of river microhabitats, and therefore more effectively reflects changes in local conditions (Bis & Mikulec 2013, Czerniawska-Kusza 2001). The presence, persistence and composition of both biotic assemblages depends on natural morphological characters that are key functional elements for river ecosystems. These include stony-gravel reefs that spawn rheophilic fish (Prus et al. 2016), as well as ponding water areas that are essential sites for young fish development (Brylińska 2000). The presence of shelters against strong currents and predation (Prus et al. 2018, Wolter 2010), as well as of natural barriers, including debris, may favor fish and zoobenthos development (Kałuża & Radecki-Pawlik 2014, Wyżga et al. 2012).

In spite of the wide use of biotic responses to anthropogenic stressors for the assessment and monitoring of ecosystem integrity, the causal relationship between environmental and biotic characteristics is still largely to be clarified. The aim of the study was to supplement the knowledge about changes in the species structure of ichthyofauna and zoobenthos of a small lowland river as a function of the level of habitat degradation. To this aim we assessed how the main sources of directional variability – fragmentation, hydromorphological transformations and pollution – affect the diversity of two assemblages.

The following research hypothesis was formulated: The studied communities show a different response to pressures. Fish better represent large, while macrozoobenthos local scale of impact.

To represent a wide degree of anthropogenic impact we identified the Lutynia and its tributaries Żybura and Lubianka (West Poland), as an optimal experimental site. These rivers experienced strong anthropopressure during the past Kołaczkowski & Kniat (1959), data from the Voivodeship Inspectorate for Environmental Protection- VIEP, while have been gradually improving in more recent times, but comprehensive hydrobiological studies are still lacking.

2. Study area

Lutynia flows through the Wielkopolskie Voivodship and its basin is an area characterized by the occurrence of small water reservoirs of anthropogenic origin (RZGW 2015). Land cover is dominated by a 76% of agricultural, while only a 17% is made by semi-natural areas (Corine Land Cover 2012). Water covers 0.08% of the Lutynia basin.

Lutynia is a third-order stream (Strahler 1957) through its left side of the Warta with a length of 63 km and basin of 606 km^2. According to the abiotic typology of rivers proposed by Błachuta et al. (2010), watercourse should be classified according to the height and size of the basin as a small lowland river. There are 19 damming devices along the entire course of the river, the watercourse river channel is subjected to regulatory works for a considerable length, while the quality of water can be affected by sewage from three cities and area pollution of agricultural origin (VIEP).

Żybura and Lubianka are fourth-order streams, and permanent tributaries of Lutynia with a length of 9 and 21 km, respectively. These are lowland streams whose catchment area does not exceed 100 km^2. Two damming dams were located on each of the watercourses, the quality of water may be affected by pollution from the agricultural catchment (VIEP).

The location of watercourses and research sections along with the types of pressure is shown in Figure 1 and Table 1.

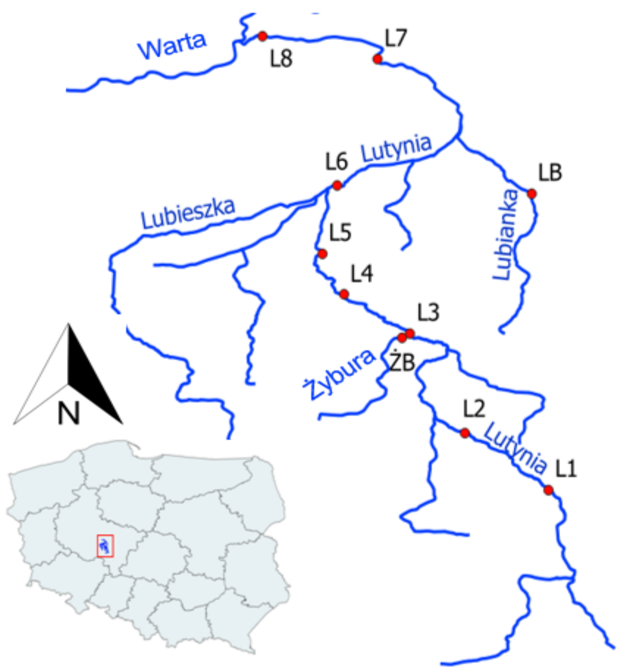

Fig. 1. Location of study sites in the Lutynia river system

Table 1. Types of pressure and GPS research section

Research section	GPS	Expected Pressures			Depth	Width	Bottom Substrate
		B	HM	P	[MIN.MAX./AVER.]		
L1	51.861575 17.680681	+	+++	++	18-70 34	265-400 375	M/S
L2	51.894653 17.629475	++	++	+++	4-30 20	210-315 275	S/M/G
L3	51.952111 17.596211	++	+++	+++	9-115 57	290-460 400	S/M/ST
L4	51.974561 17.555461	-	+	+	5-140 55	315-670 550	S/G/ST/M
L5	51.998467 17.542314	-	+	+	10-125 48	500-990 850	S/G/ST/M
L6	52.037967 17.551286	++	+++	+++	30-85 52	650-810 720	S/M
L7	52.111183 17.576344	+++	++	++	10-96 25	400-515 475	S/M
L8	52.124175 17.506128	++	++	++	22-150 74	370-580 475	S/M
ŻB	51.951389 17.595303	+	++	++	7-94 18	90-220 156	S/M
LB	52.033225 17.670222	++	++	+++	5-70 42	110-190 160	S/M

Explanations: B – barriers, HM – hydromorphology, P – pollutions, (+) - strength of anthropopressure, S – sand, G – gravel, ST –stones, M – mud. Abiotic typology (according to Błachuta et al. 2010): loess or clay lowland stream (L1, L3, ŻB, LB), sandy lowland stream (L2), gravel lowland stream (L4, L5), sandy-clay lowland river (L6, L7, L8)

3. Material and Methods

The research was carried out in 2015-2016 on 10 river stretches. These were defined by dividing the course of the river into sections of 2-3 km and identifying in each a stretch of 200 representative of the local conditions as a reference area for the study. One 150 m long stretch was tested on the tributaries.

The level of impact of the analyzed pressures was expressed on a 5-point scale, where class I corresponds to the lowest level, while class V corresponds to the highest. The degree of disturbance of watercourse continuity was estimated based on the number of barriers per section. This number ranged from 0 (class I) to 4 and more (class V). Transformations of the river channel morphology were characterized by the method of scoring selected parameters: depth and flow variation, the presence of shelters and natural elements of the river channel (riffle-pool sequences, meanders), the structure of the bottom substrate (Table 2).

Table 2. Scoring assessment of hydromorphological parameters of the watercourse

Parameter	Component	Points
Flow	Imperceptible	1
	Two types of flow	2
	Three types	3
	Four types	4
	Over four types	5
Shelters	Absence	1
	One type of shelter	2
	Two types	3
	Three types	4
	Four and more shelters	5
Morphometry of river channel (natural elements)	Absence	0
	Riffle-pool sequence	1
	Meander	2
Coefficient of variation for depth (Depth CV)	0-15	1
	16-30	2
	31-45	3
	46-60	4
	> 60	5
Bottom substrate	Slime	1
	Clay	2
	Sand	3
	Gravel > 20%	4
	Gravel and stones > 20%	5
W/D	> 50	1
	41-50	2
	26-40	3
	16-25	4
	< 15	5

Explanations: W/D – ratio of average width to average watercourse depth
(source: Dajewski 2016, Golski et al. 2010, 2013, 2015, Graczyk 2014)

The higher the sum of points on a given research section, the smaller the hydromorphological transformations (Table 3). A maximum of 35 points can be awarded if there are at least 3 meanders and 4 riffle-pool sequences (a total of max. 10 points). All hydromorphological surveys were made once a year.

Table 3. Final classification of evaluation of waterway morphology transformations

Class	Total points
I	≥ 28
II	21-27
III	14-20
IV	7-13
V	≤ 6

Source: Dajewski 2016, Golski et al. 2010, 2013, 2015, Graczyk 2014

The degree of watercourse pollution was determined using selected physicochemical indicators (Table 4). Temperature, oxygen content, conductivity and reaction were measured in the field with a YSI 556MPS multiparameter device. Water samples were collected at each site every month during summer (June-September) and transported to the laboratory for chemical and BOD5 analyses. The obtained results were assigned to one of five water quality classes according to modified Regulation of the Minister of the Environment of February 11, 2004. The use of a five-point scale, which is not currently applied to physicochemical parameters, allowed for a more precise differentiation of the stands in terms of their contamination.

Table 4. Limit values of indicators in surface water quality classes modified in terms of fish requirements

Quality of water indicator	Unit	Limit values in class I-V				
		I	II	III	IV	V
Water temperature	°C	≤ 15	≤ 18	≤ 20	≤ 23	>23
Oxygen dissolved	mg O_2 l^{-1}	≥ 8	≥ 6	≥ 5	≥ 3	< 3
pH reaction	pH	6.5-8.5	6.0-8.5	6.0-9.0	5.5-9.0	<5.5>9.0
Conductivity	µS cm^{-1}	≤ 300	≤ 500	≤ 800	≤ 1000	> 1500
Substance dissolved	mg l^{-1}	≤ 300	≤ 500	≤ 800	≤ 1200	> 1200
BOD_5	mg O_2 l^{-1}	< 2	< 3	< 6	< 12	> 12

Source: Regulation of the Minister of the Environment, modified data

The degree of anthropogenic transformation was determined by scoring the naturalness of the river channel, coastal zone and river valley zone based on: the degree of river channel adjustment, the presence of barriers, the development of the river basin, the shape of the coastal zone, the presence of vegetation, according to Ilnicki & Lewandowski (1997) parameters.

Benthic macroinvertebrates were collected twice in Spring, during the period of the highest taxonomic diversity. Tubular (L1, ŻB) and Surber (other sites) samplers were used. On each site 15 tubular or 3 Surber samplers were taken. The organisms were marked to the level of genus, and their density was expressed on 1 m^2 of bottom surface. The fish were caught twice, in Autumn, by the electro-fishing to ford up a watercourse over a distance of 150-200 meters. An IUP12 type backpack generator set was used. The collected fish species were ranked according to ecological reproductive groups, according to the division proposed by Balon (1990). The density was calculated per 100 m^2 of the bottom surface. After the measurements were completed, all fish were released into the river at the place of catch. In order to assess biodiversity, the Shannon-Wiener species diversity index was selected. Biocenotic indices of dominance in abundance and stability of occurrence were also used. For benthic organisms, the $ASPT_B$ (Average Score Per Taxa), EPT (Ephemeroptera, Plecoptera, Trichoptera) indices and the share of stenotype taxa (S) were also calculated. For ichthyofauna, the $ASPT_F$ (Average Score Per Taxa) indices and the ratio of eurytopic to rheophilic species (E/R) were calculated. Indexes used in national monitoring were also calculated when assessing the ecological status of rivers - the European Fish Index (Adamczyk et al. 2013) and the Polish Multi-Metrics Index MMI_PL based on the benthic macroinvertebrates assemblages (Bis & Mikulec 2013). Both indicators are based on a probabilistic model, referring the current state of fauna to the reference state. Thus, they reflect the degree of change resulting from anthropopressure. The calculations were made in the XLSSTAT 2016 and SAS Enterprise Guide 4.3 programs. Relationships between environmental parameters and assemblage diversity were estimated using Spearman rank correlations. The paper contains only statistically significant correlations, where "R" is the correlation coefficient, while "p" the significance of the correlated variables. Species similarity between assemblages at individual survey sites was depicted using dendrograms, performing cluster analysis using the complete linkage method based on the Jaccard formula (Czachorowski 2004).

4. Results

4.1. Environmental conditions

The largest diversity of habitats and the lowest degree of anthropopression was found in the middle – L4, L5 and downstream current Lutynia, on section L8

(Table 5). These sites were characterized by a significant diversity in the structure of the river channel – the coefficient of depth variation in the flow exceeded 60%. High morph-dynamic activity of the watercourse was found here, including the meandering the river channel and the occurrence of numerous riffle-pool sequences. On sections L4 and L5 no damming devices were noted, while on the lowest section L8 there are two gabion buildings, and the river banks are partially profiled.

According to the ecomorphological valorization of watercourses, sections L4, L5 and L8 were placed in II and III category of the degree of naturalness, respectively, which means that they are slightly transformed by humans (Table 5). They belong to the semi-natural section.

Table 5. Anthropopression and environmental conditions in the studied rivers

	L1	L2	L3	L4	L5	L6	L7	L8	ŻB	LB
Barriers	II	III	III	I	I	III	IV	III	III	II
Hydromorphological parameters	III	III	IV	II	II	IV	III	III	III	III
Physicochemical parameters	III	IV	IV	II	II	IV	IV	III	III	IV
Anthropogenic modification	IV	IV	IV	II	II	IV	IV	III	IV	IV

The river valleys of these sections are relatively intact and well preserved, and the shore zone is dominated by forests and rush vegetation, with many species of grass and ruderal flora. In terms of river channel hydromorphology, the best-looking forest sections are L4 and L5 (II class), which are characterized by a significant depth variation and the presence of shelters. The best thermal-oxygen conditions were also observed on these sections. More pressure and less hydromorphological diversity were found in the headwater of Lutynia – L1, L2, L3, as well as in downriver – L6, L7 and tributaries – ŻB, LB (Table 5). The aforementioned group of sections was classified into the IV category of naturalness. These are anthropogenically modified river stretches, which are characterized by low landscape attractiveness and low depth variation – up to 48% for ŻB. Relatively narrow river valleys are dominated by agricultural areas, and the width of the coastal zone does not exceed 10 meters. The hydromorphological parameters of the river channel were between class III and IV, and the final low assessment of physicochemical indicators was primarily due to low oxygen content.

4.2. Species structure of zoobenthos

There were 24 families of benthic macroinvertebrate in the Lutynia River system. Chironomidae (Diptera), Sphaeriidae (Bivalvia) and Tubificidae (Oligochaeta) had the highest stability of occurrence as well as the highest values of the dominance index in abundance (Table 6). The highest density (2274 sp./m^2) was recorded at section L8. In turn, the largest number of families (12) took place at L4 section.

Table 6. Benthic macroinvertebrates in the Lutynia River system

Family	Index		Research section D [%]									
	D [%]	C [%]	L1	L2	L3	L4	L5	L6	L7	L8	ŻB	LB
Bithynidae	0.5	20	-	-	1	-	-	-	-	-	6	-
Lymnaeidae	1.0	40	11	-	-	-	-	-	-	1	4	2
Planorbidae	1.0	40	4	-	-	-	-	-	4	-	4	1
Sphaeriidae[1]	14	70	16	19	2	-	-	-	16	1	38	74
Unionidae	0.5	10	-	-	-	-	-	-	-	1	-	-
Lumbriculidae[1]	3.0	40	21	23	2	-	-	-	8	-	-	-
Naididae	2.5	20	-	-	-	1	1	-	-	-	-	-
Tubificidae[1]	17	70	-	-	38	9	19	33	60	20	19	-
Erpobdellidae	1.5	40	5	-	3	1	-	-	-	-	7	-
Asellidae[1]	2.0	60	6	8	1	-	-	18	7	-	-	7
Gammaridae	14	50	5	-	-	12	17	-	-	62	-	10
Baetidae[2]	1.5	30	-	-	-	5	6	3	-	-	-	-
Coenagrionidae[2]	0.2	10	-	-	-	-	-	-	-	-	-	2
Mesoveliidae	0.2	10	-	3	-	-	-	-	-	-	-	-
Sialidae	0.5	10	15	-	-	-	-	-	-	-	-	-
Nepidae	0.3	20	-	-	-	-	-	-	-	1	1	-
Glossosomatidae[2]	0.5	20	-	-	-	2	3	-	-	-	-	-
Hydropsychidae[2]	1.0	30	-	-	1	29	7	11	-	-	-	-
Leptoceridae[2]	1.5	20	-	-	-	1	-	-	-	-	-	-
Limnephilidae[2]	0.5	10	-	5	-	4	-	-	5	-	-	-
Polycentropodidae[2]	2.6	20	-	-	-	10	9	-	-	-	-	-
Gyrinidae	0.5	10	-	-	-	1	-	-	-	-	-	-
Chironomidae[1]	33	90	17	42	52	24	35	35	-	14	21	4
Limoniidae	0.7	20	-	-	-	1	3	-	-	-	-	-
Total 24 family			**9**	**6**	**8**	**13**	**9**	**5**	**6**	**7**	**8**	**7**
ASPT$_B$			**3.4**	**4.0**	**3.5**	**5.4**	**5.6**	**3.8**	**3.7**	**4.3**	**4.0**	**4.1**
EPT			**0.0**	**1.0**	**1.0**	**5.0**	**3.0**	**2.0**	**1.0**	**0.0**	**0.0**	**0.0**
H			**0.9**	**0.6**	**0.5**	**0.8**	**0.7**	**0.6**	**0.6**	**0.5**	**0.8**	**0.4**
S [%]			**0.0**	**5.0**	**1.0**	**51**	**25**	**14**	**5.0**	**0.0**	**0.0**	**0.0**
MMI/class			**0.2 V**	**0.2 V**	**0.1 V**	**0.6 III**	**0.5 III**	**0.2 V**	**0.2 V**	**0.2 V**	**0.0 V**	**0.1 V**
Density (ind.* m^{-2})			**452**	**861**	**1319**	**982**	**781**	**1727**	**500**	**2274**	**931**	**1501**

Explanations: D - Structure of dominance, C - stability of occurrence ASPT$_B$ – Average Score Per Taxa index, EPT- Ephemeroptera, Plecoptera, Trichoptera index,
H – Shannon-Wiener index, S(%) – share of stenotype taxa, MMI – Multimetric Macroinvertebrate Index, **Bolded[1] – eurytopic taxa, Bolded[2] – stenotypic taxa**

Oligochaeta (*Lumbriculus sp.*, *Tubifex sp.*), Chironomidae (*Chironomus plumosus*) and Sphaeriidae (*Pisidium sp.*) dominated most of the surveyed sites, only on sections L4 and L8 Hydropsychidae and Gammaridae, respectively (Table 6). The share of organisms from the EPT group (Ephemeroptera, Plecoptera, Trichoptera), with the exception of L4 and L5 sites, was limited to only one taxon at the site (L2, L3, L6) or none at all (L1, L7, ŻB, LB). The highest share of stenotype taxa, as well as the highest values of the $ASPT_B$ index, were recorded on sections L4 and L5, the lowest on L1, L3, ŻB and LB.

Species diversity is different from other indicators. The highest diversity values were found on the anthropogenically modified section L1 as well as on the more natural section close L4. The MMI macroinvertebrate multimeter was the highest in sections L4 and L5 – class III (Table 6).

The largest taxonomic similarity is found in the L4 and L5 sites, i.e. the middle, forest course of Lutynia (Fig.2). The families of Beatidae (Ephemeroptera), Glossosomatidae, and Polycentropodidae (Trichoptera) were only found here. Other cluster groups are pairs L1 and LB, L2 and L7 as well as L3 and L6. The L1 and LB positions had 6 common taxa, including the Sphaeriidae, Asellidae and Gammaridae families. At two sites with the highest pressure (L3 and L6) 5 common taxa were recorded, including the dominant species *Chironomus plumosus* and *Tubifex tubifex*.

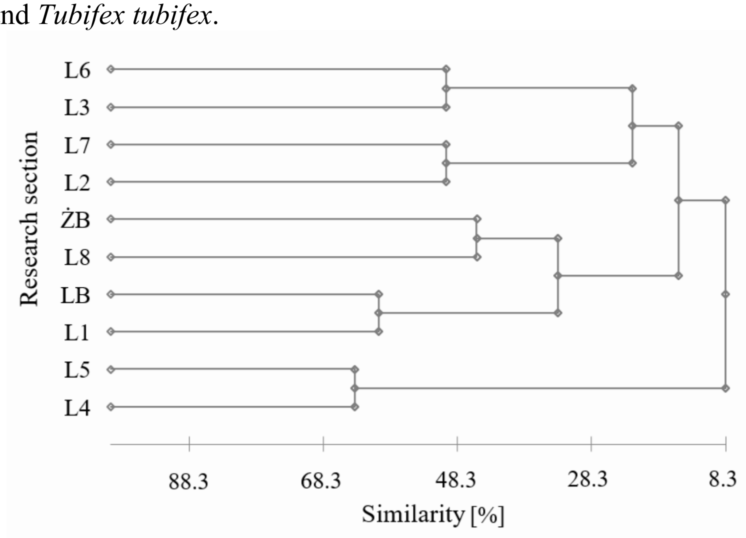

Fig. 2. Agglomerative hierarchical clustering by Jaccard coefficient for zoobenthos

Statistically significant correlations were noted between biological indexes and individual parameters describing the pressure on the river (Table 7). The $ASPT_B$ index was highly significantly correlated with almost all parameters, except temperature and conductivity. The strongest compounds are found in dissolved matter content ($R = -0.891$, $p < 0.01$), oxygen content ($R = 0.867$, $p < 0.01$) and bottom substrate ($R = 0.812$, $p < 0.01$). The EPT index was strongly correlated only with the number of shelters available ($R = 0.926$, $p < 0.01$ and the type of bottom substrate ($R = 0.752$, $p < 0.02$). Species diversity was significantly influenced by the five parameters tested, of which the conductivity was the most correlated ($R = 0.818$, $p < 0.01$) and oxygen content ($R = 0.771$, $p < 0.01$). Invertebrate multimeter which includes, among others, ASPT, EPT and Shannon-Wiener species diversity, significantly correlates with the availability of shelters ($R = 0.871$, $p < 0.01$), but also depth variations, flow and bottom substrate strongly influence this index.

Table 7. Correlations of biotic indexes with environmental conditions – zoobenthos

	Barriers	Depth CV	Natural elements	Flow	Shelters	Bottom substrate	Temperature	Oxygen	Conductivity	Dissolved matter
$ASPT_B$	**-0.789**	**0.768**	**0.752**	**0.766**	**0.792**	**0.812**	-0.15	**0.867**	-0.085	**-0.891**
	0.007	**0.009**	**0.012**	**0.009**	**0.006**	**0.004**	0.681	**0.001**	0.815	**0.0005**
EPT	-0.397	0.261	0.283	0.342	**0.826**	**0.752**	-0.39	0.006	-0.215	-0.095
	0.25	0.466	0.427	0.332	**0.003**	**0.012**	0.261	0.986	0.550	0.794
H	**-0.630**	0.062	0.265	0.276	0.046	0.067	**-0.68**	**0.771**	**-0.818**	**-0.638**
	0.041	0.864	0.459	0.44	0.899	0.853	**0.029**	**0.009**	**0.004**	**0.047**
MMI	-0.406	**0.611**	0.201	**0.743**	**0.871**	**0.631**	-0.15	0.207	-0.243	-0.480
	0.24	**0.041**	0.577	**0.014**	**0.001**	**0.04**	0.662	0.567	0.498	0.160

Explanations: **bold font** was used for statistically significant correlations ($p < 0.05$)

4.3. Species structure of fish

The ichthyofauna of Lutynia and its tributaries was represented by 19 species (Table 8). The gudgeon (*Gobio gobio*), which was found in all positions (C = 100%), was the numerically dominant species, while the share of other species did not exceed 10%. The highest species richness was recorded at L7 and L8 sites – 12 and 10 species of fish, respectively, while the highest density was found at L8 and L4 sites.

The most ecologically demanding lithophilic fish occurred almost exclusively at L4 and L5 sites in the middle course of the river. Single asp (*Aspius aspius*) fry were caught in the downstream section (L8). Protected species were represented by a spined loach (*Cobitis taenia)* and a bitterling (*Rhodeus sericeus amarus)*, found in the lower part of Lutynia and the stone loach found in both main watercourse and tributaries. Alien species, including the Prussian carp (*Carassius gibelio)* and topmouth gudgeon (*Pseudorasbora parva)*, appeared on heavily modified sections of Lutynia and Lubianka.

The structure of dominance in terms of abundance, $ASPT_F$ indexes, H species diversity, E/R ratio and EFI+ value are presented in Table 8. In seven positions, the dominant was a gudgeon or stickleback (*Gasterosteus aculeatus)*. Only the L8 position was dominated by a dace – 40%, while the LB topmouth gudgeon – 50%. The positions in the lower reaches of the L7 and L8 were characterized by the largest species diversity – the Shannon-Wiener index exceeded 0.70. The smallest species diversity of ichthyofauna was found at L2 (D = 0.37) and L3 (H = 0.25). The $ASPT_F$ index reached the highest values at L4 and L5 stations, the lowest on L6 sections and in the LB inflow. The E/R index looks similar. As far as EFI+ values are concerned, the index reached the highest values in positions L4, L8 and L5 – II class. In other positions, it adopted class III or IV, respectively.

The similarities in the species structure between the sites are presented by means of cluster analysis in Figure 3. Sites L1 and L3 as well as L2 and ŻB had the same species structure (100%). The similarity between the two groups located in the upper reaches was 65%. The psammophilic species observed in these stretches – gobies, stone loaches and sticklebacks. L4 and L5 grouped in another cluster. They have 88% identical species composition. The middle course of Lutynia was characterized by the occurrence of lithophils, namely brown trout (*Salmo trutta* m. *fario*) and barbell (*Barbus barbus)* not found in other sites. Another cluster formed the lower reaches of Lutynia – L7, L8, with a 58% of similarity in species.

As already mentioned, the greatest species richness was observed here (Table 8). Common species for both sites are chub (*Leuciscus cephalus)*, dace (*Leuciscus leuciscus)* and spined loach, while asp and bitterling were also caught at L8. The Lubianka inflet (LB) was characterized by a significantly different species composition compared to the other sites, and two out of four caught species were alien: the Prussian carp and topmouth gudgeon.

Table 8. Ichthyofauna of the Lutynia (L1-L8) and its tributaries Żybura (ŻB) and Lubianka (LB)

Ecological guilds	Scientific name		D [%]	C [%]	L1	L2	L3	L4	L5	L6	L7	L8	ŻB	LB
Lithophilic	**Chub**	***Leuciscus cephalus* (L.)**	6.2	50	—	—	—	4	4	11	9	10	—	—
	Asp	***Aspius aspius* (L.)**	0.2	10	—	—	—	—	—	—	—	1	—	—
	Barbel	***Barbus barbus* (L.)**	0.9	20	—	—	—	4	3	—	—	—	—	—
Phytolitophilic	**Roach**	***Rutilus rutilus* (L.)**	4.3	50	—	—	—	2	2	14	15	4	—	—
	Dace	*Leuciscus leuciscus* (L.)	20.3	40	—	—	—	7	4	—	26	40	—	—
	Ide	*Leuciscus idus* (L.)	0.3	20	—	—	—	—	—	—	1	1	—	—
	Bleak	*Alburnus alburnus* (L.)	7.5	20	—	—	—	—	—	—	5	17	—	—
	Bream	***Abramis brama* (L.)**	0.1	10	—	—	—	—	—	—	1	—	—	—
	Perch	***Perca fluviatilis* (L.)**	0.3	30	—	—	—	—	—	3	1	—	—	13
	Topmouth gudgeon	***Pseudorasbora parva* (Schl.)**	1.6	30	—	—	—	—	—	20	5	—	—	50
Phytophylic	Rudd	*Scardinius erythrophthalmus* (L.)	0.1	10	—	—	—	—	—	—	1	—	—	—
	White bream	***Blicca bjoerkna* (L.)**	2	20	—	—	—	—	—	—	2	4	—	—
	Prussian carp	***Carassius gibelio* (Bloch)**	0.1	20	—	—	—	—	—	6	—	—	—	6
	Spined loach	*Cobitis taenia* (L.)	2.6	20	—	—	—	—	—	—	1	6	—	—
Psammophilic	Gudgeon	*Gobio gobio* (L.)	40.9	100	44	78	73	58	59	29	33	15	75	31
	Stone loach	*Barbatula barbatula* (L.)	2.4	50	—	11	—	3	8	17	—	—	12	—
Lithophilic	**Brown trout**	***Salmo trutta m. fario* (L.)**	8	20	—	—	—	22	15	—	—	—	—	—
Ostracophilic	Bitterling	*Rhodeus sericeus amarus* (Bloch)	0.5	10	—	—	—	—	—	—	—	2	—	—
Ariadnophilic	Stickleback	*Gasterosteus aculeatus* (L.)	1.6	50	56	11	27	—	5	—	—	—	13	—
Total species					**2**	**3**	**2**	**7**	**8**	**7**	**12**	**10**	**3**	**4**
$ASPT_F$					**3.0**	**4.0**	**3.0**	**5.6**	**5.1**	**2.3**	**3.3**	**4.0**	**3.0**	**2.3**
S [%]					**0**	**0**	**0**	**30**	**22**	**11**	**10**	**11**	**0**	**0**
H					**0.3**	**0.3**	**0.3**	**0.6**	**0.6**	**0.5**	**0.8**	**0.8**	**0.3**	**0.5**
EFI+/class					**0.42 IV**	**0.43 IV**	**0.38 IV**	**0.83 II**	**0.78 II**	**0.49 III**	**0.65 III**	**0.82 II**	**0.38 IV**	**0.21 V**
Density (ind.*100 m^2)					**2**	**7**	**6**	**30**	**19**	**4**	**21**	**45**	**10**	**20**

Explanations: $ASPT_F$ – Average Score Per Taxa index, S – share of stenotypic (lithophilic) species, H – Shannon-Wiener index, EFI(+) – European Fish Index, **Bolded – stenotypic species, Bolded – eurytopic species, Bolded – alien, invasive species**

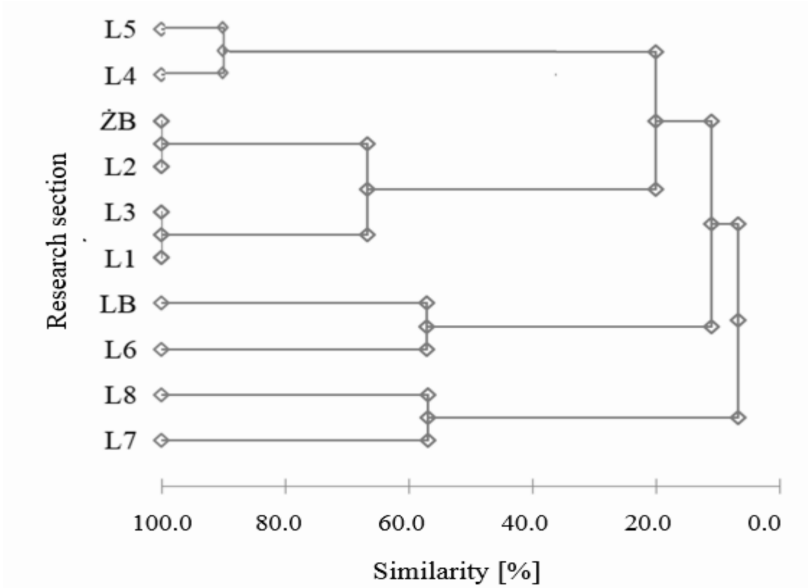

Fig. 3. Agglomerative hierarchical clustering by Jaccard coefficient for ichthyofauna

The results of the Spearman correlation analysis between the indices describing the state of ichthyofauna and the environmental parameters describing the pressures are presented in Table 9. The $ASPT_F$ index was significantly correlated with almost all environmental parameters reflecting the pressures. The analysis shows that the index has the greatest impact on the oxygen content ($R = 0.906$, $p < 0.001$), conductivity ($R = -0.863$, $p < 0.01$) and the presence of barriers ($R = -0.839$, $p < 0.01$). The correlations of the S index look similar, but the relationships are not that strong. Species diversity is significantly related to depth ($R = 0.676$, $p < 0.05$) and flow ($R = 0.669$, $p < 0.05$), number of shelters ($R = 0.662$, $p < 0.05$) and the type of bottom substrate ($R = -0.674$, $p < 0.05$). Attention is drawn to the negative, recent correlation, which shows that the high proportion of gravel in the bottom substrate negatively affects the species diversity. The most advanced EFI+ index significantly correlates with depth variation ($R = 0.875$, $p < 0.01$) and flow ($R = 0.944$, $p < 0.001$).

Table 9. Correlations of biotic indexes with environmental conditions – ichthyofauna

	Barriers	Depth CV	Flow	Shelters	Bottom substrate	Temperature	Oxygen	Conductivity	Dissolved matter
N. spec.	0.169	**0.615**	**0.612**	**0.694**	0.480	0.453	0.306	0.324	-0.073
	0.639	**0.048**	**0.049**	**0.026**	0.160	0.189	0.390	0.361	0.840
$ASPT_F$	**-0.839**	**0.741**	**0.859**	**0.725**	**0.592**	**-0.735**	**0.906**	**-0.863**	**-0.802**
	0.002	**0.015**	**0.001**	**0.018**	**0.051**	**0.015**	**0.0003**	**0.001**	**0.005**
E/R	**0.703**	**-0.625**	**-0.659**	-0.321	**-0.749**	**0.732**	**-0.745**	**0.788**	**0.615**
	0.023	**0.043**	**0.038**	0.366	**0.012**	**0.016**	**0.0135**	**0.007**	**0.048**
H	0.038	**0.676**	**0.669**	**0.662**	**-0.674**	0.409	-0.116	0.237	-0.262
	0.917	**0.032**	**0.034**	**0.037**	**0.032**	0.241	0.749	0.508	0.464
EFI+	-0.336	**0.875**	**0.944**	0.507	0.561	-0.151	0.467	-0.454	-0.551
	0.342	**0.001**	**<0.001**	0.135	0.091	0.676	0.174	0.186	0.098

Explanations: **bold font** was used for statistically significant correlations ($p < 0.05$)

5. Discussion

The results presented in the work testify to the strong reaction of the studied assemblages to anthropogenic watercourse transformations. The strong correlation between anthropopression (expressed by the indicator of naturalness) and the diversity of microhabitats, which in turn is reflected by the structure of zoobenthos and ichthyofauna. On the untransformed river stretches, the multi-structured shape of the river channel, the presence of boulders and limbs of trees, spawn optimal living conditions for fish and invertebrates as stated by relevant literature (Branco et al. 2014, Pander & Geist 2016, Thompson et al. 2017, Wolter et al. 2013). Most of the river stretches were dominated by eurytopic benthic taxa (Oligochaeta, Chironomidae, Sphaeriidae) while the most exigent taxa were rare or absent due to the synergistic impact of three pressures, out of which the most important appeared to be river channel modification and pollution. Confirming the causal relationship between environmental quality and macrobenthos composition, stenotypic taxa are present with significantly greater frequency and abundance in the two river sections with little or no impact that cross the forest. According to Liu et al. (2016) and Wolter et al. (2013) the dominance of Oligochaeta and Diptera along with the reduction or elimination of other taxa is evidence of watercourse degradation. As can be logically expected, this study also confirmed that macro-invertebrate diversity is correlated negatively with temperature and positively with oxygen. The decisive role of thermal regime and oxygenation in shaping aquatic biocenoses is also emphasized by (Bis et al. 2013, Krepski et al. 2018, Łaszewski et al. 2016). Since the presence shore vegetation and the covering the river channel with tree crowns is a determinant factor that influences temperature of the watercourses (Broadmeadow et. al. 2011, Kalny et al. 2017) the most natural river stretches crossing the forested areas also provided the most favorable conditions for macro-invertebrate assemblages. This further confirms the important role played by the riparian areas that provide both a mitigation of temperature variation and a source of organic matter, from large woody debris which is a component of habitat diversification, to the smallest organic particulate that is an important food supply for aquatic invertebrates (Thompson et al. 2017).

The ichthyofauna was dominated by the gudgeon, and in the most-changed sections almost exclusively this species was found, with only a small contribution of the stickelback and stone loach. This corresponds to the results of Witkowski et al. (2007) who noted the dominance of the gudgeon in all sub-basins of the Oder, in particular those degraded anthropogenically. According to many authors, the occurrence of only a few psammophilic species is a phenomenon typical of small rivers, organically polluted (Marszał et al. 2014, Mueller et al. 2020, Penczak et al. 1991, Prus et al. 2016).

Brown trout and barbell only occurred at two forest sites with minimal pressure. Both taxa belong to the group particularly susceptible to negative changes resulting from anthropopressure (Marszał et al. 2014, Przybylski et al. 2020) and their presence positively indicates the ecological status of the watercourse (Admaczyk et al. 2013, Prus et al. 2016, Rechulicz & Płaska 2016). Forested watercourse sections are least exposed to pressure, and the presence of the riparian zone has also a positive effect on ichthyofauna (Broadmeadow et al. 2011, Four et al. 2017, Prus et al. 2018).

The highest number of fish species was found in estuaries, of which only one (L8) has a relatively high degree of naturalness. The high number of species in the heavily impacted section L7 is not surprising, since mainly eurytopic or stagnophilic species, including one alien species, were present. The occurrence of rheophiles, such as chub, ide and dace, as well as a protected spined loach, can be explained by the location of the section a few kilometers from the mouth of the river (near Warta), from which, despite the presence of two gabion buildings, they migrate up Lutynia. The general tendency, repeatedly emphasized in the literature, confirms that along with the size of the watercourse and the distance from the sources, the quantity and diversity of species increases (Broadmeadow et al. 2011, Four et al. 2017, Prus et al. 2018).

The significant correlation between species composition and environmental conditions shows that fish assemblages react very clearly to all kinds of pressure, that act contemporarily making difficult to disentangle the relative importance. Only species diversity appears to be strongly correlated only with hydromorphological transformations. According to the authors, the Sh-W index in some cases does not reflect the actual state of ichthyofauna. This is especially true for small gravel streams, in which several (2-4) species are often found, but they are fish with high environmental requirements. The above thesis can be confirmed by the example of sections L4 and L5.

Alien species – Prussian carp and topmouth gudgeon were caught in the sites under pressure, with the second species appearing in significant densities just on one sampling date. The presence of these taxa is associated with carp and grass carp farming fish in nearby ponds fed with river water and with transformations of watercourses favoring tolerant over exigent species. These species are a threat to native ichthyocoenoses, because they have broad ecological tolerance and can compete for microhabitats and food resources, and Prussian carp reduces the spawning efficiency of common crucian carp (*Carassius carassius*) through gynogenesis (Kirankaya & Ekmekci 2013, Jakubčinová et al. 2013, Simonović et al. 2017, Szumiec et al. 2006, Witkowski & Grabowska 2012).

Alien species that get into the fish farming ponds along with young fish, are then easily introduced into the connected rivers (Witkowski & Grabowska 2012, Záhorská et al. 2013). In addition, fish ponds negatively affect the ecological state of the receiving rivers through post-production water discharges (Four et al. 2017, Francová et al. 2019, Hlavac et al. 2014, Szumiec et al. 2006).

The ASPT index calculated for both biotic assemblages indicates a strong response to most of the tested parameters and reflects well all types of disturbances. Similar results for invertebrates can be found in the publication of Bis & Mikulec 2013, however, no attempt has been made to apply this indicator to ichthyofauna so far.

Comparing the results of our own study with general, accessible data from Kołaczkowski & Kniat (1959) and archival results of physicochemical analyzes conducted by VIEP in Poznań, we can notice a progressive improvement of the ecological condition of the middle and down current of Lutynia. Reduction of impacting activities in the river surroundings and of pollution loads prompted a gradual recovery of habitat conditions, as well as a slow increase in the number of species.

6. Conclusions

- The watercourses studied, despite the observed improvement in water quality, are still subject to strong anthropopressure, which is manifested mainly by modifications of the river bed reducing the diversity of microhabitats, continuity disturbances limiting the possibility of organism migration and organic pollutants deteriorating oxygen conditions.
- The level of pressure on individual sections is varied, and this is reflected in the differences in the composition and structure of the groups studied. The sections least transformed in terms of continuity and hydromorphology are also characterized by the highest water quality. In these sections, an increase in species diversity and the presence of indicator species with higher requirements were noted.
- The presence of the wide, well developed riparian zone is one of the most important factors determining the high diversity in the river biocenoses.
- Alien fish species are found mainly in transformed environments. The presence of all three disturbances is conducive to the occurrence and even the dominance of alien species.
- Macroinvertebrates and fish assemblages are responding slightly differently to each single impact source. For macroinvertebrates, the value of biological indexes depends on maintaining continuity; diversification of flow, depth and bottom substrate; the presence of hiding places; oxygen content and dissolved organic matter. Fish respond to all types of pressure, but the diversity of microhabitats and the water quality expressed in oxygen are particularly important.
- Zoobenthos and fish are very good, universal bioindicators and both groups should be used together providing a complimentary view on large and small scale impacts.
- The thesis about a different reaction of communities to pressures has been confirmed, but it is difficult to link a specific group of organisms with the scale of the pressure impact.
- The analyses show that ASPT is the most reliable among the biological indices used, for both benthos and fish.

References

Adamczyk, M., Prus, P,. Wiśniewolski, W. (2013). Possibilities of applying the European fish index (EFI+) to assess the ecological status of rivers in Poland. *Scientific Annual of the Polish Angling Association*, *26*, 21-51, (in Polish with English summary).

Allan, D. J. (1998). *Stream Ecology: Structure and Function of Running Waters*. Warszawa: Polish Scientific Publishers PWN (in Polish).

Balon, E.K. (1990). Epigenesis of an epigeneticist: the development of some alternative consepts on the early ontogeny and evolution of fishes. *Guelph Ichthyology Reviews*, *1*, 1-42.

Bis, B., Mikulec, A. (2013). *The ecological status assessment of river ecosystems, based on the benthic macroinvertebrate assemblages*. Warszawa: Biblioteka Monitoringu Środowiska (in Polish).

Błachuta, J., Rosa, M., Wiśniewolski, W., Zgrabczyński, J. (red). (2010). *Assessment of needs and priorities for improving the morphological continuity of rivers in the context of achieving good status and potential of water in Poland*. KZGW, Warszawa (in Polish).

Branco, P., Segurado, P., Santos, J.M., Ferreira, M.T., Strecker, A. (2014). Prioritizing barrier removal to improve functional connectivity of rivers. *J. Appl. Ecol*., *51*, 1197-1206.

Broadmeadow, S.B., Jones, J.G., Langford, T.E.L., Shaw, P.J., Nisbet, T.R. (2011). The influence of riparian shade on lowland stream water temperatures in southern England and their viability for brown trout. *River Research and Applications*, *27*, 226-23.

Brylińska, M. (2000). *Freshwater fish of Poland*. Warszawa: Polish Scientific Publishers PWN (in Polish).

Czachorowski, S. (2004). *Describing biocenosis – zoocenology, electronic script for graduate students*. Typescript available in PDF format at www.uwm.edu.pl/czachor?publik/pdf inne/zoocenozy.pdf. 58 (in Polish).

Czerniawska-Kusza, I. (2001). Changes in benthic fauna assemblages in the lower course of the Nysa Kłodzka under the influence of anthropogenic abiotic factors. *Nature Journal*, *35*, 72-82.

Dajewski, K. (2016). *Assessment of the anthropopressure impact on the fish and zoobenthos species structure in the Lutynia River system*. Manuscript. Master's thesis. Poznan University of Life Sciences (in Polish with English summary).

Four, B., Arcel, E., Danger, M., Gaillard, J., Thomas, M., Banas, D. (2017). Catchment land use-dependent effects of barrage fishponds on the functioning of headwater streams. *Environmental Science and Pollution Research*, *24*, 5452-5468.

Francová, K., Šumberová, K., Janauer, G.A., Adámek, Z. (2019). Effects of fish farming on macrophytes in temperate carp ponds. *Aquaculture International*, *27*, 413-436.

Golski, J., Przybył, A., Mazurkiewicz, J., Andrzejewski, W., Trawinski, J. (2010). Habitat variability and fish species structure in Konczak stream. *Oceanological and Hydrobiological Studies*, *9*, 83-98.

Golski, J., Andrzejewski, W., Mazurkiewicz, J., Przybył, A., Grupa, D., Kucharczyk, M., Przybylska, K. (2013). *Occurrence of brown trout (Salmo trutta m. Fario L.) and white-finned bullhead (Cottus gobio L.) in rivers of Wielkopolska against the background of environmental conditions*. Conference materials. Nature protection in Poland in the face of contemporary civilization challenges. Krakow 24-25.10.2013.

Golski, J., Graczyk, L., Mazurkiewicz, J., Andrzejewski, W., Sierpowska, K. (2015). *The Gammarus : Asellus ratio as indicator of ecological state of running waters – preliminary results*. Conference Materials. XXIII Zjazd Hydrobiologów Polskich. Koszalin 01-04.09.2015.

Graczyk, L. (2014). *Hydrobiological characteristics of the Czarna Woda River and its tributaries*. Manuscript. Master's thesis. Poznan University of Life Sciences (in Polish with English summary).

Hlavac, D., Adámek, Z., Hartman, P., Masilko, J.(2014). Effects of supplementary feeding in carp ponds on discharge water quality: a review. *Aquaculture Internationale*, *22*, 299-320.

Ilnicki, P., Lewandowski, P. (1997). *Eco-morphological valorization of waterways in Wielkopolska*. Poznań: Bogucki Wydawnictwo Naukowe, Poznań (in Polish).

Jakubčinová, K., Haruštiaková, D., Števove, B, Švolíková, K., Makovinská, J., Kováč, V. (2018). Distribution patterns and potential for further spread of three invasive fish species (*Neogobius melanostomus, Lepomis gibbosus and Pseudorasbora parva*) in Slovakia. *Aquatic Invasions*, *13*(4), 513-524.

Kalny, G., Laaha, G., Melcher, A., Trimmel, H., Weihs, P., Rauch, H.P. (2017). The influence of riparian vegetation shading on water temperature during low flow conditions in a medium sized river. *Knowledge and Management of Aquatic Ecosystems*, *418*, 5.

Kałuża, T., Radecki-Pawlik, A. (2014). Influence of coarse and fine plant debris on river channel hydrodynamics. *Acta Scientiarum Polonorum*, *13*, 67-80 (in Polish with English summary).

Kirankaya, S.G., Ekmekçi, F.G. (2013). Life-history traits of the invasive population of Prussian carp, Carassius gibelio (actinopterigi: cypriniformes: cyprinidae), from Gelingüllü reservoir, Yozgat, Turkey. *Acta Ichthyologica et Piscatoria*, *43*(1), 3.

Kołaczkowski, T., Kniat, J. (1959). *Lutynia River and its tributaries.* Warszawa: Wydawnictwo Arkady (in Polish).

Krepski, T., Czerniawski, R. (2018). Shaping of macroinvertebrate structures in a small fishless lowland stream exposed to anthropopressure, including the environmental conditions. *Knowledge and Management of Aquatic Ecosystems*, *419*, 19.

Kruk, A,, Ciepłucha, M., Zięba, G., Tybulczuk, SZ., Tszydel, M., Marszał, L., Błońska, D., Galicka, W., Przybylski, Z. (2016). Recovery of fish fauna in the upper Warta River, Poland: Long-term (1963-2012) monitoring study. *Ecological Informatics*, *33*, 109-118.

Liu S., Xie G., Wang L., Cottenie K., Liu D., Wang B. (2016). Different roles of environmental variables and spatial factors in structuring stream benthic diatom and macroinvertebrates in Yangtze River Delta, China. *Ecological Indicators,* 61, 602-611.

Łaszewski, M. (2016). Summer water temperature of lowland Mazovian rivers in the context of fisheries management. *Archives of Polish Fishe*ries, *24*, 3-13.

Marszał, L., Janic, B., Pietraszewski, D., Galicka, W. (2014). Comparison of ichthyofauna between the Flis stream and lowland streams of similar size. *Scientific Annual of the Polish Angling Association*, *27*, 185-203 (in Polish with English summary).

Mazurkiewicz-Boroń, G., Starmach, J. (2009). Ecological consequences of building water bars. *Chrońmy Przyrodę Ojczystą*, *65*(2), 83-92. Instytut Ochrony Przyrody PAN (in Polish with English summary).

Mueller, M., Bierschenk, A., M., Bierschenk, B. M., Pander, J., Geist, J. (2020). Effects of multiple stressors on the distribution of fish communities in 203 headwater streams of Rhine, Elbe and Danube. *Science of the Total Environment*, *703*, 10, 134523.

Pander, J., Geist, J. (2016). Can fish habitat restoration for rheophilic species in highly modified rivers be sustainable in the long run? *Ecological Engineering*, *88*, 28-38.

Penczak, T., Kruk, A., Grabowska, J., Śliwińska, A., Koszaliński, H., Zięba, G., Tybulczuk, Sz., Galicka, W., Marszał, L. (2010). Influence of gradual improvement in water quality on the regeneration of fish fauna in the Ner river. *Scientific Annual of the Polish Angling Association*, *23*, 97-117 (in Polish with English summary).

Penczak, T., Zaczyński, A., Koszaliński, H., Koszalińska, M., Ułańska, M. (1991). Ichthyofauna of the Narew river basin. Część IV. Lewobrzeżne dopływy Narwi, 4, 83-99 (in Polish with English summary).

Pietraszewski, D., Marszał, L., Zięba, G., Przybylski, M., Zieliński, P. (2008). Fish fauna of the Sanna river system. *Scientific Annual of the Polish Angling Association*, *21*, 129-146 (in Polish with English summary).

Prus, P., Wiśniewolski, W., Adamczyk, M (red.). (2016). *Methodological guide for fish fauna monitoring in rivers*. Warszawa: Biblioteka Monitoringu Środowiska (in Polish).

Prus, P., Popek, Z., Pawlaczyk, P. (2018). *Good practice of river maintenance*. Warszawa: World Wide Fund for Nature (in Polish).

Przybylski, M., Głowacki, Ł., Grabowska, J., Kaczkowski, Z., Kruk, A., Marszał, L., Zięba, G., Ziułkiewicz, M. (2020). *Riverine Fish Fauna in Poland*. In: Polish River Basins and Lakes – Part II. Biological Status and Water Management. Editors: Korzeniewska E., Harnisz M. The Handbook of Environmental Chemistry. Springer.

Pytka, A., Jóźwiakowski, K., Marzec, M., Gizińska, M., Sosnowska, B.(2013). Impact assessment of anthropogenic pollution on water quality of Bochotniczanka River. *Infrastructure and Ecology of Rural Areas*, *3*(II), 15-29 (in Polish with English summary).

Rechulicz, J., Płaska, W. (2016). Diversity of fish fauna in small rivers located in forested and non-forested areas. *Sylwan*, *160*(4), 344-352.

Simonović, P., Piria, M., Zuliani, T., Ilić, M., Marinković, N., Kračun-Kolarević, M., Paunović, M. (2017). Characterization of sections of the Sava River based on fish community structure. *Sci. Total Environ*., *574*, 264-271.

Starting materials for formulating the conditions for using the waters of the Warta basin from Prosna to Maskawa. (2015). Regionalny Zarząd Gospodarki Wodnej [RZGW] w Poznaniu, Poznań (in Polish).

Strahler, N. A. (1957). Quantitative analysis of watershed geomorphology. *Transactions of the American Geophysical Union*, *38*(6), 913-920.

Szumiec, M.A., Augustyn, D., Kolasa-Jamińska, B. (2006). Quality of waters discharged from fishponds during the fall Carp (*Cyprinus carpio* L.) harvest. *Archives of Polish Fisheries*, *14*(2), 257-270.

Thompson, M.S.A. Brooks, S.J., Sayer, C.D., Woodward, G., Axmacher, J.C., Perkins, D.M., Gray C. (2017). Large woody debris "rewilding" rapidly restores biodiversity in riverine food webs. *Journal of Applied Ecology*, *55*, 895-904.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*, *37*, 130-137.

Witkowski, A., Penczak, T., Kotusz, J., Przybylski, M., Kruk, A., Błachuta, J. (2007). Rheophilous cyprinid fishes of the Odra river basin. *Scientific Annual of the Polish Angling Association*, *20*, 5-33 (in Polish with English summary).

Witkowski, A., Grabowska, J.(2012). The non-indigenous freshwater fishes of Poland: Threats to the native ichthyofauna and consequences for the fishery: a review. *Acta Ichthyologica et Piscatoria*, *42*(2), 77-87.

Wolter, C. (2010). Functional vs scenic restoration – challenges to improve fish and fisheries in urban waters. *Fisheries Management and Ecology*, *17*, 176-185.

Wolter, C., Lorenz, S., Scheunig, S., Lehmann, N., Schomaker, C., Nastase, A., De Jalón, D. G., Marzin, A., Lorenz, A., Kraková, M., Brabec, K., Noble, R. (2013). Review on ecological response to hydromorphological degradation and restoration. *Restoring rivers FOR effective catchment Management*. Seventh Framework Programme. 1-119.

Wyżga, B., Kaczka, R., Zawiejska, J. (2012). Storage patterns of large woody debris in mountain watercourses of medium and large width. *Studies in Geography*, *50*, 159-169 (in Polish with English summary).

Záhorská, E., Balážová, M., Šúrová, M. (2013). Morphology, sexual dimorphism and size at maturation in topmouth gudgeon (*Pseudorasbora parva*) from the heated Lake Licheńskie (Poland). *Knowledge and Management of Aquatic Ecosystems*, *411*, 07.

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Calculation of Hydrodynamic Characteristics of Apparatus with Regular Tubular Packing

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Abstract: Among the apparatuses with a regular arrangement of packing elements creating an in-phase mode of vortex interaction, which ensures high efficiency of the processes, it is interesting to use a standard tubular packing. Such packing allows additional advantages associated with heat supply or extraction directly in the contact zone of the interacting phases, which is very important for conducting some chemisorption processes. The research covers such hydrodynamic regularities as hydraulic resistance during a heat carrier movement in pipes and during external flow around a tubular beam, retained liquid amount and gas content of layer in the external flow around the tubular beam with liquid and gas flows. The research was carried out using an experimental setup with a heat and mass transfer apparatus with regular tubular packing. The medium used during experiments is water-air. The research methodology included standard methods for determining hydraulic resistance and retained liquid amount and visual observation and photographing of gas-liquid flows. The novelty of the research was equations – one for calculating the hydraulic resistance in pipes, taking into account local resistances and pipe roughness. The other ones for determining the pressure losses during the external flow around the tubular beam, the retained liquid amount, and the gas content of the layer, taking into account the vortex interaction of gas and liquid flows. Graphical and calculated dependences of the investigated hydrodynamic characteristics were obtained as a result of the conducted research of the hydraulic resistance during the heat carrier movement in the pipes, as well as the hydraulic resistance and the retained liquid amount during the external flow around the tubular beam with a change in the gas velocity and irrigation density. When the heat carrier flows in the pipes, the numerical values of the hydraulic resistance in the transient mode do not exceed 1.5 kPa, in the developed turbulence mode in the range of the Reynolds number from $1\cdot10^4$ to $6\cdot10^4$ ΔP varies from 1.5 to 53 kPa. With the external flow around the tubular beam, in the developed turbulence mode w_g = 4 m/s and L = 25 m^3/m^2h, the hydraulic resistance is 85 Pa, the retained liquid amount is $4.5\cdot10^{-3}$ m. The change in the irrigation density in this mode (developed turbulence) in the L range from 10 to 100 m^3/m^2h leads to an increase in the hydraulic resistance from 65 to 160 Pa, the retained liquid amount from $2.16\cdot10^{-3}$ to $13.6\cdot10^{-3}$ m. The calculated dependencies are the basis of the method for calculating the hydrodynamic characteristics of the apparatus with the regular tubular packing, which can be used to calculate industrial devices.

Keywords: regular tubular packing, vortex interaction, local resistance, roughness, hydraulic resistance, retained liquid amount, gas content

1. Introduction

Packed apparatuses are widely used in chemical technology, petrochemistry, and oil refining during absorption, rectification, extraction, etc. (Lapteva 2019, Kagan et al. 2013). These apparatuses use stationary irregular and regular packing as contact elements (Laptev et al. 2017). Irregular packings (Raschig rings, Pall rings, Berl saddles, HY-PAK, CASCADE-RINGS, Inzhekhim packings) (Lapteva 2019, Laptev et al. 2017) increase hydraulic resistance, have relatively low efficiency, and are not able to work with contaminated gases and liquids. Regular packings (INTALOX, Sulzer, Koch, Inzhekhim, Norton, Vakupak, Glitch-Grid, Mellapak, MellapakPlus, Mellagrid, mesh packings BX and CY) contain channels of a regular structure. Therefore, they have slightly lower hydraulic resistance and higher performance indicators (Lapteva 2019). However, they are prone to overgrowth with solid deposits.

So there are many heat and mass exchangers with regular packing, the operation of which is based on the vortex interaction of gas and liquid flows (Einstein et al. 2002). Moreover, it is known that apparatuses with a regular arrangement of packing elements have proven themselves well in the absorption and dust collection processes in the production of phosphorus and chromium compounds due to low hydraulic resistance and relatively high efficiency (Volnenko 1999, Serikuly et al. 2020).

It is of interest to use regular tubular packing to carry out the heat transfer and the combined processes of heat transfer and mass transfer. Its functional area is a series of horizontal layers in height from regularly arranged pipes with fixed steps (distances) between the pipes in the vertical and radial directions.

The pipe mouth and orifice are equipped with collectors set on the outside of the body. The heat carrier overflows from the upper layer of the regularly arranged pipes through the collector bends. During operation, the spray from the irrigator does not mix with the heat carrier moving inside the pipes (Volnenko et al. 2013).

The use of tubular packing provides additional advantages associated with the heat supply or extraction directly in the interacting phases' contact zone, which is essential when carrying out some chemisorption processes.

The literature contains limited information on the research results of the hydrodynamic laws of regular tubular packing, which hinders the use of such apparatuses in industry.

The article presents research results on the main hydrodynamic characteristics of a liquid flow in the pipes and the external flow around the tubular beam in an apparatus with regular tubular packing. Also, to obtain the calculated dependences of the hydraulic resistance, the retained liquid amount, and the gas content of the layer for engineering calculations.

The research methodology includes standard methods for determining hydraulic resistance and retained liquid amount and visual observation and photographing of gas-liquid flows.

2. Experimental setup and research technique

An experimental setup was created to study the main hydrodynamic characteristics of the apparatus with regular tubular packing. Its technological diagram is shown in Fig. 1.

The airflow blown by fan 1 enters through the collecting tank into the apparatus column 10 (cross-section of 340x340 mm and a working area height of 1.3 m). Then, it passes through the tubular beam 8, rinsed with a liquid entering through the irrigator 7, and is released into the atmosphere. The airflow rate is regulated by gate 2 according to the readings of a standard diaphragm with a differential pressure gauge. The irrigation liquid from the lower container of apparatus 10 through the intermediate container 9 is supplied by pump 3 to pressure container 5, from which it is fed through the irrigator 7 for irrigation. The water flow rate is regulated by valve 6 according to the readings of a rotameter.

The technological scheme supplies the heat carrier to the pipe space in a closed circuit, including pump 3, the pressure container 5 with heater 4, and the tubular beam 8.

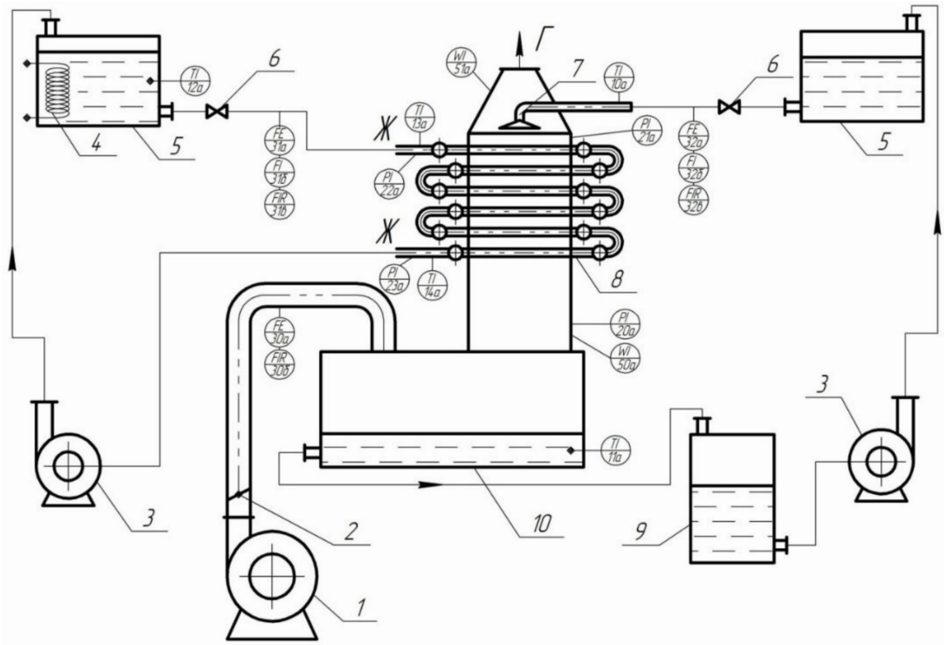

Fig. 1. Technological diagram of the experimental setup for determining the hydrodynamic characteristics of the apparatus with a tubular packing 1 – fan; 2 – gate; 3 – pump; 4 – heater; 5 – pressure container; 6 – valve; 7 – irrigator; 8 – tubular beam; 9 – intermediate container; 10 – apparatus with a tubular packing

Fig. 1 also shows the points where the gas flow rates, spray, heat carrier, pressure, temperature, and liquid level are measured.

The equipment used during studies is an apparatus with regular tubular packing (Fig. 2) (Volnenko et al. 2013), including an irrigated tubular beam, where the pipes are evenly spaced in vertical and radial directions with specific steps. In the vertical direction, a corridor arrangement of pipes is adopted. On the outer side of the apparatus body, the ends of the outgoing pipes are layer-by-layer connected to liquid collectors and a fitting for overflowing liquid to the downstream row. One of the collectors has a branch pipe for supplying liquid, and on the opposite side, a branch pipe for draining it.

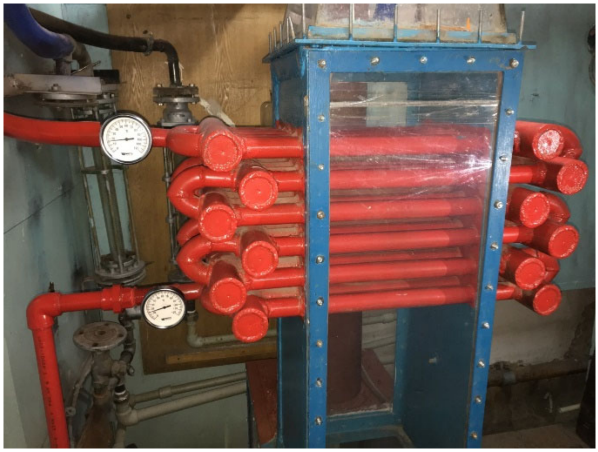

Fig. 2. The fragment of the working area of the apparatus with the regular tubular packing

The range of operating and design parameters of the hydraulic resistance and the retained liquid amount during the study on the external flow around the tubular beam is given below.

Operating parameters:

- gas velocity W_g – 1-5 m/s,
- irrigation density L – 10-75 $m^3/m^2 \cdot h$,
- air temperature t_{air} – 20-100°C.

Design parameters:

- step between the pipes in the vertical direction t_v/d – 2,
- step between the pipes in the radial direction t_r/d – 2,
- the pipe size: d = 0.025 m; ℓ = 0.34 m.

When the heat carrier flows in the pipes:

- liquid velocity w_l – 0.5-3.5 m/s (Re_l = 9000-70000),
- heat carrier temperature t_l – 16-100°C.

The hydraulic resistance of the apparatus *ΔP* was measured by a differential pressure gauge and controlled by a DSR-type device.

The retained liquid amount, referred to as the section of the column h_0, was determined by the "cut-off" method (Ramm 1976, Idelchik 1992). For this, the gate on the gas path and the valves on the irrigation liquid supply were simultaneously closed (Fig. 1). The retained liquid amount was determined using measuring containers.

3. The research results and calculated dependences

The research of the hydrodynamic characteristics was carried out for two cases. In the first case, the hydraulic resistance was determined during the heat carrier flow in the pipes. In the second case, the hydraulic resistance and the retained liquid amount were determined during the external flow of liquid and gas around the tubular beam.

For the first case, when the heat carrier flows in the pipes, hydraulic calculation of resistances determined by the pressure losses is complicated due to friction and local resistances.

Fig. 3 shows a graph of the dependence between tubular beam's hydraulic resistance ΔP and the Reynolds number Re_l.

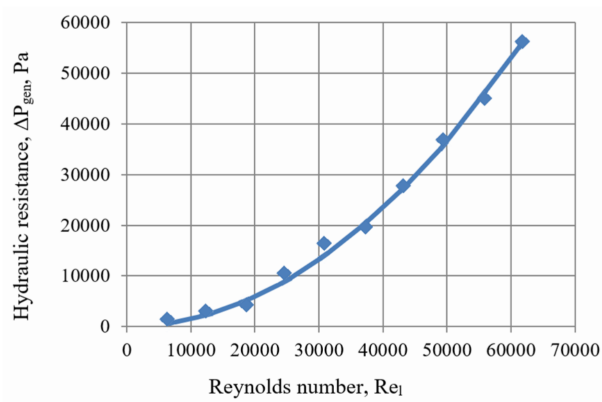

Fig. 3. The tubular beam's hydraulic resistance ΔP vs. the Reynolds number Re_l

The graph shows that liquid flows in the tubular beam in a transient mode ($2300 < Rel < 10000$) and a mode of developed turbulence ($Rel > 10000$). Within the whole range of Reynolds numbers, a steady increase in the hydraulic resistance is observed. Obviously, with an increase in the liquid flow velocity, the flow energy consumption for overcoming local resistance and friction resistance increases.

The total resistance of the pipe space is calculated based on the heat carrier movement pattern from the entry to the tubular beam to its exit. Fig. 4 shows the tubular beam and indicates the places of local resistance and friction resistance.

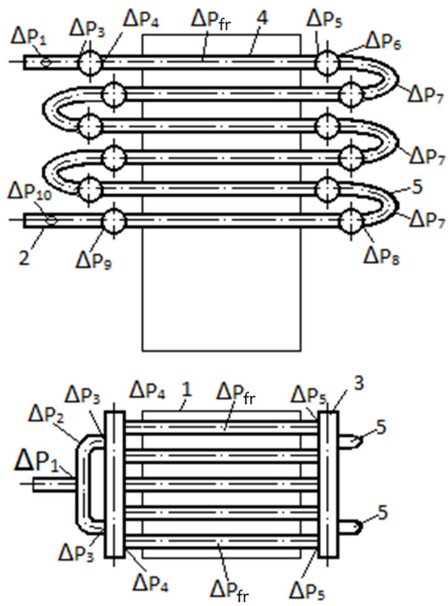

Fig. 4. Calculation of the hydraulic resistance of the tubular beam: 1 – body; 2 – tee; 3 – collector; 4 – pipes; 5 – branches; Δp_1 – pressure loss in the tee, Pa; Δp_2 – pressure loss in the elbow, Pa; Δp_3 – pressure loss at the split flow exit to the collector, Pa; Δp_4 – pressure loss at the flow exit from the collector to the beam pipes, Pa; Δp_{fr} – friction pressure loss in the heat exchanger pipes, Pa; Δp_5 – pressure loss at the flow entry from the pipes to the collector, Pa; Δp_6 – pressure loss at the flow exit from the collector to the branches, Pa; Δp_7 – pressure loss at the liquid movement along the branches, Pa; Δp_8 – pressure loss at the flow entry from the branches to the collector, Pa; Δp_9 – pressure loss at the flow entry from the collector to the tee pipes, Pa; Δp_{10} – pressure loss at the flow entry from the tee to the pipe, Pa.

The structure of the equation for calculating the hydraulic resistance depends on the route configuration in which the heat carrier flows. For our case of the heat carrier flow (Fig. 3), the structure of the equation for calculating the hydraulic resistance has the following form:

$$\Delta p = \Delta p_1 + (z-2)\cdot\Delta p_2 + z\cdot(\Delta p_3 + \Delta p_4 + \Delta p_{fr} + \Delta p_5) + \\ (z-1)\cdot(\Delta p_6 + \Delta p_7 + \Delta p_8 + \Delta p_9) + \Delta p_{10}, \quad (1)$$

where:
z – number of strokes in the tubular beam. The error between the calculated values and the experimental data is ± 9%.

The pressure loss in local resistances is calculated using the following formula:

$$\Delta p_i = \zeta_i \left(\frac{\rho \cdot w_i^2}{2}\right), \qquad (2)$$

where:
ζ_i – local resistance coefficient in the considered area of the heat exchanger (index i = 1, 2, ..., n) (Idelchik 1992);
w_i – liquid velocity in a narrow section of the considered area, m/s.

Friction pressure loss in the heat exchanger pipes (Domansky et al. 1982):

$$\Delta p_{fr} = \lambda_{fr} \frac{l}{d_v} \frac{\rho w_{fr}^2}{2}, \qquad (3)$$

where:
λ_{fr} – friction coefficient,
l – pipe length, m,
d_v – internal pipe diameter, m,
ρ – liquid density, kg/m^3,
w_{fr} – liquid velocity in the pipes, calculated from the area of the free section of one stroke, m/s.

The friction coefficient λ_{fr} depends both on the flow mode and on the roughness of the pipes or channels walls.

During turbulent flow, the friction coefficient substantially depends on the pipe wall roughness. The value λ_{fr} can be calculated using the formula (Domansky et al. 1982):

$$\lambda_{fr} = 0{,}11 \left(\frac{10}{Re} + 1{,}16 \frac{\Delta}{d_v}\right)^{0{,}25}, \qquad (4)$$

where:
Δ – pipe roughness, mm.

The hydraulic resistance and the retained liquid amount were studied in the external flow of liquid and gas around the tubular beam within the range of the operating parameters.

Balabekov & Volnenko (2015) summarize the research results of the hydrodynamic characteristics and parameters of mass transfer of various regular packing types (Balabekov et al. 2004, Balabekov 1984, Seitkhanov 2002, Bekibayev 2008, Yesskendirov, 2005, Sabyrkhanov, 1996, Kumisbekov 1999, Korganbayev 1999) (lamellar, cylindrical, prismatic with different cross-sections, etc.). These results allowed to establish the patterns described in (Balabekov & Petin 2000, Balabekov et al. 2004). During flow around solids located regularly in the direction of flow, it is possible to achieve modes of simultaneous vortex formation (in-phase modes) when the time of formation and time of motion of vortices behind the chain of bodies coincides (Balabekov & Petin 2000). An increase in energy consumption accompanies this phenomenon.

For the apparatus with the tubular packing of a regular structure, the extreme points corresponding to the achievement of the simultaneous vortex formation modes are the steps of the pipes in the vertical direction $t_v/d = 2$ and 4 (Serikuly 2015, Serikuly et al. 2020).

When changing the steps of the arrangement of solids in the radial direction, another pattern was established (Balabekov et al. 2004). Up to the critical step between solids, the width of the gap between adjacent bodies determines the vortex formation size and frequency. Exceeding the crucial step leads to each solid forming vortices independently, and the solid width determines their frequency. The critical step in the radial direction for the tubular packing is $t_r/d = 2$ (Volnenko 1999, Serikuly 2015, Serikuly et al. 2020).

With the established steps of the pipe arrangement ($t_v/d = 2$ and $t_r/d = 2$), the studies of the hydraulic resistance and the retained liquid amount with a change in the operating parameters were carried out.

It is known that for most apparatuses with a regularly placed packing, when the gas flow velocity changes, the presence of three modes is characteristic: film-drop, drop and drop entrainment (Volnenko, 1999). At the same time, the most rational, in terms of the combination of energy consumption and the achieved efficiency, is the drop mode (gas velocity 2.5-4 m/s) (Volnenko 1999). The studies of the hydrodynamic characteristics are presented in Fig. 5 and 6.

Fig. 5 shows that an increase in the gas flow velocity causes an increase in the hydraulic resistance and the retained liquid. Due to the dynamic pressure increase, the hydraulic resistance rises along with the gas velocity increase. In this regard, the energy costs for overcoming the contact zone of the apparatus are growing. Furthermore, the dynamic pressure increase also contributes to the retention of more liquid in the packing volume.

The irrigation density increase (Fig. 6) leads to increased hydraulic resistance and the retained liquid. It is evident since more liquid is involved in the interaction process.

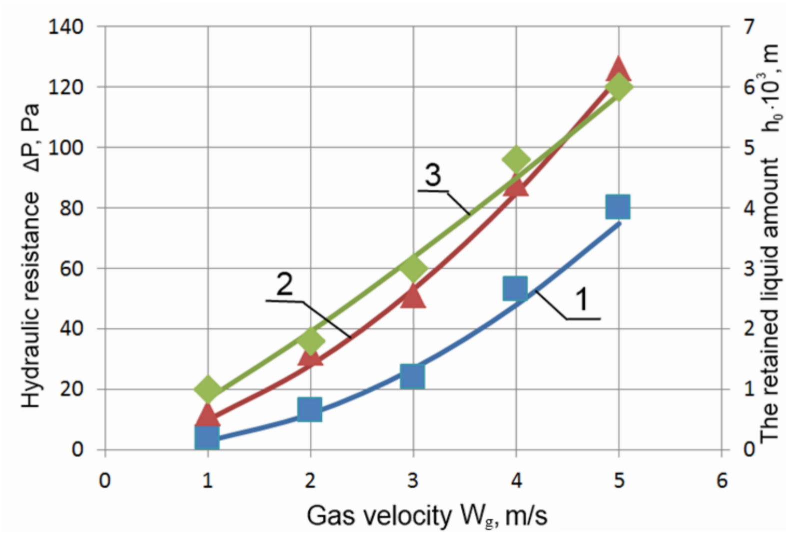

Fig. 5. Dependence of the hydraulic resistance ΔP_C, ΔP_L and the retained liquid amount h_0 on the gas velocity W_g; *Experimental conditions:* $t_v/d = 2$ *and* $t_r/d = 2$. $L = 25\ m^3/m^2h$; $1 - \Delta P_C$; $2 - \Delta P_L$; $3 - h_0$

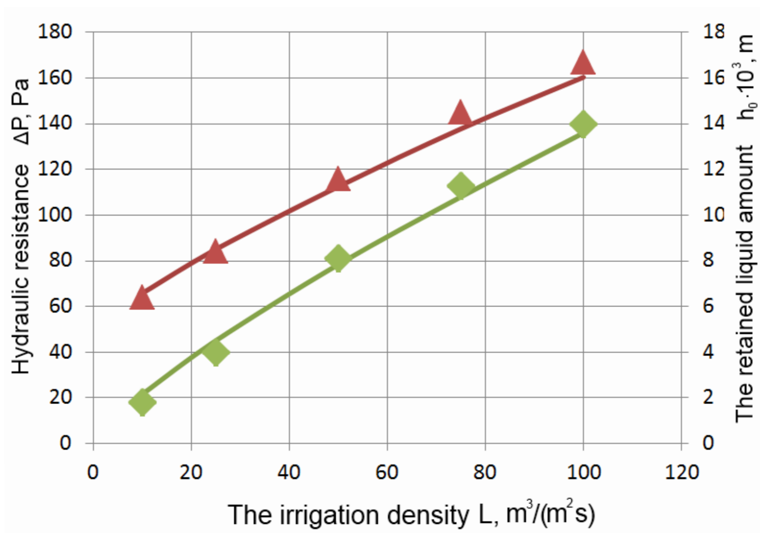

Fig. 6. Dependence of the hydraulic resistance ΔP_L and the retained liquid amount h_0 on the irrigation density L: *Experimental conditions:* $t_v/d = 2$ *and* $t_r/d = 2$. $W_g = 4\ m/s$; $1 - \Delta P_L$; $2 - h_0$

To calculate the hydraulic resistance of the apparatus without irrigation, including the flow pressure loss caused by the vortex formation and interaction in the tubular beam, the change in the gas flow direction, the friction of the gas against the packing elements' surface, the following dependence (Volnenko 1999) may be used:

$$\Delta P_c = \xi \cdot \frac{H}{t_v} \cdot \frac{\rho_g \cdot W_g^2}{2 \cdot \varepsilon_0^2}\ , \tag{5}$$

where:
H – packing area height, m,
ρ_g – gas density, kg/m^3.

The coefficient of resistance, taking into account the pressure loss during the vortex interaction in the vertical and radial directions, is calculated using the formula:

$$\xi = \mathrm{A} \cdot \theta_v \cdot \theta_r\ , \tag{6}$$

where:
A = 0,226 is a result of the processing of experimental data.

The following formula determines the porosity of the tubular packing:

$$\varepsilon_0 = 1 - \frac{d}{t_r} \tag{7}$$

The coefficient characterizing the vortex interaction degree in the vertical direction for the tubular packing elements θ_v (Balabekov & Volnenko, 2015):

$$\theta_v = 0{,}85 + 0{,}15\sin\left[\frac{\pi}{2}\left(\frac{4t_v \cdot S\ell}{m_k} + 1\right)\right], \tag{8}$$

where:
Sl – Strouhal number for the tubular elements, *Sl = 0,2*,
m_k – parameter that considers the vortex formation, the streamlined elements shape and the vortex velocity decrease.

For the tubular elements:

$$m_k = 0{,}44\left(1 - \exp(-t_v)\right) \tag{9}$$

The coefficient characterizing the vortex interaction degree in the radial direction and taking into account the change in the vortex formation frequency, θ_r can be determined by the formula (Balabekov & Volnenko, 2015):

$$\theta_r = \frac{\mathrm{t_r} - \lambda}{\mathrm{t_r} - d}, \tag{10}$$

Pulse elements located in the same row perpendicular to the streamlined flow contribute to the vortex formation with the scales λ. There are two cases for discretely located bodies in one row, perpendicular to the streamlined flow: at $t_r > 2d$ $\lambda = d$; at $t_r < 2d$ $\lambda = t_r - d$.

The error between the calculated values (using formula (5)) and the experimental data is ± 12%.

The hydraulic resistance of the irrigated packing, taking into account the flow pressure loss caused by the gas friction against the surface of the packing elements and the liquid film, can be calculated using the following dependence:

$$\frac{\Delta P_L}{\Delta P_c} = 1 + B \cdot \left(\frac{L_m}{G_m}\right)^{0,8} \cdot \left(\frac{\rho_g}{\rho_l}\right)^{0,4}, \qquad (11)$$

where:
B = 8,5 – experimental coefficient. The error between calculated values and experimental data is ± 14%.

The mass flow of the gas (kg/s):

$$G_m = W_g \cdot S_{ap} \cdot \rho_g \qquad (12)$$

The mass flow of the liquid (kg/s):

$$L_m = \frac{L}{3600} \cdot S_{ap} \cdot \rho_l \qquad (13)$$

The retained liquid amount may be calculated using the balance equation:

$$\Delta P_L - \Delta P_C = \rho_l \cdot g \cdot h_0 \qquad (14)$$

After substituting the hydraulic resistances of dry and irrigated apparatuses:

$$\xi \frac{H}{t_v} \cdot \frac{\rho_g W_g^2}{2\varepsilon_0^2} \cdot 12{,}4 \left(\frac{L_m}{G_m}\right)^{0,8} \cdot \left(\frac{\rho_g}{\rho_l}\right)^{0,4} = \rho_l \cdot g \cdot h_0, \qquad (15)$$

the retained liquid amount h_0 is obtained in the following form:

$$h_0 = \mathrm{C} \cdot \xi \cdot \frac{H}{t_v \cdot g} \cdot \left(\frac{W_g}{\varepsilon_0}\right)^2 \cdot \left(\frac{L_m}{G_m}\right)^{0,8} \cdot \left(\frac{\rho_g}{\rho_l}\right)^{1,4}, \qquad (16)$$

where:
C = 5,06 – experimental coefficient. The error between the calculated values and the experimental data is ± 15%.

The gas content in the layer is determined by formula (Balabekov & Volnenko, 2015, Volnenko & Balabekov, 2016):

$$\varphi = \varepsilon - \frac{h_0}{H} \tag{17}$$

The following formula determines the volumetric porosity of the tubular packing in equation (17):

$$\varepsilon = 1 - \frac{\pi d^2}{4t_r \cdot t_v} \tag{18}$$

The novelty of the results presented in this article is the obtained experimental data of the hydrodynamic characteristics in various forms. First of all, graphical dependencies. Then, the calculated equations of the hydraulic resistance during the heat carrier flow in the pipes, the hydraulic resistance during the external flow around the tubular beam, the retained liquid amount and the gas content in the layer.

4. Conclusions

The laboratory setup was created and the research methods were selected to examine the main hydrodynamic characteristics of the apparatus with a regular tubular packing – the hydraulic resistance (when the liquid flows in the pipes and at the external flow around the tubular beam) and the retained liquid amount.

The research results of the hydraulic resistance in the pipes, the pressure loss during the external flow around the pipes and the retained liquid amount in the apparatus with a regular tubular packing with the change in the gas velocity and the irrigation density were obtained. It was noted that with the gas flow velocity increase, its dynamic pressure grows, and therefore, the hydraulic resistance and the retained liquid amount increase. Furthermore, the irrigation density increase also causes an increase in the hydraulic resistance and the retained liquid amount. The reason for that is the increase in the fluid volume involved in the interaction with the gas.

The equation for calculating the hydraulic resistance in the pipes is proposed. It takes into account the local resistances and the pipe roughness. The formulas for determining the pressure loss during the external flow around the tubular beam, the retained liquid amount, and the gas content in the layer take into account the vortex interaction between the gas and liquid flows.

The calculated dependencies (hydraulic resistance in the pipes, hydraulic resistance in the external flow around the tubular beam, retained liquid amount, gas content in the layer) are the basis for the calculation method of the hydrodynamic characteristics of the apparatus with the regular tubular packing. Such a method may be used to calculate industrial devices.

References

Balabekov, O.S., & Petin, V.F. (2000). *Regularity of vortex interaction arising in the separated flow around a gas or liquid flow discretely located along it.* Certificate of Scientific Discovery № 144. Moscow: International Association of Authors of Scientific Discoveries.

Balabekov, O.S., & Volnenko, A.A. (2015). Calculation and design of heat and mass transfer and dust collectors with movable and regular packing. Shymkent, 184.

Balabekov, O.S., Volnenko, A.A., Korganbayev, B.N. (2004). Regularities of the flow around a system of regularly placed elements with different spatial arrangement. *Proceedings of International Scientific Conference "Energy and resource saving technologies and equipment, environmentally friendly productions"*, V.1. Ivanovo: ISCTU, 340-354.

Balabekov, O.S., Volnenko, A.A., Praliyev, S., Korganbayev, B.N., Balabekova, M.O., Viktorov, S.V. (2004). *Regularity of formation of parallel moving vortex jets during the flow of a gas or liquid flow through the system across to it located discrete sources*. Certificate of Scientific Discovery № 269. Moscow: International Association of Authors of Scientific Discoveries,.

Balabekov, OS (1984). *Hydrodynamics, mass transfer and dust collection in counterflow and direct-flow two-phase drop and film flows in the layer of a movable packing*. [Doctoral dissertation: Moscov], 430.

Bekibayev, NS (2008). *Scientific foundations of coupled heat and mass transfer processes in in-phase vortex apparatuses*. [Doctoral dissertation, South Kazakhstan State University named by. M.Auezov, Shymkent].

Domansky, I.V., Isakov, V.P., Ostrovsky, G.M. (1982). *Machines and devices for chemical productions: Examples and tasks.* (Under the general editorship of Sokolov V.N). L.: Mechanical engineering.

Einstein, V.G., Zakharov, M.K., Nosov, G.A. (2002). *General course of processes and chemical engineering apparatuses: Textbook: in 2 volumes*. Moscow: Logos; Higher school.

Idelchik, I.E. (1992). *Handbook of hydraulic resistances*. (Under the editorship of M.O. Steinberg. 3rd ed., rev. and add). Moscow: Mechanical engineering.

Kagan, AM (2013) Contact packings of industrial heat and mass transfer apparatuses. Kazan.

Korganbayev, BN (1999). *Hydrodynamics and heat-mass transfer in devices with regularly rotating packings*. [Disertation candidate technical sciences, South Kazakhstan State University named by. M.Auezov, Shymkent].

Kumisbekov, SA (1999). Hydrodynamics and mass transfer in an apparatus with a regular lamellar vibrating packing. [Disertation candidate technical sciences, South Kazakhstan State University named by. M.Auezov, Shymkent].

Laptev, A.G., Basharov, M.M., Lapteva, E.A. (2017). Separation and energy efficiency of packed apparatuses for purifying gases from aerosols, *Theoretical Foundations of Chemical Engineering*, *51*(5), 639-646. DOI: https://doi.org/10.1134/S0040579517050335

Lapteva. E.A. (2019). Efficiency of transfer phenomena in gas-liquid media during desorption and cooling of liquids. Kazan.

Ramm, V.M. (1976). *Gas absorption*. Moscov: Chemistry. http://booksonchemistry.com/index.php?id1=3&category=other&author=ramm-vm&book=1976

Sabyrkhanov, DS (1996). *Development, calculation and implementation of mass transfer and dust collecting devices with movable and regular packing*. [Doctoral dissertation, South Kazakhstan State University named by. M.Auezov, Shymkent].

Seitkhanov, NT (2002). *Structure of flows and contact heat and mass transfer in a device with a regular lammelar packing*. [Disertation candidate technical sciences, South Kazakhstan State University named by. M.Auezov, Shymkent].

Serikuly, Z., Volnenko, A., Kumisbekov, S. (2020). Optimum Values Regular Structure Converters for Converting the Vibration into Electric Energy *International Review of Mechanical Engineering (IREME), 14*(6), 388-395. DOI: https://doi.org/10.15866/ireme.v14i6.18844

Serikuly, Zh (2015). *Development and calculation of heat and mass transfer apparatuses with a movable packing taking into account a large-scale transition*. [Dissertation PhD. South Kazakhstan State University named by. M.Auezov, Shymkent]

Volnenko AA (1999). *Scientific bases for the development and calculation of vortex mass transfer and dust collecting devices*. [Doctoral dissertation, South Kazakhstan State University named by. M.Auezov, Shymkent], 300.

Volnenko, A.A., & Balabekov, O.S. (2016). *Calculation of heat and mass transfer and dust collectors with weighted and regular packing*. Examples and tasks. Shymkent.

Volnenko, A.A., Balabekov, O.S., Korganbayev, B.N., Khussanov, Zh.Ye., Bekibayev, N.S. (2013) *Innovative patent № 27719 of the Republic of Kazakhstan, IPC B01D 53/20, B01D 47/14. Apparatus with a packing for heat and mass transfer and dust collection*. Bul. 12(4). URL: https://kzpatents.com/4-ip27719-apparat-s-nasadkojj-dlya-teplomassoobmena-i-pyleulavlivaniya.html

Yesskendirov, MZ (2005). *System-element-wise modeling of the processes of coagulation and deposition of aerosols in direct-flow multiphase flows of organized vortex structure.* [Doctoral dissertation, South Kazakhstan State University named by. M.Auezov, Shymkent].

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Remote Reading of Water Meters as an Element of a Smart City Concept

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Abstract: The provisions of the European law have defined "Smart Metering" as a tool for remote meter readings and management of energy networks. Currently, after years of research and many real-life applications, it is one of the most popular solutions that defines friendly and modern cities. Similarly to automatic street lights, traffic signals or waste management systems, monitoring and control of water supply and sewage systems significantly improves the quality and comfort of life of city residents. The city infrastructure managers may use it as a tool that primarily allows for some cost savings and better resource management. The paper describes a remote transfer of water meters data through the Internet of Things technology. Also additional options have been presented, which are available once the data on water demand has been acquired. They can be communicated to other clients, e.g. other municipal services, as an element of Smart City, and to the customers. Thanks to this technology, the customers may analyze and better manage their actual water consumption trying to optimize it. Over time, it seems that saving water has become not only a fashionable whim but a trend to stay.

Kaywords: smart city, water meter, reading

1. Introduction

Metering of water supplies (as a part of metrology) has been developing since only municipal water systems have been organized, so over a hundred years. First information about water meters appeared in publications in the late 19th century. At the beginning, water meter was used for correct billing for water supply services. Measuring and counting mechanisms used in water meters undergo continuous upgrading to increase their efficiency and reliability. What has remained unchanged is their purpose; water meters measure the volume of water consumed by the customer. In the 21st century, global digitization creates a new dimension for the use of water meters. It is a remote transfer of water meter readings, together with current water consumption analysis and early notification about possible emergency alarms. A possibility to record the data in short intervals throughout the day and then report them regularly to the supplier has created completely new options for data management. The water consumption data are also made available for the consumers, at their premises. (Billewicz 2011, Cichoń & Królikowska 2019).

The amount of water consumed by a statistical resident has been changing over the last several decades. First of all, it depends on the standard of household appliances as well as available services, e.g. sewage system. In Poland, until the late 1980s, the economic factor in water consumption was of a rather minor importance; water consumption increased as new properties were connected to water supply networks. Once a market economy was introduced and a water price followed real production and distribution costs, water consumption started to decrease. Actually, the City of Kraków Waterworks observed this trend until the second decade of the 21st century. The annual water production since the very beginning of the City of Krakow Waterworks operation is shown in Figure 1.

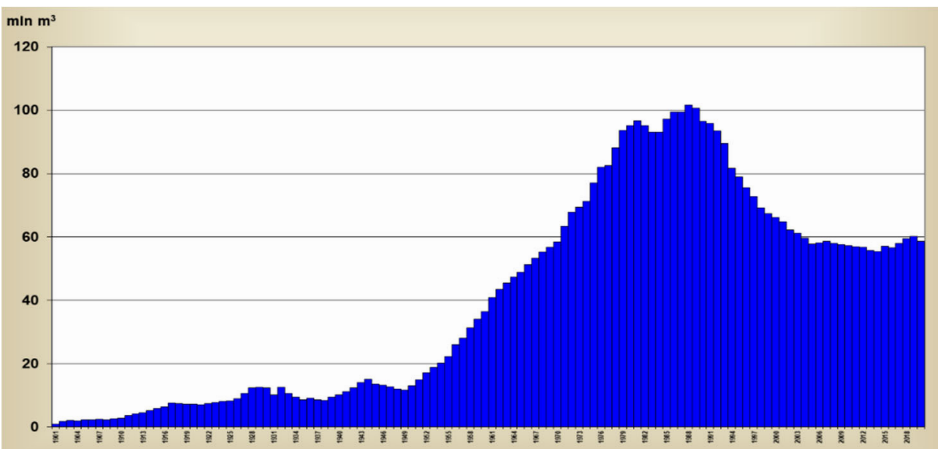

Fig. 1. Annual production of water at the City of Krakow Waterworks in years 1901-2020

However, not only economy has an impact on a lower water consumption. The new decisive factor is environmental awareness. The popular household appliances are not only more energy- efficient, they also consume less and less water, e.g. in washing or dishwashing cycles. All this means that even though the actual real number of residents served by the system becomes higher, the water demand remains constant, or only slightly increases (A).

The analysis of the water production at the City of Krakow Waterworks have exposed completely new relationships and trends that emerged during the COVID-19 coronavirus pandemic. Imposed restrictions and a shutdown of many industries resulted in a clear revision of consumers habits concerning a water demand. The largest drop in consumption was observed in services related to tourism and education, which remained closed for some time. It is a large group of consumers that includes hotels, restaurants, public utility facilities and schools of all levels, universities and dormitories. Also many corporations working mainly in large office buildings sent their employees back home to work remotely. This in turn, resulted in a higher water consumption in households while in office buildings a water demand dropped down. One should also notice a substantial migration outside the cities. As a result, a water demand in neighboring communes, located around large cities, has increased significantly. Pandemic-related changes observed in a water demand are difficult to accurately analyze since water consumption readings, in case of multiple consumers, have been collected only once per the accounting cycle.

2. Water consumption readings vs billing for services and reduction of water losses

Water consumption readings are carried out by residents, as specified in the contract; usually, the readings are done in monthly or longer periods of time. The billing systems convert consumption into daily average values, however, these are just approximate and not actual values. Such data is sufficient for selection of a water meter or for monitoring of consumption trends during the period of normal water consumption. However, such a system is obviously insufficient if more accurate metering of water consumption is required as well as more precise analysis of its different aspects. Management of municipal infrastructure, which primarily means savings and better management of resources, is undoubtedly one of such aspects.

Water resources protection has become increasingly important in recent years and as such it demands reduction of water losses. Poland, similar to other European Union countries, is obliged to rationally use and protect water resources following the principles of sustainable development, i.e. while improving the quality of life, one should not intrude upon the natural environment, in particular water resources (Jakuta 2015). Approximately 40% of population have a limited access to drinking water while about 20% of the world's population do not have access to clean drinking water at all. The countries of northern and central Africa, South America and Central Asia are most severely affected by the water deficit. Also, water resources of Poland are not sufficient; their average size is about 62 km^3 while the more difficult renewable groundwater resources are estimated at about 16 km^3. According to the European Commission, the annual volume of water per person in Poland was 1580 m^3 (year 2009); such value is three times lower than the European average (4580 m3) and 4.5 times lower than the world's average (Skwarzyńska et al. 2014).

Combination of the diagnostic system and a well-tuned model of the water supply system (working in real time) enables a precise detection, localization and determination of the size of the leak, thus reducing water losses. Hence, a careful monitoring and measurements of water consumption will also contribute to protection of water resources (Cichoń & Królikowska 2018).

A precise measurement system, operating in real time, is essential for operation of the diagnostic system. To obtain sufficient number of data on water consumption and balance the flow in the network divided into zones, it is necessary to collect readings from consumers' water meters at least in daily intervals. Daily water consumption and daily readings from water meters are have to be compared with a water volume pumped into the distribution system in order to get the system balanced. The balance should be made at the beginning of each day on the basis of data collected at midnight. Then, it is possible to compare the volume of water that has flowed to individual network nodes with the volume showed on the main water meters, at the customer's premises. Once the threshold values for individual zones are determined, the water balance should not be altered by fluctuations observed at the individual water meters. On the other hand, a higher water flow into a given zone that is not balanced with water meter readings points to the failure risk in the zone. As the automatic reading of water meters at the customers premises is implemented, the system will bring more accurate and real data on current water losses in individual zones on a daily basis.

Remote readings of water meters not only resulted in a faster and better access to meter readings at the customer premises, but also provided other valuable information (Kubiak & Urbaniak 2013, Kubiak & Urbaniak 2015). The system, comprising electronic modules (overlays) installed on water meters, allows to monitor an instantaneous water consumption; it also detects and stores emergency alerts or any abnormal situations that are observed in the system. The information on alerts (failures) is valuable not only for the water company, but also for the consumer, who this way can be aware of a failure at a very early stage and may limits its potential effects. The effects could be either financial (for the client or the company) or can be related to the water resources management. Modules furnished with a memory function may store both measurements and time of their occurrence, i.e. to record measurement data. Such registration can be a helpful option in situations when the consumer questions readings from the measuring devices. The meters supported by data transmission modules are also more resistant to unauthorized interference and to errors and distortions in the reading process. All of these features allow for implementation of advanced technologies to reduce the volume of water that does not create profit as well as water losses; it applies to both hardware and software technologies, based on data analysis.

3. Water consumption as an input parameter for city life modeling

When only mechanical devices were used as popular meters, reading of instantaneous flows required professional tools or it was impossible. Information about the actual instantaneous water demand is necessary for a successive monitoring of guidelines for selecting a water meter, sizing of connections, but also for calculating an actual capacity of the existing pipes. It applies to both the current real-life situation and forecasts for the future designs. New algorithms for modeling water supply networks offer much better results when they work on real measurement data; that is why there is a huge demand for more and more frequent readings from the water meters.

On the other hand, the read-out data is available only once per accounting period and that is the main limitation in verification of network models. It turns out that data on daily water consumption, developed for balancing water consumption and water losses, is insufficient and using hourly readings would be better option. Such approach is not impossible, but it requires a more advanced reading databases and tools for their management (Kubiak et al. 2016).

Water meter readings are needed not only for the water utilities (billing for the services), but they also may help to more accurately synchronize functions of the city, as a whole. In the era of development of cities and their advanced services, management of the city's organism as a system of intelligent connections becomes more and more important (Billewicz 2011). Such phenomenon is the widely known as the idea of Smart City.

Water consumption is related more to the presence of people than other utilities. While in the case of electricity or gas, their consumption may be related to operation of automatically controlled systems (e.g. heating) not always directly related to the presence of residents at home, water consumption almost always results from operation of man-operated water intake points. This means that tracking down a water consumption can be correlated with tracking of people's movement, e.g. between home and workplace. This cannot be said for electricity, especially because of the widespread use of renewable electricity sources, which make households prosumers of energy. Thus, the demand for water verifies the actual number of people staying at a given property or in agiven area of the city. Currently, more and more cities ties charges for waste disposal with the amount of water used. For example, Łódź estimated that tens of thousands of residents have disappeared from the of waste collection system. In 2016, the system recorded 675,000 residents while in 2020 only 615,000. In recent years, water consumption in the city remained at a similar level, which means that the population in Łódź has not decreased – contrary to declarations submitted to the City of Łódź Office (https://www.teraz-srodowisko.pl/aktualnosci/oplata-opdady-dla-inhabitants-zuzycie-water-Warsaw-Lodz-9628.htm). Each water company may collects such data about customers, but there is a formal limitation related to the privacy issues and solutions complying with the provisions on the protection of personal data (GDPR) have to be respected.

Another more advance example is the use of water consumption data for modeling of resident migration within the city. Various institutions have showed interest in such an issue and it is becoming more and more popular with time. Companies and organizations that deal with specific public services, e.g., modeling of a public transport system where intelligent solutions are often used, turn to water utilities. Such systems may help to improve both a traffic flow and a travel comfort, as well as a comfort of living in the entire city (e.g. when limited traffic zones are created). As part of this task, special maps with grids of settlements or areas characteristic for the people relocations are prepared.

There are three main constraint factors in applying the water consumption data. The first one are the GDPR requirements, which severely limit the rights of water and sewage companies to share knowledge about water consumption. To do so, they have to inform residents and obtain their consent to share the data and also they have to protect the data against unauthorized use e.g. giving away information about the absence of residents at home.

The second limitation is a difference in a spatial distribution of the water supply network and road and communication system. Due to this limitation, data on water intake from nodal points of the water supply network (e.g. entire housing estates) is usually insufficient and data from individual properties has to be collected and then analyze in particular sub-classes, characteristic for the area served by individual stops.

The third limitation involves frequency of data collection. Daily data collections were defined as a target frequency for the water supply system. For migration modeling purposes, such frequency is completely insufficient and data collection at least on an hourly basis is required. Such limitation may be of crucial importance if there is no access to stationary data transfer technologies, i.e. the Internet of Things (IoT) technology. The technology allows for a frequent transmission of small packages of data and this way one can process data collected even more often than every hour. To achieve such a goal it is necessary to build large databases and create efficient tools for data managing.

Another very valuable feature of using the IoT technology for transmission of data from water meters is the fact that consumers may analyze their water consumption; This way an environmental consciousness and a pro-environmental behavior related to a climatic footprint can be promoted in the households.

4. Conclusions

The use of the Internet of Things technology to collect water meters readings opens new, much wider possibilities of their application. While the daily data transfer has expanded possibilities of using the data for balancing water flows in the network, and thus for a successive monitoring of water losses, the IoT technology enables transfer in the hourly consumption data for modeling of the city, as a flexible but resistant structure. The SMART CITY is an expertise and interconnection that are driven by the use of technology and communication to solve urban issues. It combines many elements related to the economic, social and spatial zones and allows the city authorities for a systemic approach to the decision-making process. Currently, the idea of SMART CITY is based on IoT and intelligent computing methods used in the design and operation of water supply systems (Czapczuk et al. 2015, Dawidowicz 2012). Learning algorithms allow you to adapt in the process of operation on an ongoing basis to changing conditions.

Readings of water meters at consumers sites, at the smart city, not only help to protect water resources, but also provide information necessary for urban services, such as: transport or traffic management. By monitoring water consumption, residents save not only water but also energy.

References

Billewicz, K. (2011). *Smart metering – Inteligentny system pomiarowy*, Wydawnictwo Naukowe PWN, Warszawa.

Cichoń, T., Królikowska, J. (2016). Ewolucja procesu odczytu wodomierzy na podstawie doświadczeń Wodociągów Krakowskich, *Instal, 12*, 45-48.

Cichoń, T., Królikowska, J. (2018). Protection of water resources for sustainable development. *Desalination and Water Treatment, 128*, 442-449.

Cichoń, T., Królikowska, J. (2019). W jakim kierunku zmierza gospodarka wodomierzowa – szanse i zagrożenia wynikające z zastosowania elektronicznych liczników. *Instal, 11*, 51-54.

Czapczuk, A., Dawidowicz, J., & Piekarski, J. (2015). Artificial Intelligence Methods in the Design and Operation of Water Supply Systems. *Rocznik Ochrona Srodowiska, 17*, 1527-1544.

Dawidowicz, J. (2012). Expert System for Evaluation of Water Distribution System Created with an Inductive Inference. *Rocznik Ochrona Srodowiska, 14*, 650-659.

Jakuta, D. (2015). Woda surowcem bezcennym. *Wodociągi Kanalizacja, 5*, 6.

Koral, W. (2019). Wodomierze – nowoczesne rozwiązania. *Wodociągi-Kanalizacja, 4*, 42-44.

Kubiak, Z., Urbaniak, A. (2013). Inteligentny system pomiarowy – rozwój standardu, przykładowe rozwiązania. *Rynek Energii*, 43-49.

Kubiak, Z, Urbaniak, A. (2019). Smart Metering a woda. Mat. VIII Ogólnopolskiej KNT. Politechnika Śląska, Instytut Technologii Wody i Ścieków, Szczyrk 2015, *Instal, 5*, 23-27.

Kubiak, Z. et al. (2016). *Technologia Lora w kontekście sieci bezprzewodowych oraz Internetu przedmiotów w systemach pomiarowych przedsiębiorstw wodociągowych i kanalizacyjnych.* Mat. Konferencyjne Zaopatrzenie w Wodę, Jakość I Ochrona Wód, 605-622.

Skwarzyńska, A., Jóźwiakowski, K., Sosnowska, B., Pytka, A., Marzec, M., Gizińska, M., Szyszlak-Bargłowicz, J., Słowik, T. & Zając G. (2014). Jakość wód opadowych i ocena możliwości ich wykorzystania w indywidualnych gospodarstwach domowych. *Technologia Wody, 6*, 20-23.

https://www.teraz-srodowisko.pl/aktualnosci/oplata-opdady-dla-mieszkancow-zuzycie-wody-Warszawa-Lodz-9628.htm

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Methodology for the Formation of a New Economic Model for Geological Exploration in Subsoil Use

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Abstract: In modern realities, there is no unified methodology for the economic assessment of geological exploration in subsoil use. The main research question of this study was to develop a methodology for the new economic model formation for assessing geological exploration in the subsoil use for the mineral resource base rational use. The new methodology can facilitate the assessment of subsoil users of hydrocarbon reserves and resources and government bodies when putting resources and reserves on the balance sheet. In the course of the study, modeling, observation, description, and analysis methods were used. The result of the study was a new economic model for evaluating geological exploration in subsoil use. The main conclusions can be characterized by the optimization of the main indicators of the valuation of mineral raw materials. The basic principles for calculating discounted cash flow, discount rate, payback period and internal rate of return were developed.

Keywords: methodology, geological exploration, hydrocarbon reserves and resources, modeling methods, cash flow, discount rate, payback period

1. Introduction

In geological study of subsoil, exploration and preliminary assessment, it is customary to define it as a comprehensive study, which contains a number of different assessments, such as geological, technological, environmental, economic indicators. The absence of a unified model for evaluating geological exploration in subsoil use leads to contradictions in the correctness of the result obtained for assessing the efficiency of the use of subsoil and mineral resources. In recent years, the mineral resource base of Russia and the world has been experiencing a shortage of various types of raw materials; for instance, there are changes in the raw material base of the Russian gas industry (Abramov et al. 2018). All this may lead in the future to a profound transformation of the country's economy. The most obvious reason for the occurrence lies in the relative uncertainty of the results when calculating reserves, a sufficiently long term of development of deposits, the presence of its own specific life cycle, and a high capital intensity of production. The result may be the uncertainty of the resulting geological and economic estimates. From the point of view of fundamental science, there is a need for a unified economic model for evaluating geological exploration work, which will regulate the system for evaluating the geological and economic indicators of the geological exploration process, providing for calculating the effectiveness of geological exploration work in Russia at all stages and stages aimed at increasing the validity of management decisions when choosing objects of geological exploration. Consequently, the scientific task within the framework of the research topic is the creation of a new methodology for the transformation of the most important branch of the national economy. The relevance from the point of view of fundamental science is that there is a need for a unified economic model for evaluating geological exploration, which will regulate the system for evaluating the geological and economic indicators of the exploration process, which provides for calculating the effectiveness of exploration in Russia and the world at all stages and stages, aimed at increasing the validity of management decisions when selecting objects for geological exploration.

The current state of research in the field of methodology and modeling of economic efficiency was presented by Trofimov et al. (2017); their position is based on the study of the discounting method and financing of work from their own funds. The study will focus on the application of a unified methodology for evaluating geological exploration in order to select the most effective areas and targets for exploration and rational distribution of financial resources. A significant part of researchers is limited to the presentation of quantitative estimates of efficiency and forecasting (Abrikosov & Beilin 1983). Also, a number of authors considered the geological and economic indicators used in assessing the effectiveness of geological exploration work on the example of an oil field and gave methods of their calculation and application features on the example of a field (Ampilov & Lapo 2010). There are a number of developments and hypotheses aimed at comparing the methodology of using integral indicators of the economic efficiency of projects for the development of hydrocarbon reserves in the formation of a resource base in the planned and market economies of Russia (Anashkin & Rokhlin 2015). The question of the correct determination of the economic efficiency of geological exploration, despite its obvious importance and relevance, has not been finally resolved. In production practice, for this purpose, the value of costs per unit of explored reserves of mineral raw materials is used, that is, the cost of exploration for a unit of reserves. Bochkarev and Pashkevich (1973) tried to define the economic efficiency of exploration. It should be noted that the literature reflects two types of approach to the economics of geological exploration from the point of view of state influence on this category of work and autonomous participation in exploration (Brenner 1979). In the literature, there are two approaches that are aimed at assessing the effectiveness of exploration work. The first approach is due to the development of the mineral resource base of the complex of Russia to ensure energy security and determine approaches to risk assessment (Vasiliev et al. 2015). The second approach is aimed at ensuring rational subsoil use, covering various aspects of the management of the mineral resource complex (Volovich 2013). Authors such as Haldar (2018), Evseenko (2018), Mikhalchuk (2020) conducted research in the field of sources of financing for geological exploration (Sharf et al. 2016).

Other researches are based on the application of the principle of discounting cash flows in assessing the effectiveness of exploration work, from which follows the calculation of the net discounted profit (Novoselov et al. 2014), the internal rate of return and the return-on-investment index (Novoselov et al. 2014, Melekhin & Afonina 2018).

The purpose of the study is to develop a methodology for the formation of a new economic model for evaluating geological exploration in subsoil use for the rational use of the mineral resource base and the development of the national economy of Russia and the world.

The tasks for the realization of the research goal are as follows:

- consider the problems of valuation of the extraction of minerals;
- to determine the main indicators for evaluating the conduct of geological exploration work in Russia and the world, such as net discounted cash flow, discount rates, gross appraised value etc.;
- to find the optimal distribution of indicators of the economic efficiency of geological exploration.

2. Materials and methods

Thus, in modern studies, there are practically no materials related to the role of methodological aspects of assessing the economic efficiency of geological exploration. There are no uniform criteria for evaluating the effectiveness of exploration work for making managerial decisions in the implementation of projects for the development of hydrocarbon deposits.

I chose modeling as the methodological basis of our research. This approach in the study creates a model for evaluating geological exploration in subsoil use. It is effective for generalizing various objects, processes and phenomena for effective subsoil use. This model is aimed at imitating a real economic process, which will reduce labor costs for making managerial decisions to study the economy (Evseenko 2018). This is also relevant when justifying changes in the structure of the mineral resource base in the context of the transformation of the country's fuel and energy complex under the influence of external and internal factors.

General scientific methods planned for use in research (Kuzina 2020b):

1. Method of observation. It will be used for direct observation of changes in the structure of the mineral resource base and indicators of the fuel and energy complex in order to further apply deeper methods corresponding to the objectives of the study.
2. Description method. It is a system of procedures for collecting, primary analysis and presentation of data and their characteristics. In our study, it will be used following the observation method, or the data analysis method, in order to summarize the changes in resources and hydrocarbon reserves, occurring at the present time, or in the future.
3. The method of analysis will be used to identify and study the individual stages of the process of forming a model for balancing subsoil use.
4. Application of the induction method as a process of logical inference based on the transition from a particular position to a general one will make it possible to form a unified model for assessing the market of means of production for field development. This will allow the development of unified algorithms for calculating indicators of the effectiveness of geological exploration.
5. The forecasting method in our study will imply a special scientific study of specific prospects for the further development of the region in which geological exploration is being carried out to assess the environment of the geological exploration object.

3. Results and discussion

The economic assessment of the exploration work is important for the initial stage. At the same time, the methodology for creating a new economic model for geological exploration, according to the author, is based on the following stages:

- preparation of the geological base, while in the author's opinion it is necessary to use the classification of the Society of Petroleum Engineers (SPE), the classification of the American Association of Petroleum Geologists (AAPG) (Hodler & Bhattacharyya 2014);
- conducting an integrated assessment of hydrocarbon reserves and resources, while using the potential income from the use of predicted resources;
- bringing the economic assessment of geological exploration works on the basis of discounting. This method was chosen by the author, because on the basis of the net discounted value (NPV), decisions are made to continue or refuse work or to adjust the parameters of the project for assessing hydrocarbons in the field.

To draw up an economic model, it is necessary to be determined in the composition of the cost estimates of mineral deposits (CEMD) (Emelyanova & Poroskun 2016).

The main purpose of the valuation of mineral resources and subsoil plots is to determine the commercial benefits from their industrial development. The indicator of such a valuation is considered being the net discounted value (NPV) taken into account to determine the effectiveness and feasibility of implementing the developed investment projects related to the development of minerals. The development of investment projects according to the current standards and methods is a very laborious and expensive process that requires taking into account a variety of input indicators and calculation factors and the use of special computer programs. The use of the NPV indicator in the economic assessment was chosen due to the fact that on the basis of modeling cash flows, including all cash receipts and expenses associated with prospecting, exploration and development of a predicted or discovered hydrocarbon field.

The problem of adequately assessing the attractiveness of any investment project associated with raising capital is to determine how much future receipts (or savings) justify today's costs (Voskresenskaya 2019). Therefore, when performing long-term financial calculations, such as a business plan or an investment project, there is no doubt that it is necessary to take into account the changing nature of the cost of monetary resources (Mikhalchuk 2020). Therefore, it is necessary to clearly understand the logic of calculating or choosing the discount rate and clearly interpret the resulting NPV value.

Let's turn to the formula for calculating NPV.

$$\mathrm{NPV} = \sum_{t=1}^{N} \frac{CF_t}{(1+i)^t} - I_0 \tag{1}$$

where:
I_0 – initial investment,
CF_t – cash flows in t years,
N – duration of the project (years),
i – discount rate.

In Equation (1), the discount rate is constant over time. Provided that the discount rate during the year can change an arbitrary number of times M at any time j and act for an arbitrary periodΔ, then we get the following value of the annual discount rate (Kuzina 2020a):

$$\mathrm{i_t} = \sum_{j=1}^{M} i_j \Delta_j . \tag{2}$$

Substituting the value of the calculated rate i_t from expression (2) instead of the value of the discount rate i into Equation (1), we obtain the refined formula for calculating NPV:

$$\text{NPV} = \sum_{t=1}^{N} \frac{CF_t}{(1+\sum_{j=1}^{M} i_j \Delta_j)^t} - I_0. \quad (3)$$

Thus, Equation (3) takes into account the possibility of changing the discount rate during various stages of the investment project. To do this, it is enough to set the forecast dynamics of rate changes and the duration of the period in which it will operate.

As the main indicator of such calculations for the objects of preliminary assessment, it is proposed to determine the estimated value of mineral raw materials in the subsoil, equivalent to the proceeds (gross income) from the sale of commercial products, which can potentially be obtained in the process of full development of the evaluated mineral deposit (subsoil plot) (Sharf 2018).

The indicator that determines the estimated cost of mineral raw materials in the subsoil can be used for the rating assessment of subsoil use objects, as well as in cases where analysis, comparison and selection of subsoil use objects is necessary, in particular, when developing licensing programs for subsoil use, when preparing the terms of tenders and auctions, as well as directly in the process of selecting bidders' bids (Sharf & Grinkevich 2016).

The model of economic appraisal of geological exploration works is as follows: an indicator of the appraised value of mineral raw materials in the subsoil is created. The model is based on the commodity value of mineral raw materials in the bowels of a specific subsoil use object and is determined by the Equation (4).

$$S_{val} = M_{priv} * C_{wl} * I_w \quad (4)$$

where:
S_{val} – gross estimated value of mineral raw materials in the subsoil;
M_{priv} – amount of reserves and (or) predicted resources of the mineral resource of the object of assessment in the subsoil, reduced by their reliability to the amount of reserves of categories A + B + C1;
C_{wl} – average estimated forecast price determined for the Kondratyev cycle;
I_w – end-to-end extraction of the final product from mineral raw materials in unit fractions.

$$M_{priv} = D_0 \times k_1 + D_1 \times k_2 + C_2 \times k_3 \quad (5)$$

where:
D_0 – prepared resources,
k_1 – confidence factor of category resources D_0,
D_1 – promising resources,

k_2 – confidence factor of category resources D_1,
C_2 – estimated reserves,
k_3 – confidence factor of category reserves C_3.

M_{priv} is calculated using decreasing confidence factors to the amount of reserves with a low degree of exploration and to the amount of predicted resources, depending on the degree of their validity. For specific geometrized objects with a high degree of exploration, predicted resources of low degrees of validity (D2 and D3) (Sharf 2012, Sharf et al. 2016, Sharf 2017) are not included in the calculation. Off-balance reserves, the use of which at the time of assessment is impossible for mining, technical, environmental and technological reasons, are also inappropriate to include in the calculations (Sharf et al. 2016, Sharf et al. 2018). Only those off-balance reserves are included in the calculation, the use of which may become economically feasible as a result of an increase in the price of this type of mineral raw materials. The values of the reliability coefficients are established for groups of fields according to the complexity of their geological structure.

$$P_{wl} = \frac{\sum p_i}{12} \tag{6}$$

where:
P_i – average price for hydrocarbons for a year.

The calculation used a floating discount rate based on changes in the interest rate Federal Reserve System (FED) (Swierzbinski 2013).

So, for example, when producing natural gas, it is worth taking into account the change in well flow rates; the calculations take into account the maximum flow rates and the minimum flow rates, as well as the application of incentives and their absence in relation to income and property tax, as well as preferences for payment of land lease. The calculations were based on the principles of calculating NPV (according to the formula presented above), while various debit rates and changes in the tax environment were assumed. The result of calculations using the model in Excel was Table 1.

Table 1. Distribution of economic efficiency indicators for various scenarios of natural gas production

Indicators / scenario options	Min rates		Max rates	
	no benefits with a constant discount rate	with benefits with a floating discount rate	no benefits with a constant discount rate	with benefits with a floating discount rate
Accumulated cash flow, RUB mln	45,678.33	47,922.12	91,616.52	96,494.15
Net present value (NPV), RUB mln	-5,634.92	9,162.87	6,509.35	14,723.32
Internal rate of return (IRR), %	7.47	12.58	12.59	13.78
Payback period (simple), years	–	11.00	8.00	7.80
Payback period (discounted) (PP), years	–	17.00	15.00	12.00
Return on capital investment index (ID)	0.80	1.26	1.22	1.30

Source: compiled by the author based on the research of Kuzina (2020a)

Taking into account the improvement in the quality and reliability of data even at the stage of development of hydrocarbon fields, Russian projects calculated by the discounted cash flow method (DCF) in 100% of cases have significant deviations from the calculated values. Costs and revenues discounted for a 25-30 year period after 20 years have practically no effect on NPV and internal rate of return (IRR) (Haldar 2018). In addition to the initial data, which are "probabilistic" in nature, discount rates (Dr) have a great influence on the reliability of calculations (Sharf et al. 2016). The conducted studies (Table 2) showed that, depending on the value of the discount rate, the economic estimates of the same object differ by +, - 16.5% of the discount rate adopted in the calculations = 10%.

The need to carry out calculations in Table 2 is that the discount rate in various options shows the change in all indicators of economic efficiency included in the model of economic evaluation of exploration work.

The following results were obtained, according to the hypothesis at the beginning of the work: the main indicators for evaluating the conduct of geological exploration work were determined, such as net discounted cash flow, discount rates, gross appraised value etc. The results obtained can be used for making decisions in the operation of deposits both on the part of the subsoil user and on the part of state bodies.

Table 2. Analytical generalization of the parameters of calculations using the DCF method at various discount rates

Calculation options parameters	Value of indicators		
	IRR	PP	ID
1. calculation at Dr = 5%	14.80	9.8	1.40
2. calculation at Dr = 8%	13.60	10.2	1.36
3. Basic calculation for Dr = 10%	**12.73**	**12.0**	**1.24**
4. calculation at Dr = 12%	12.05	13.2	1.20
5. calculation at Dr = 15%	10.30	14.8	1.18
6. calculation at Dr = 20%	8.60	15.2	1.06

Source: compiled by the author based

Most of the author, whose works I refer to in the introduction, touch upon the problem of assessing the value of a deposit, and not geological exploration for development. These conclusions contradict my point of view, since I believe that, first of all, it is necessary to assess the economic efficiency of geological exploration, and then proceed to the cost estimate of the field.

There are limitations in the assessment of geological exploration work, since all possible risks of a subsoil user making a decision were not taken into account. These contradictions will serve as the basis for my further research.

4. Conclusion

1. An analysis was made of the current state of the literature in the field of methodology and modeling of the economic efficiency of geological exploration in subsoil use.
2. The main methods for the study were considered, the modeling method was chosen, since it is the most optimal when generalizing various objects, processes and phenomena for effective subsoil use.
3. The author has compiled a model of economic evaluation of geological exploration work, which is based on the commodity value of mineral raw materials in the bowels of a particular subsoil use object.
4. The uniqueness of the results lies in the optimization of the main indicators of the valuation of mineral raw materials, the basic principles of calculating the discounted cash flow, discount rate, payback period and internal rate of return are given.

References

Abramov, R., Tronin, S., Brovkin, A., & Pak, K. (2018). Regional features of energy resources extraction in eastern Siberia and the far east. *International Journal of Energy Economics and Policy, 8*(4), 280-287.

Abrikosov, I. Kh., Beilin, A. M. (1983). On the methodology of quantitative forecasting of the effectiveness of prospecting and exploration for oil and gas. *Geology of Oil and Gas*, *12*, 44-48. (in Russian)

Ampilov, Yu. P., Lapo, A. V. (2010). Analysis of geological and economic indicators in assessing the effectiveness of exploration and development of subsoil areas. *Mineral Resources of Siberia*, *5*, 29-34. (in Russian)

Anashkin, O. S., Rokhlin, S. M. (2015). Integral indicators of economic efficiency in the formation of the raw material base of hydrocarbons in Russia. *Subsoil Use XXI Century*, *7*, 130-136. (in Russian)

Bochkarev, A. I., Pashkevich, N. V. (1973). On the economic efficiency of geological exploration. In *Notes of the Mining Institute*, Vol. LXV, Issue 2 (139-142). Leningrad: Leningrad Mining Institute. (in Russian)

Brenner, M. M. (1979). *Economics of oil and gas exploration in the USSR*. Moscow: Nedra. (in Russian)

Emelyanova, N. M., Poroskun, V. I. (2016). Methods of geological and economic evaluation of objects of exploration of oil and gas fields, taking into account uncertainty and risk. *Nedropol'zovaniye, 5*(62), 190-201. (in Russian)

Evseenko, V. V. (2018). *Increasing the economic efficiency of exploration work based on the concept of company value management* (PhD thesis). Saint Petersburg: Saint Petersburg Mining University.

Haldar, S. K. (2018). *Mineral exploration: principles and applications* (pp. 54-65). Elsevier. DOI: 10.1016/B978-0-12-814022-2.01001-7

Hodler, R., Bhattacharyya, S. (2014). Do Natural Resource Revenues Hinder Financial Development? *The Role of Political Institutions // World Development. 57*, 101-113. DOI: https://doi.org/10.1016/j.worlddev.2014.12.003

Kuzina, E. S. (2020a). Aspects of financing geological exploration in subsoil use. *Journal of Advanced Research in Dynamical and Control Systems, 12*(6), 1356-1360. DIO: 10.5373/JARDCS/V12I2/S20201331

Kuzina, E. S. (2020b). Principles and methods of investing in geological exploration in subsoil use. *International Journal of Disaster Recovery and Business Continuity, 11*(3), 2808-2817.

Melekhin, E. S. (2018). *Economic aspects of the formation of a system of rational subsoil use in modern conditions*. Moscow: Russian State University of Oil and Gas (NIU) named after I. M. Gubkin. (in Russian)

Melekhin, E. S., Afonina, I. A. (2018). Problems of geological, economic and cost assessment of subsoil use. *Microeconomics*, *1*, 28-30.

Mikhalchuk, V. (2020). *Anti-crisis strategies of geological exploration and oil service companies.* Deloitte. Retrieved from: https://www2.deloitte.com/content/dam/Deloitte/ru/Documents/energy-resources/Russian/anti-crisis-strategies.pdf (10-02-2021).

Novoselov, A. L., Novoselova, I. Yu., & Melekhin, E. S. (2014). Economic assessment of mineral resources taking into account risks and uncertainties. *Mineral resources of Russia. Economics and Management, 6*, 29-33. (in Russian)

Sharf, I. V. (2012). Analysis of the oil companies' performance (on the example of Tomsk Region). *Economy of Region/Ekonomika Regiona*, *3*, 189-196. DOI: 10.17059/2012-3-18.

Sharf, I. V. (2017). Financial and organizational aspects of the recovery of hydrocarbon resource base in the regional context. *Ekonomika Regiona*, *13*(2), 628-640. DOI: 10.17059/2017-2-26.

Sharf, I. V., Grinkevich, L. S. (2016). Assessing the extraction potential of Tomsk region's difficult-to-obtain oil reserves. *Ekonomika Regiona*, *2*(1), 201-210. DOI: 10.17059/2016-1-15.

Sharf, I. V., Tsibulnikova, M. R., Grinkevich, A. M., & Grinkevich, L. S. (2016). Tax burdens of Russian oil producing companies-comparative analysis. In: *The 27th International Business Information Management Association Conference: 37 Proceedings IBIMA, Milano, May 4-5, 2016* (pp. 440-447). Norristown: IBIMA.

Sharf, I. V., Tsibulnikova, M. R., Ivanova, M. P., & Karpova, E. G. (2018). Formation and distribution of oil and gas revenues. In: *Proceedings of the 32nd International Business Information Management Association Conference, IBIMA* (pp. 751-761). Retrieved from: https://ibima.org/accepted-paper/formation-and-distribution-of-oil -and-gas-reve-nues/ (10-02-2021).

Sharf, I., Sokolova, M., Kochetkova, O., & Dmitrieva, N. (2016). Economic tools for realization of methane production project on Kuzbass coal deposits. *IOP Conference Series: Earth and Environmental Science, 43*(1), 012093). DOI: 10.1088/1755-1315/43/1/012093

Sharf, I., Sundetov, M., Shenderova, I., & Grinkevich, L. (2016). Financial aspects of technological concept for energy efficiency enhancement during stripper wells development in Tomsk region. *IOP Conference Series: Earth and Environmental Science, 43*(11), 012084. DOI: 10.1088/1755-1315/43/1/012084.

Swierzbinski, J. (2013) Economics of Exploration for and Production of Exhaustible Resources. *Encyclopedia of Energy, Natural Resource, and Environmental Economics, 2,* 1-9.

Trofimov, D. M., Shuvaeva, M. K., Chistyakova, K. V., Naumov, K. K., Feofilov, S. A., Shabalin, N. Y., ... & Uspenskii, B. V. (2017). Geological expediency for inclusion of the "easy" methods complex into the geological exploration for oil and gas. *Georesursy*, *19*(2), 97-102. DOI: 10.18599/grs.19.2.2 (in Russian)

Vasiliev, Yu. N. et al. (2015). *Modern economic problems of the development of the mineral resource complex*. Moscow: Gornaya Kniga. (in Russian)

Volovich, V. N. (2013). Ways and forms of rational use of natural resources in conditions of intensification of social production. *Obshchestvo. Sreda. Razvitiye (Terra Humana), 3*(28), 20-24. (in Russian)

Voskresenskaya, E. V., Vorona-Slivinskaya, L. G., Snetkov, V., & Tebryaev, A. (2019). Ecological and legal regulation of geological survey, exploration and extraction of minerals during construction. *E3S Web of Conferences, 91*, 08013. DOI: 10.1051/e3sconf/20199108013

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State of the Art in the End-of-Life Vehicle Recycling

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Abstract: Growing ecological awareness in society and legal regulations aimed at reducing the negative impact of used products on the environment means that waste management begins to play a significant role in the modern world. Therefore, it is necessary to conduct research towards the organization and implementation of waste management. It has been noticed that an important link in the economy is the recycling of used products. Thus, numerous studies are undertaken in the direction of organization, improvement, automation and computerization of the product and material recycling process. The article presents the results of literature research in terms of the implementation of the end-of-life vehicle recycling process.

Keywords: waste management, reuse, recovery, recycling,
end-of-life vehicle (ELV), recycling network, recycling system, disassembly

1. Introduction

Efficient waste management is a challenge to be faced by today's society. Waste generated at the stage of production is being called post-production waste, it results from production technology and defective products (Woźniak et al. 2017, Nawrocki et al. 2018, Kielec et al. 2018). In the area of production, measures are taken, environmental research is carried out (Lenort et al. 2019), the aim of which is to reduce the amount of waste generated by this sector. One of such activities is the use of 3D scanning and 3D printing technology in the production process

(Jakubowski et al. 2016, Jakubowski et al. 2017, Jakubowski et al. 2018, Królikowski et al. 2019, Królikowski et al. 2019a, Pałka et al. al. 2020). The reduction of post-production waste is in line with the implemented concept of Industry 4.0 (Kostrzewski et al. 2020, Królikowski et al. 2021). Waste generation can also be counteracted by modern technologies (Szajna et al. 2020, Zwolińska et al. 2020, Szajna et al. 2020a, Szajna et al. 2019) implemented in the industry, which are also part of the Industry 4.0 concept.

However, an important element in waste management are urban areas, which have to cope with a significant amount of waste generated by city dwellers (Zajac et al. 2019, Zajac et al. 2019a, Zajac et al. 2020, Zatrochova et al. 2020). The waste generated in this way should be collected and transported (Izdebski & Jacyna 2018), with minimized amount of partially filled transports (Wozniak et al. 2016, Wozniak et al. 2018) and an environmentally friendly transport system (Jacyna et al. 2018) in the scope of the implemented concept of sustainable transport (Chamier-Gliszczyński 2011, Chamier-Gliszczyński & Bohdal 2016, Chamier-Gliszczynski 2016a).

Pursuant to Directive 2008/98/EC, waste management refers to the implementation of processes related to the collection, accumulation, transport and processing of waste. Taking into account the provisions of the directive, waste management covers a number of processes, i.e. segregation $\boldsymbol{SE}$, collection $\boldsymbol{ZB}$, transport $\boldsymbol{TR}$, storage $\boldsymbol{MA}$, recovery $\boldsymbol{OD}$, disposal $\boldsymbol{UN}$, supervision $\boldsymbol{NA}$, which are necessary for the implementation of waste management. Thus, we can write $\boldsymbol{MWM}$ waste management in the form of an ordered set of seven:

$$\boldsymbol{MWM} = \langle \boldsymbol{SE}, \boldsymbol{ZB}, \boldsymbol{TR}, \boldsymbol{MA}, \boldsymbol{OD}, \boldsymbol{UN}, \boldsymbol{NA} \rangle \tag{1}$$

The article focuses on the recovery process, which includes all activities leading to the reclamation of waste in whole or in part, leading to obtaining substances, materials or energy. Pursuant to EU legislation, a recovery process is any activity which does not pose a threat to life, human health or the environment, which leads to the use of waste in whole or in part, recovery of substances, materials or energy from waste and their use. Thus, recovery can be written as a two-element set of processes, i.e.:

$$\boldsymbol{OD} = \{\boldsymbol{OE}, \boldsymbol{R}\} \tag{2}$$

The elements in such a set are the energy recovery process $\boldsymbol{OE}$ and the recycling process $\boldsymbol{R}$.

The article presents analysis of the recycling process, which means the re-processing of waste in the production process in order to obtain substances or materials for primary or other purposes.

The aim of the article is to present selected activities and research that are undertaken towards the implementation of the recycling process in the area of transport with special focus on the end-of-life vehicle recycling process. The implementation of the goal will be based on the literature analysis of the issue. The research process will use data available on the Scopus and Web of Science platforms.

2. Recycling in transportation

Waste management in transportation is an important element of activities, here – recycling is the most common process. Recycling is a component of two forms of recycling, i.e. product recycling $\boldsymbol{RP}$ and material recycling $\boldsymbol{RM}$, i.e.:

$$\boldsymbol{R} = \{\boldsymbol{RP}, \boldsymbol{RM}\} \tag{3}$$

Product recycling $\boldsymbol{RP}$ consists of recovering parts and components in good technical condition from used products (e.g. end-of life vehicles (ELV)). The elements recovered in such a way become spare parts that can be successfully reused. The recycling defined in this way can be divided into two forms of recovery, i.e.:

$$\boldsymbol{RP} = \{\boldsymbol{RP_B}, \boldsymbol{RP_R}\} \tag{4}$$

The first form is direct product recycling $\boldsymbol{RP_B}$, that is disassembly of parts and subassemblies that can be directly reused. The second form is product recycling in the form of $\boldsymbol{RP_R}$ regeneration, which consists in restoring the functional properties of the recovered part through the regeneration process. It is important that regeneration requires additional expenditure in the form of manpower, the use of appropriate technology and raw materials, as opposed to direct product recycling.

On the other hand, material recycling consists in processing the parts recovered from used products into raw materials. Regarding end-of life vehicles, the set $\boldsymbol{RM}$ can be written as (Chamier-Gliszczyński 2011a):

$$\boldsymbol{RM} = \boldsymbol{MS} \cup \boldsymbol{MN} \cup \boldsymbol{MT} \cup \ldots \cup \boldsymbol{MP} \tag{5}$$

The elements of the $\boldsymbol{RM}$ collection are recovered raw materials, i.e. $\boldsymbol{MS}$ – steel scrap, $\boldsymbol{MN}$ – non-ferrous scrap, $\boldsymbol{MT}$ – plastics, $\boldsymbol{MP}$ – liquid raw materials (fuel, oils, operating fluids), etc.

The implementation of a complex recycling process in waste management allows not only material and energy savings but is also a necessity resulting from the recommendations relating to waste management. The recommendations state that waste generation should be avoided, and if it cannot be avoided, it should be reused for the same or a different purpose. If this is not possible, it should be stored or disposed in an environmentally safe way.

3. Research project

The research project concerns a literature review on the implementation of research in the field of vehicle recycling. The research will be based on the Web of Science and Scopus databases. For the purposes of the research, the end-of life vehicles $\boldsymbol{MRELV}$ model was defined in the form of an ordered five, i.e.:

$$\boldsymbol{MRELV} = \langle \boldsymbol{RS}, \boldsymbol{NS}, \boldsymbol{DP}, \boldsymbol{RR} \rangle \tag{6}$$

The first element of the model is $\boldsymbol{RS}$ research on the treatment of ELV recycling in system categories. Interpreted ELV recycling system is an interrelated system of technical, organizational and human measures, the aim of which is to implement the process of recycling used vehicles.

Another element is research on the construction and organization of the ELV $\boldsymbol{NS}$ recycling network. The ELV recycling network consists of entities that participate in the process of waste vehicle management and a set of characteristics described on the network connections (e.g. financial, material, information characteristics). The purpose of creating the system and network is to minimize the negative impact of used vehicles on the environment and to obtain raw materials for production. The research area related to the ELV recycling system is presented in Table 1, and to the ELV recycling network in Table 2.

Table 1. Research areas for the ELV recycling system

Research area	Source
Development of assumptions for the construction of the ELV recycling system. Interpretation of the system in a block layout.	Chamier-Gliszczyński 2011b
Comparative studies of ELV recycling systems operating in the EU, Japan, Korea, China and the USA	Sakai et al. 2014
Optimization research of the ELV recycling system based on ExtendSim software	Deng et al. 2018
A conceptual approach to the problem of vehicle recycling in China	Yu et al. 2019
Research integrating the ELV recycling system in China in terms of material flow and LCA life cycle assessment	Liu et al. 2020
Research on the ELV recycling process in a systemic perspective	Li et al. 2021
SWOT analysis for the ELV recycling system	Numfor et al. 2021
Analysis of activities in the area of the ELV recycling system in the aspect of extended responsibility of the vehicle manufacturer	Khan et al. 2021

Table 2. Research areas for the ELV recycling network

Research area	Source
Identification of the recycling network in a three-stage system of collection and recycling of used vehicles	Chamier-Gliszczyński 2005
Optimization of the location of enterprises operating within the ELV recycling network with the criterion of total network operating costs	Merkisz-Guranowska 2010
Identification of a two-criteria model for the location of recycling companies, taking into account the preferences of vehicle owners and enterprises	Merkisz-Guranowska 2013
Optimization studies of the location of disassembly stations in the ELV recycling network	Gołębiewski et al. 2013
Research on the business model of SMEs participating and cooperating in the ELV recycling network	Hovest et al. 2016
Optimization research of the recycling network in terms of CO_2 emissions	Xiao et al. 2019
Optimization research on the example of the recycling network operating in Istanbul	Kusakci et al. 2019
Research in the area of ELV recycling network design	Merkisz-Guranowska 2020

The core element of the ELV recycling system and network is the $\boldsymbol{DP}$ disassembly process, which is the basis for the idea of recovering components and materials from used vehicles. It is the disassembly process that enables product and material recycling. This process is another element of the end-of life vehicles $\boldsymbol{MRELV}$ model, and the research in this area is presented in Table 3.

Table 3. Research areas for ELV disassembly

Research area	Source
Description and identification of the elements of the disassembly process	Chamier-Gliszczyński 2010
Optimization of the recovery of elements and materials from ELV based on the implementation of the disassembly process	Chamier-Gliszczyński 2011c
Optimization of the disassembly process using the PSO (particle swarm optimization) algorithm	Zhou et al. 2016
Analysis of the storage process as one of the elements in the ELV disassembly station	Kudelska et al. 2017

Table 3. cont.

Research area	Source
Implementation of the method of sustainable resource management at the ELV disassembly station	Kosacka et al. 2017
Research on the disassembly process in the aspect of the concept of sustainable development and analytical evaluation of the process using the AHP method	Zhang & Chen 2018
Research on the development of a line for disassembly of vehicles	Zhang & Chen 2018a
Automation of the ELV disassembly process, implementation of RFID technology	Dia & Zhou 2018
Multi-criteria assessment of the disassembly process as a support for the ELV recycling process	Li et al. 2019
Research on the development of decision-making processes at the stage of disassembly implementation in ELV recycling companies	Czajda et al. 2019
Description of the waste management method in the ELV dismantling process	Kosacka-Olejnik 2019
Sustainable design of a plant with an ELV dismantling line	Li et al. 2021
Optimization of the ELV disassembly process with a description of the individual process steps	Zhang & Liu 2021

Research in the field of ELV recycling is also carried out in relation to individual parts, subassemblies and given materials. Research is also carried out on the development of indicators for assessing the recycling process. In the end-of life vehicles $\boldsymbol{MRELV}$ recycling model, these studies are identified as other studies relevant to the implementation of ELV recycling. Study identifications in the area of other $\boldsymbol{RR}$ studies are presented in Table 4.

Tabele 4. Research areas in the category of other ELV recycling studies

Research area	Source
Research on the development of energy storage with the use of ELV batteries	Jajczyk & Słomczyński 2019, Filipiak et al. 2019, Jajczyk & Lorkiewicz 2018
Planning and Management of the Mechanical Assembly Sequences	Sąsiadek et al. 2018

Tabele 4. cont.

Research area	Source
End-of-life vehicle management: a comprehensive review	Karagoz et al. 2019
Optimizing energy consumption in the ELV recycling process	Petronijevic et al. 2020
The State of the Air Quality in Poland	Gabryelewicz et al. 2020
Raw material and environmental safety of industrial processes	Gabryelewicz et al. 2021
Research on the use of robots in the process of recycling batteries from vehicles	Zhou et al. 2021
Modeling the market for ELV recycling	Mohan & Amit 2021
Application of the Deep CNN-Based Method in Industrial System for Wire Marking Identification	Szajna et al. 2021
Research on the implementation of a unique recycling strategy aimed at the simultaneous use of the cathode and anode from waste batteries	Meng et al. 2022

4. Summary

The problem of managing used products with an indication of used vehicles has long been a subject of discussion. It was the European Union that was one of the first to take steps to regulate this issue. The activities focused on regulating the issue of waste collection and its processing in a manner that does not endanger the environment. An important element in these activities is the process of developing end-of-life vehicles. For this purpose, the recovery process has been defined and its components in the form of product and material recycling have been specified. It was also emphasized that the disassembly process is the basic element of recycling. The research process, the results of which are presented in the article, showed that one of the important issues in this regard is the systemic approach to the end-of life vehicle recycling process, the organization of a recycling network and research to improve the ELV disassembly process.

References

Chamier-Gliszczynski, N., Krzyzynski, T. (2005). On modelling three-stage system of receipt and automotive recycling. *REWAS'04, Global Symposium on Recycling, Waste Treatment and Clean Technology 2005*, 2813-2814, Madrid, Spain, 26-29 September 2004, Conference Paper, ISBN: 8495520060.

Chamier-Gliszczyński, N. (2010). Optimal Design for the Environment of the Means Transportation: A Case Study of Reuse and Recycling Materials. *Sold State Phenomena*, *165*, 244-249. DOI: 10.4028/www.scientific.net/SSP.165.244

Chamier-Gliszczyński, N. (2011). Sustainable operation of transport system in cities. *Key Engineering Materials*, 486, 175-178. DOI: 10.4028/www.scientific.net/KEM.486.175

Chamier-Gliszczyński, N. (2011a). Recycling Aspect of End-of Life Vehicles. Recovery of Components and Materials from ELVs. *Key Engineering Materials*, *450*, 421-424. DOI: 10.4028/www.scientific.net/KEM.450.421

Chamier-Gliszczyński, N. (2011b). Reuse, Recovery and Recycling System of End-of Life Vehicles. *Key Engineering Materials*, *450*, 425-428. DOI: 10.4028/www.scientific.net/KEM.450.425

Chamier-Gliszczyński, N. (2011c). Environmental aspects of maintenance of transport means, end-of life stage of transport means. *Eksploatacja i Niezawodnosc – Maintenance and Reliability*, *50(2*), 59-71. http://ein.org.pl/podstrony/wydania/50/pdf/07.pdf

Chamier-Gliszczyński, N., Bohdal, T. (2016). Mobility in urban areas in environment protection. *Rocznik Ochrona Srodowiska*, *18*(1), 387-399.

Chamier-Gliszczynski, N. (2016a). *City Logistics – Sustainable Urban Mobility*. CLC 2015: Carpathian Logistics Congress – Conference Proceedings, 263-268, Jesenik, Czech Republic, 04-06 November 2015.

Czwajda, L., Kosacka-Olejnik, M., Kudelska, I., Kostrzewski, M., Sethanan, K., Pitakaso, R. (2019). Application of prediction markets phenomenon as decision support instrument in vehicle recycling sector. *LogForum*, *15*(2), 265-278. DOI: 10.17270/J.LOG.2019.329

Deng, HX., Wang, WQ., Zhao, Y. (2018). Optimization design of end-of-life vehicle recycling system based on ExtendSim. *University Politehnica of Bucharest Scientific Bulletin Series C-Electrical Engineering and Computer Science*, *80*(3), 95-108.

Dia, G., Zhou, Z. (2018). Human Centered Automation System for ELV Disassembly Line. *Lecture Notes in Electrical Engineering*, *451*, 347-355. DOI: 10.1007/978-981-10-5768-7_37

Filipiak, M., Jajczyk J., Dobrzycki A. (2019). Changes in the range of electric vehicles during operation. *ITM Web of Conferences*, *28*, 01009, DOI: https://doi.org/10.1051/itmconf/20192801009.

Gabryelewicz, I., Stryjski, R., Wędrychowicz, M., Dąbrowski, T. (2020). The State of the Air Quality in Poland. *Rocznik Ochrona Srodowiska*, *22*(2), 998-1013, ISSN: 1506-218X

Gabryelewicz, I., Wędrychowicz, M., Pántya, P., Krupa, P. (2021). Raw material and environmental safety of industrial processes. *P: Environmental safety – non-energy and raw materials: scientific monograph*, / ed. I. Gabryelewicz, M. Wędrychowicz, Zielona Góra: Oficyna Wydaw. Uniwersytetu Zielonogórskiego, 11-37, ISBN: 9788378424437

Gołębiewski, B., Trajer, J., Jaros, M., Winiczenko, R. (2019). Modelling of the location of vehicle recycling facilities: A case study in Poland. *Resources, Conservation and Recycling*, *80*(1), 10-20. DOI: 10.1016/j.resconrec.2013.07.005

Hovest, G.G., Grama, C., Urosevic, L., Stokic, D. (2016). *Collaborative environment for virtual collaborative networks of ELV recycling SEEs*. 2008 IEEE International Technology Management Conference, ICE 2008, 27 April 2016, 7461998.

Izdebski, M., Jacyna, M. (2018). The Organization of Municipal Waste Collection: the Decision Model. *Rocznik Ochrona Srodowiska*, *20*, 919-933.

Jacyna, M., Wasiak, M., Lewczuk, K., Chamier-Gliszczyński, N., Dąbrowski, T. (2018). Decision Problems in Developing Proecological Transport System. *Rocznik Ochrona Srodowiska*, *20*(2), 1007-1025. http://ros.edu.pl/images/roczniki/2018/059_ROS_V20_R2018.pdf

Jajczyk, J., Słomczyński, K. (2019). A dedicated battery for an electric bike. *ITM Web of Conferences*, *28*, 01033. DOI: https://doi.org/10.1051/itmconf/20192801033.

Jajczyk, J., Lorkiewicz, W. (2018). Data bus modelling in city buses. *ITM Web of Conferences*, *19*, 01036. DOI: https://doi.org/10.1051/itmconf/20181901036.

Jakubowski, J., Woźniak, W. (2016). *Development of a new educational model for virtual measurement machina*. Proceedings of the 27th International Business Information Management Association(IBIMA), ISBN: 9780986041969, 4-5 May 2016, Milan, Italy, 2102-2109.

Jakubowski, J., Woźniak, W. (2017). *The management of product-development technologies supported by CAx techniques*. Proceedings of the 29th International Business Information Management Association (IBIMA), ISBN: 9780986041976, 3-4 May 2017, Vienna, Austria, 3218-3229.

Jakubowski, J., Woźniak, W., Stryjski, R. (2018). *The Use of 3D Scanning and Measurements, as Modern Tools in the Management of Quality*. Proceedings of the 31st International Business Information Management Association (IBIMA), ISBN: 9780999855102, 25-26 April 2018, Milan, Italy, 5946-5955.

Karagoz, S., Aydin, N., Simic, V. (2020). End-of-life vehicle management: a comprehensive review. *J. Mater. Cycles Waste Manag, 22*, 416-442. DOI: 10.1007/s10163-019-00945.

Khan, S.A.R., Godil, D.I., Thomas, G., Tanveer, M., Zia-Ul-Hang, H.M., Mahmood, H. (2021). The decision-making analysis on end-of-life vehicle recycling and remanufacturing under extended producer responsibility policy. *Sustainability*, *13*(20), 11215. DOI: 10.3390/su132011215

Kielec, R., Sąsiadek, M., Woźniak, W. (2018). *Adoption of the Evolutionary Algorithm to Automate the Scheduling of the Production Processes*. Proceedings of the 31st International Business Information Management Association (IBIMA). ISBN: 9780 999855102, 25-26 April 2018, Milan, Italy 5039-5046.

Kosacka, M., Werner-Lewandowska, K. (2017). Methodology for Sustainable Resource Management Measurement at a Company Level – Case Study. *Procedia Manufacturing*, *11*, 725-733. DOI: 10.1016/j.promfg.2017.07.173

Kosacka-Olejnik, M. (2019). How manage waste from End-of-Life Vehicles? – method proposal. *IFAC-PapersOnLine*, *52*(13), 1733-1737.

Kostrzewski, M., Chamier-Gliszczynski, N., Królikowski, T. (2020). Selected reflections on formal modeling in Industry 4.0. *Procedia Computer Science*, *176*, 3293-3300. DOI: 10.1016/j.procs.2020.09.118

Królikowski, T., Knitter, R., Blazejewski, A., Glowinski, S., Kaminski, K. (2019a). Emission of particles and VOCs at 3D printing in automotive. *Smart Innovation, Systems and Technologies*, *155*, 485-494. DOI: 10.1007/978-981-13-9271-9_40

Królikowski, T., Knitter, R., Blazejewski, A., Zmuda Trzebiatowski, P., Zuchniewicz, J., Bak, A. (2021). Industry 4.0 – supporting industry in design solutions-all-in-one computer cover. *Smart Innovation, Systems and Technologies*, *200*, 93-105. DOI: 10.1007/978-981-15-8131-1_9

Królikowski, T., Knitter, R., Stachnik, M. (2019). Hermo-mechanic tests using 3d printed elements. *Procedia Computer Science*, *159*, 2552-2559. DOI: 10.1016/j.procs.2019.09.430

Kudelska, I., Kosacka, M., Lewandowska, K. W. (2017). How to support storage process in dismantling facility with IT solutions? – case study. *Procedia Manufacturing*, *11*, 703-710. DOI: 10.1016/j.promfg.2017.07.170

Kusacki, A.O., Ayvaz, B., Cin, E., Aydin, N. (2019). Optimization of reverse logistics network of End of Life Vehicles under fuzzy supply: A case study for Istanbul Metropolitan Area. *Journal of Cleaner Production*, *215*, 1036-1051. DOI: 10.1016/j.jclepro.2019.01.090

Lenort, R., Baran, J., Wysokiński, M., Gołasa, P., Bieńkowska-Gołasa, W., Golonko, M., Chamier-Gliszczyński, N. (2019). Economic and environmental efficiency of the chemical industry in Europe in 2010-2016. *Rocznik Ochrona Srodowiska*, *21*(2), 1398-1404.

Li, C.J., Yang, W.X., Liu, X.D., Wang, Y.M., Feng, S.H., He, Y.A. (2021). Research on vehicle recycling based on ELV Directive. *IOP Conference Series: Earth and Environmental Science*, *687*(1), 012196. DOI: 10.1088/1755-1315/687/1/012196

Li, H., Wang, Y., Fan, F., Yu, H., Chu, J. (2021). Sustainable Plant Layout Design for End of Life Vehicle Recycling and Disassembly Industry Based on SLP Method, A Typical Case in China. *IEEE Access.* DOI: 10.1109/ACCESS.2021.3086402

Li, j., Barwood, M., Rahimifard, S. (2019). A multi-criteria assessment of robotic disassembly to support recycling and recovery. *Resources Conservation and Recycling*, *140*, 158-165. DOI: 10.1016/j.resconrec.2018.09.019

Liu, M., Chen, X., Zhang, M., Lv, X., Wang, H., Chen, Z., Huand, X., Zhang, X., Zhang, S. (2020). End-of-life passenger vehicles recycling decision system in China based on dynamic material flow analysis and life cycle assessment. *Waste Management*, *117*, 81-92. DOI: 10.1016/j.wasman.2020.08.002

Meng, YF., Liang, HJ., Zhao, CD., Li, WH., Gu, ZY., Yu, MX., Zhao, B., Hou, XK., Wu, XL. (2022). Concurrent recycling chemistry for cathode/anode in spent graphite/LiFePO4 batteries: Designing a unique cation/anion-co-workable dual-ion battery. *Journal of Energy Chemistry*, *64*, 166-171. DOI: 10.1016/j.jechem.2021.04.047

Merkisz-Guranowska, A. (2010). Issues related to the optimization of location of vehicle recycling network entities. *Archives of Transport*, *22*(3), 303-318. DOI: 10.2478/v10174-010-0018-x

Merkisz-Guranowska, A. (2013). Multicriteria optimization model for end-of-life vehicles' recycling network. *International Journal of Sustainable Development and Planning*, *8*(1), 88-99. DOI: 10.2495/SDP-V8-N1-88-99

Merkisz-Guranowska, A. (2020). A comparative study on end-of-life vehicles network design. *Archives of Transport*, *54*(2), 107-123.

Mohan, TVK., Amit, RK. (2021). Modeling oligopsony market for end-of-life vehicle recycling. *Sustainable Production and Consumption*, *25*, 325-346.

Nawrocki, W., Stryjski, R., Woźniak, W., Jakubowski, J. (2018). Improving the Quality of Manufacturing Processes in Toyota Motor Manufacturing, Poland. Proceedings of the 31st International Business Information Management Association (IBIMA) ISBN: 9780999855102, 25-26 April 2018, Milan, Italy 5931-5945.

Numfor, S.A., Omosa, G.B., Zhang, Z., Matsubae, K. (2021). A review of challenges and opportunities for end-of-life vehicle recycling in developing countries and emerging economies: A swot analysis. *Sustainability*, *13*(9), 4918. DOI: 10.3390/su13094918

Pałka Ł., Kuryło P., Klekiel T., Pruszyński P. (2020). A Mechanical Study of Novel Additive Manufactured Modular Mandible Fracture Fixation Plates – Preliminary Study with Finite Element Analysis 2020, Injury: International Journal of the Care of the Injured, *51*(7), 1527-1535, ISSN: 0020-1383, eISSN: 1879-0267.

Petronijevic, V., Dordevic, A., Stefanovic, M., Arsovski, S., Krivokapic, Z., Misic, M. (2020). Energy Recovery through End-of-Life Vehicles Recycling in Developing Countries. *Sustainability*, *12*(21), 8764. DOI: 10.3390/su12218764

Sakai, S., Yoshida, H., Hiratsuka, J., Vandecasteele, C., Kohlmeyer, R., Rotter, VS., Passarini, F., Santini, A., Peeler, M., Li, JH. (2014). An international comparative study of end-of-life vehicle (ELV) recycling systems. *Journal of Material Cycles and Waste Management*, *16*(1), 1-20. DOI: 10.1007/s10163-013-0173-2

Sąsiadek, M., Kielec, R., Woźniak, W., Niedziela, M. (2018). *Planning and Management of the Mechanical Assembly Sequences*. Proceedings of the 31st International Business Information Management Association (IBIMA) ISBN: 9780999855102, 25-26 April 2018, Milan, Italy 4712-4719.

Szajna, A., Szajna, J., Stryjski, R., Sąsiadek, M., Woźniak, W. (2019). The Application of Augmented Reality Technology in the Production Processes. *Advances in Intelligent Systems and Computing*, *835*, 316-324. ISBN: 9783319974897

Szajna, A., Kostrzewski, M., Ciebiera, K., Stryjski, R., Wozniak, W. (2021). Application of the Deep CNN-Based Method in Industrial System for Wire Marking Identification. *Energies*, *14*(12), 1-35. DOI: 10.3390/en14123659

Szajna, A., Stryjski, R., Wozniak, W., Chamier-Gliszczynski, N., Królikowski, T. (2020a). The production quality control process, enhanced with augmented reality glasses and the new generation computing support system. *Procedia Computer Science*, *176*, 3618-3625. DOI: 10.1016/j.procs.2020.09.024

Szajna, A., Stryjski, R., Woźniak, W., Chamier-Gliszczynski, N., Kostrzewski, M. (2020). Asessment of augmented reality in manual wiring production process with use of mobile AR glasses. *Sensors*, 20(17), 1-26, 4755. DOI: 10.3390/s20174755

Woźniak, W., Kielec, R., Sąsiadek, M., Wojnarowski, T. (2018). A Functional Analysis of Selected Transport Exchanges and Tendering Platforms in the Transport Orders Market. Proceedings of the 31st International Business Information Management Association (IBIMA) ISBN: 9780999855102, 25-26 April 2018, Milan, Italy 5047-5055.

Woźniak, W., Nawrocki, W., Stryjski, R., Jakubowski, J. (2017). Identification and Reduction of Product Defects in Mass Production at Toyota Motor Manufacturing, Poland. Proceedings of the 30th International Business Information Management Association (IBIMA), ISBN: 9780986041990 8-9 November 2017, Madrid, Spain 4774-4782.

Woźniak, W., Stryjski, R., Mielniczuk, J., Wojnarowski, T. (2016). *The concept of the profitability for the transport orders acquired from the transport exchange market*. Proceedings of the 27th International Business Information Management Association (IBIMA), ISBN: 9780986041969, 4-5 May 2016, Milan, Italy 2375-2383.

Xiao, Z., Sun, J., Shu, W., Wang, T. (2019). Location-allocation problem of reverse logistics for end-of-life vehicles based on the measurement of carbon emissions. *Copmuter and Industrial Engineering*, *127*, 169-181. DOI: 10.1016/j.cie.2018.12.012

Yu, LF., Chen, M., Yang, B. (2019). Recycling policy and statistical model of end-of-life vehicles in China. *Waste Management & Research*, *37*(4), 347-356. DOI: 10.1177/0734242X19833150

Zajac, P., Haladyn, S., Kwasniowski, S. (2019). *Concept of reducing harmful emissions by road transport vehicles in the tourist route Karpacz, Jelenia Góra*. In E3S Web of Conferences, 100, 00091. EDP Sciences. DOI: 10.1051/e3sconf/201910000091

Zajac, P., Skoczynski, W., Romanowicz, W. (2019a). *Studies of properties of RFID tags used in mechatronic and logistic systems*. 25th International Conference Engineering Mechanics 2019, Svratka, Czech Republic, 13-16 May 2019, 415-418. DOI: 10.21495/71-0-415

Zajac, P., Stas, D., Lenort, R. (2020). Noise Charge in Rail Transport-EU Regulations Versus Operation of Logistics Systems. *Rocznik Ochrona Srodowiska*, *22*, 226-241.

Zatrochova, M., Kuperova, M., Golej, J. (2020). Analysis of the Principles of Reverse Logistics in Waste Management. *Acta logistica*, *8*(2), 95-106. DOI: 10.22306/al.v8i2.208.

Zhang, C., Liu, C. (2021). An Improved GA with Matrix-Coding for Optimizing a Complex Disassembly Sequence Problem on ELV. *International Journal of Pattern Recognition and Artificial Intelligence*. DOI: 10.1142/S0218001421590461

Zhang, CL., Chen, M. (2018). Prioritising alternatives for sustainable end-of-life vehicles disassembly in China using AHP methodology. *Technology Analysis & Strategic Management*, *30*(5), 556-568. DOI: 10.1080/09537325.2017.1340640

Zhou, Z., Dia, G., Cao, J., Guo, G. (2016). A novel application of PSO algorithm to optimize the disassembly equipment layout of ELV. *International Journal of Simulation: Systems, Science and Technology*, *17*(46), 16.1-16.6.

Zhou, L., Garg, A., Zheng, J., Gao, L., Oh, KY. (2021). Battery pack recycling challenges for the year 2030: Recommended solutions based on intelligent robotics for safe efficient disassembly, residual energy detection, and secondary utilization. *Energy Storage*, *3*(3), e190. DOI: 10.1002/est2.190

Zhang, CL., Chen, M. (2018a). Designing and verifying a disassembly line approach to cope with the upsurge of end-of-life vehicles in China. *Waste Management*, *76*, 697-707. DOI: 10.1016/j.wasman.2018.02.031

Zwolińska, B., Tubis, A.A., Chamier-Gliszczynski, N., Kostrzewski, M. (2020). Personalization of the MES system to the needs of highly variable production. *Sensors*, *20*(22), 1-25, 6484. DOI: 10.3390/s20226484