Rocznik Ochrona Środowiska

Volume 23 | Year 2021 | ISSN 1506-218X | pp. 384-407

https://doi.org/10.54740/ros.2021.026 | open access

Received: 29 June 2021 | Accepted: 20 July 2021 | Published: 06 December 2021

Management Model Improving Environmental Protection

*Paweł Zając**
Faculty of Mechanical Engineering,
Wroclaw University of Science and Technology, Poland
https://orcid.org/0000-0003-3103-832X

Jarosław Poznański
Warsaw University of Technology, Warsaw, Poland
https://orcid.org/0000-0001-6708-7401

**corresponding author's e-mail: pawel.zajac@pwr.edu.pl*

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).

$$Q_a = (\sum_1^{12} Q_{week}) \cdot 4{,}33 \quad \text{[Mg/year]} \qquad (1)$$

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.

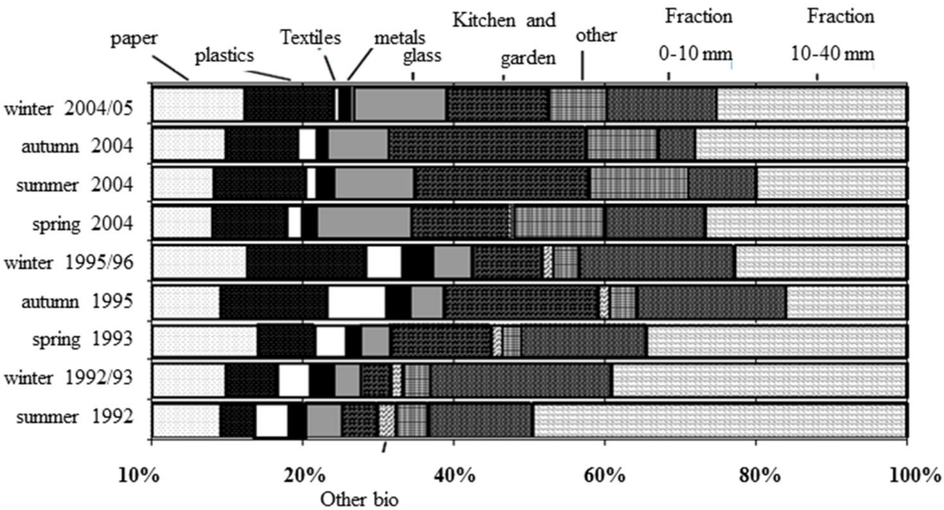

Fig. 1. Composition of municipal waste in 1992-2005 in Wrocław

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.

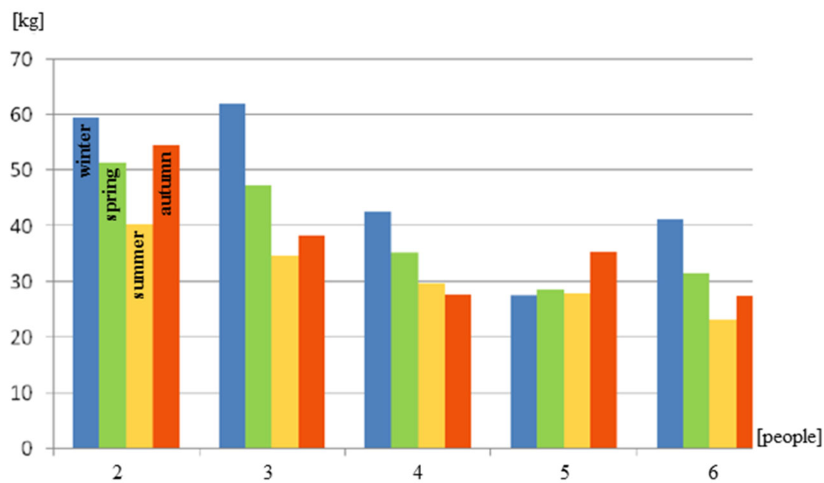

Fig. 2. Seasonal household waste accumulation rates in rural areas [kg/M]

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).

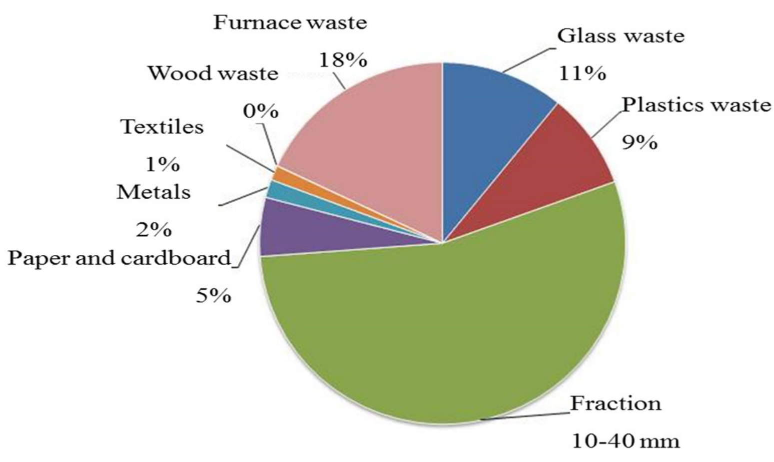

Fig. 3. Waste composition in rural areas during winter

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.

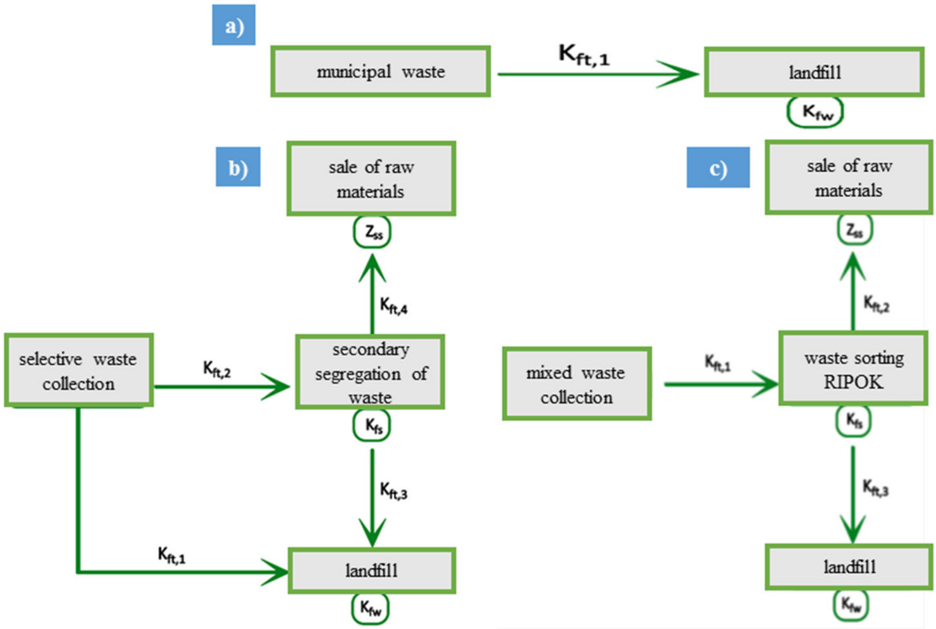

Fig. 4. Model in total landfilled waste, where: K_{ft}means the cost of operation of the transport company, while K_{fs} means the cost of operation of the RIPOK: Polish acronym: Regional Municipal Waste Processing Facility, and K_{fw} means the cost of landfilling waste, while Z_{ss} means profit from 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.