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Proposal of a Logistics Solution for an Emergency at a Nuclear Facility

Oľga Végsöová, Martin Straka, Kamil Kyšeľa*
Technical University of Kosice, Slovakia
**corresponding author's e-mail: e-mail: martin.straka@tuke.sk*

1. Introduction

At present, when solutions are being sought to mitigate the effects of global warming and climate change, nuclear energy is one of the interesting alternative energy sources in the ecological energy sector, of course assuming it is used in a safe form.

Proponents consider nuclear energy to be one of the possible solutions to the looming energy crisis, while its opponents fight against the use of nuclear energy, because of: fear of radiation, the risks associated with the operation itself or problems with nuclear waste.

As already indicated, a nuclear power plant and its operations have only a minimal negative impact on the environment. Nuclear power plants do not emit any greenhouse gases, so they contribute to reducing emissions. Zhang et al. (2020) points out that the aim of using nuclear and renewable energy is to reduce greenhouse gases and improve the quality of the environment. Soder (2009) argues that at a time of climate change, dwindling oil supplies and high consumer prices, nuclear energy is an essential part of the future energy spectrum. Chen et. al. (2019) stated that nuclear energy has become a common source of energy for communities around the world. Despite the relatively small number of global incidents, there is still potential for a nuclear disaster. The construction of a nuclear power plant has a great economic benefit in terms of the development of a region, having a positive impact on employment and therefore on the living standards of the population living in the vicinity. Fuentes-Saguar et al. (2017), point out in their work that a possible decommissioning of a nuclear power plant would have a demonstrably adverse effect on employment and created added value in the region.

Over time, however, the impact on the environment and ecology has become the most important criteria. According to Deng et.al. (2018) The development of nuclear energy is a key measure for implementing energy saving and emission reduction strategies worldwide.

One of the chief elements acting on humans is radon, which is found in building materials, Ali et al. al. (2019) point to the direct effect of radon on human health and the possibility of cancer when it enters the lungs. Humans are also commonly exposed to radiation from TVs, watches and, last but not least, X-rays used in medicine. Pogue et. al. (2018) consider the possible carcinogenic effects to be one of the disadvantages of X-rays. Furukawa et. al. (2020), in their work, unequivocally confirmed the negative impact of radiation on human DNA as well as the mechanisms of its natural regeneration.

Nuclear power plants are a critical part of infrastructure from the perspective of safety. The failure of a nuclear power plant causes not only economic losses, but it is a particular threat to the safety of the whole country and significantly affects the surrounding environment. Connor et. al. (2020) argue that immediately after a large-scale release of radioactive material into the environment, it is necessary to quickly determine the spatial distribution of radioactivity. Mlakar et. al. (2019) point out that nuclear power plants should constantly invest resources in improving safety and risk management. Persons in the immediate vicinity of a nuclear power plant are exposed to the greatest risks. Therefore, it is important to properly create and model situations describing evacuation from the power plant. Liu et. al. (2012) argue that that emergency evacuation is one of the most important nuclear accident risk management measures. Evacuation management systems contain various complexities that present many challenges for decision makers. Lee et. al. (2019) state that the occurrence of an emergency or crisis situation usually requires an immediate solution for the protection of the population.

Failure management includes pre-planned, dedicated activities that ought to make optimal use of the plant's existing equipment in a normal as well as unusual manner if the design limits are exceeded. The main objective in the event of a nuclear power plant failure is to protect human lives. Shimada et. al. (2018) point out that the decision to evacuate is crucial, especially for vulnerable populations. The primary problem that must be solved in the event of an exceptionally undesirable circumstance in a nuclear power plant is the evacuation of people located in the power plant building itself. In order to actively react to these emergencies, it is necessary to develop an emergency rescue plan before an adverse event occurs. Zong et. al. (2019) hold the opinion that emergency evacuation research has become an important and urgent issue. The evacuation process places high organizational demands on cooperation among the rescue and security forces. Řehák and

Folwarczny (2012) and Folwarczny and Pokorný (2006) argue that the rescue process requires the cooperation of different actors in a complex environment, so effective communication is needed to streamline emergency operations. Effective communication is a prerequisite for timely and therefore successful intervention. The aim must be predetermined communication with a predetermined range of communication topics, having a positive effect on the accuracy and speed of obtaining information from the communication partner. Gallego et. al. (2017) argue that the aim of communication is to provide accurate and clear messages that can serve to reassure the public. Gershon et. al. (2012) state that time is the most valuable resource in an emergency. Shorter rescue times could save more lives and reduce overall damage. Xie et al. (2020) are of the opinion that accident detection and rescue response times should be shortened in order to enable victims to receive the necessary emergency care as soon as possible.

Phark (2018) points out that evacuation performed by recommendation and leading through natural authority and social contact is most effective. Yang et. al. (2015) point out that the efficiency of evacuation increases with an increasing number of escorts until the number reaches the optimal level. Murakami et.al. (2015), Koščo et al. (2019), Trebuna et al. (2019) and Dyntar et al. (2020) state that it is necessary to adapt the evacuation plan to the specific conditions in order to increase the success of the evacuation.

Based on the studied literature, the article deals mainly with the time aspect of the evacuation of persons located in the nuclear power plant. In this paper, we model the evacuation from one building in the power plant complex, which has a nuclear shelter.

2. Theoretical basis, safety assessment at a nuclear facility

The importance of safety is significant in the production of electricity in a nuclear power plant. It is therefore necessary to address the situation of an emergency caused by the failure of a nuclear installation, and it is important to inform the public in a timely and thorough manner. Table 1 from Bromová et al. (2013) offers us an overview of the severity of individual areas affected by an emergency.

The information flow and the procedure for dealing with emergencies differ based on certain degrees of severity of these events. The internal emergency plan states the classification and assessment of incidents based on their severity that have an actual or potential impact on the level of nuclear safety. According to Table 2, which is part of the internal emergency plan of Slovenské elektrárne (2011) we classify extraordinary events according to their severity into three degrees.

Table 1. Description of the impact of degrees of severity on the individual areas affected by the emergency. Source: own elaboration

Stage	Relevant name	Impact on			Source	Measures
		People and the environment	Radiation barriers	Depth protection		
1	Anomaly	little impact	negligible impact	deviation from the approved operating mode	stolen or lost source with low radioactivity	
2	Accident	excess irradiation of the employees of the given operation (above the permitted values)	spread of contaminati on - significant	serious breach of security measures without real consequences	finding an abandoned high-level radioactive source, equipment or transport container with intact safety precautions; insufficient packaging of a sealed highly radioactive source	
3	Serious accident	greater impact on the health of employees (acute effects of irradiation); little impact on the population living in the vicinity of the SW	spread of contaminati on - large	safety barriers gone	a lost or stolen highly radioactive sealed source; a highly radioactive sealed source that has been delivered to a different location than the intended delivery location	

Table 1. cont.

Stage	Relevant name	Impact on			Source	Measures
		People and the environment	Radiation barriers	Depth protection		
4	Accident with effects in a nuclear facility	irradiation of the population within the permitted limits; lethal irradiation of employees	there is significant damage to the reactor core			
5	Accident with effects on the environment	leakage of radioactive material – limited	serious damage to the reactor core occurs			likely deployment of some of the planned measures (considering gravity of the situation)
6	Serious accident	leakage of radioactive material – serious				likely deployment of planned countermeasures
7	Large accident	extensive impact on public health and the environment				deployment of the planned measures and, depending on the gravity of the situation, the deployment of extended measures

Table 2. Characteristics of degrees of classified events based on severity.
Source: Slovenské elektrárne (2011)

1st degree	Alert	A condition in which the performance of safety functions is endangered or impaired.
		Safety barriers are compromised or inoperable.
		There is a possible threat of leakage, or the leakage of radioactive substances has occurred in the facilities of the nuclear facility.
2nd degree	Emergency on the site of a nuclear facility	A situation in which there is a possibility of leakage or the result of the situation is the leakage of radioactive substances outside the structures of the nuclear facility and into adjacent territory.
3rd degree	Emergency around a nuclear facility	A situation in which there is a possibility of a serious leakage of radioactive substances or the result of this situation is a serious leakage of radioactive substances into the area around a nuclear installation.

Since the intended evacuation takes place in groups for calculation, formulas will be used which focus on calculating the evacuation of the stream of evacuees. Therefore, first of all, it is necessary to calculate the density of the stream, where we use formula proposed by Folwarczny and Pokorný (2006), defined as:

$$D_p = \frac{E \,.\, f}{b \,.\, l} \tag{1}$$

where:
D_p – density of stream [-],
E – number of persons [persons],
f – area per person [$m^2 \cdot person^{-1}$],
b – current width [m],
l – current length [m].

Since we assume that people will move only on horizontal paths without obstacles, we will use the formula for the calculation:

$$v = 112 \,.\, D_p^4 - 380 \,.\, D_p^3 + 434 \,.\, D_p^2 - 217 \,.\, D_p + 57 [m.min^{-1}] \tag{2}$$

where:
v – speed of movement of persons [$m \cdot min^{-1}$],
D_p – current density [-].

3. Case study, proposal of an evacuation plan for the Mochovce Nuclear Power Plant

Evacuation, as one of the basic ways of protecting the population, ensures the safe movement of persons from the endangered building at the Mochovce Nuclear Power Plant (Mochovce NPP) to the open area and the possible transfer of persons by means of transport to the designated evacuation points. The analysis evaluated the possibilities for the potential arrival times of the external rescue services with which Mochovce NPP has a contractual agreement.

The proposed evacuation is intended for a building with a capacity of 400 people and at the same time this building has a shelter in case of an emergency.

The case study offers two proposals. Both proposals involve evacuation in groups; group A consists of 20 people and group B consists of 50 people.

The calculations are adapted to the assumption that only one pair of firefighters will escort the groups. The building from which the evacuation takes place is defined as follows. The entrance of the building is oriented to the west, directly feeding onto the road along which the evacuation will take place. Assuming that the building is single-storey, we are working with an area of 700 m^2. Due to this area, a capacity of 400 people was chosen. If each person has an area of 1 m^2 available, the rest is calculated as non-efficient area (walls etc.). The length of the road leading from the evacuation building to the assembly point is 70 metres. The width of the road is 7.5 metres (3 metres per lane). The assembly in the form of the parking lot has dimensions of 50x100 metres. We work with an area of 5000 m^2. It follows that evacuees can gather at this location. Given that both men and women can move in this building, and we know that the structures of the bodies of the sexes are different. The calculations be based on the physiological structure of the figure of the man as the largest possible alternative. The width of a person is measured at shoulder height and for a man this average value is 510 mm. For the front-back dimension, this value is approximately 280 mm. Fig. 1 shows the structure described.

The following variants were considered for the evacuation plan of Mochovce NPP, labelled A and B.

Group A will consist of 20 people. Evacuees will be moved in a formation consisting of two lines and the number of persons in a row will be 10. For this reason, the approximate width of the stream of persons will be 1020 mm and the approximate length of the lines will be 3000 mm. The area per person is a table value for an adult in moderate clothing, $f = 0.113$ m^2 per person.

The results of variant A show the total time of evacuation from the given building to the assembly point in groups of 20 people and accompanied by only one group of accompanying firefighters; the time taken is expected to be 122 minutes.

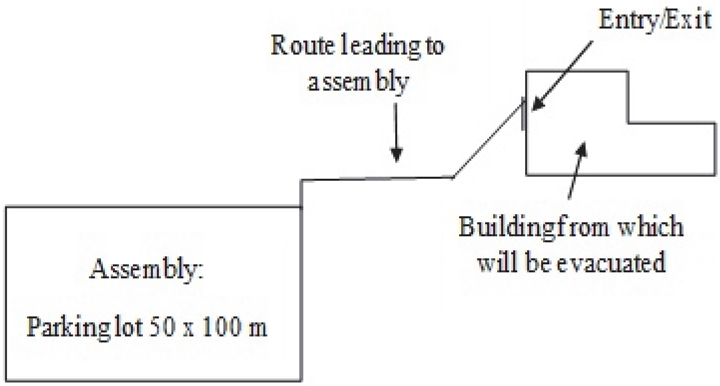


Fig. 1. Drawing of the structures that we need for evacuation. Source: own elaboration

Group B will consist of 50 people. Evacuees will be moved in a formation of 3 lines, in each of which there will be 16 persons, with the exception of 1 row that will consist of 17 persons. However, we ignore the data on this last person in the calculation; due to the number of people in this large group, it is not necessary to take this data into account. The width of the stream will be 1530 mm and the length of a row will be approximately 4800 mm. The area per person is a tabular value for an adult in moderate clothing, f = 0.113 m^2 per person.

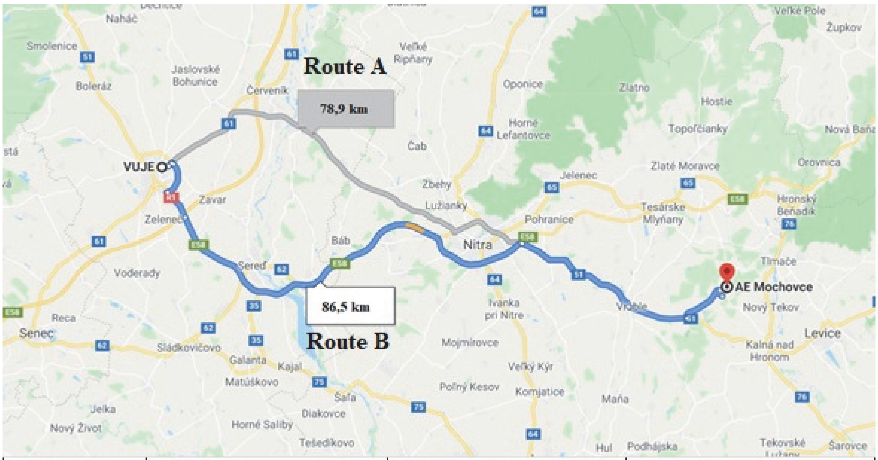
The design of Option B results in a total expected evacuation time of 52 minutes from the given building to the assembly point in groups of 50 people and accompanied by only one group of accompanying firefighters.

In the event of an emergency, Mochovce NPP has the opportunity to call on the help of external organizations. Due to the fact that the organizations are not in close proximity to the facility, it is necessary to calculate the approximate time of arrival after which the organizations could start the activities necessary to deal with the emergency situation.

When looking for the route, there are two suitable routes in the direction from the premises of VUJE a.s., Trnava to the premises of Mochovce NPP, which are marked on the map in Fig. 2. As seen on the map, they vary in length. Travel time is calculated for both routes, due to the fact that the routes differ in length and particularly differ in terms of the roads the routes follow. Route A leads along first-class roads as we can see on the map, therefore the maximum speed is 50 $km \cdot h^{-1}$. Route B, which is longer, runs on expressways and on the roads of the European road network, where the maximum permitted speed is 130 $km \cdot h^{-1}$. It also includes first class routes, on which the maximum permitted speed is 50 $km \cdot h^{-1}$. Therefore, in the case of B, the average speed is 90 $km \cdot h^{-1}$.

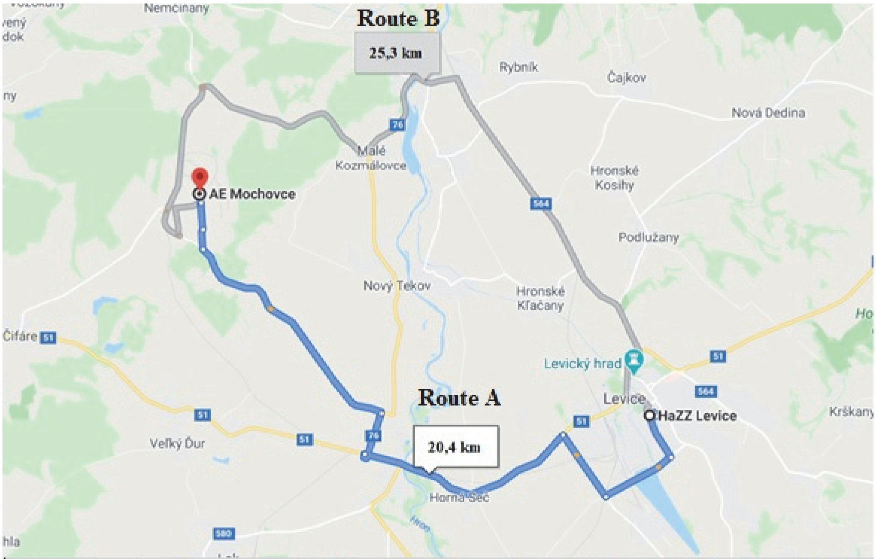
The map in Fig. 3 shows two routes from the premises of the fire station in Levice to the premises of Mochovce NPP. Both of the routes follow first class roads, where the max. allowed speed 50 km · h^{-1}. With regard to regulations, the speed for the calculations is set at 45 km · h^{-1}.

From the Fire and Rescue Brigade's station based in Malacky, there are three potential roads leading to the Mochovce NPP site, as shown in Fig. 4. The shortest, route A, leads mostly along roads that are part of the European road network in combination with first class roads. Assuming that the vehicles used in the intervention will be fire engines or larger, the average speed will be 83 km · h^{-1} because on expressways and motorways, vehicles weighing more than 3500 kg have a maximum permitted speed of 100 km · h^{-1}. Routes B and C are also combinations of European network routes and first-class roads, but the average speeds are different in the calculations due to the varying lengths of the different types of roads used.



Route	Route lenght [km]	Driving speed [km.h^{-1}]	Driving time [min]
A	78,9	50	95
B	86,5	90	58

Fig. 2. Lengths routes VUJE as, Trnava - Mochovce NPP. Source: own elaboration



Route	Route lenght [km]	Driving speed [km.h^{-1}]	Driving time [min]
A	20,4	45	29
B	25,3	45	35

Fig. 3. Route lengths Fire and Rescue Corps Levice - Mochovce NPP. Source: own elaboration

Route	Route lenght [km]	Driving speed [km.h^{-1}]	Driving time [min]
A	142	83	190
B	160	70	138
C	164	87	114

Fig. 4. Route lengths Fire and Rescue Brigade to Mochovce NPP. Source: own elaboration

4. Conclusion

A nuclear power plant is a complex and extensive facility in which special emphasis is placed on safety and evacuation procedures. Even during the design stage of the nuclear power plant, care must be taken to ensure that the location of the buildings and the nuclear shelter is such that the transfer to the evacuation assembly point is as efficient as possible.

An important role for government authorities is to anticipate the deployment of rescue services, so as to ensure, as far as possible, their quick arrival at the site of an emergency at a nuclear power plant. The proper location of all rescue services is essential for the safety of the whole area. The construction of such a system will significantly increase the protection of employees of the Mochovce NPP, as well as the population living in the area around of the structure in question.

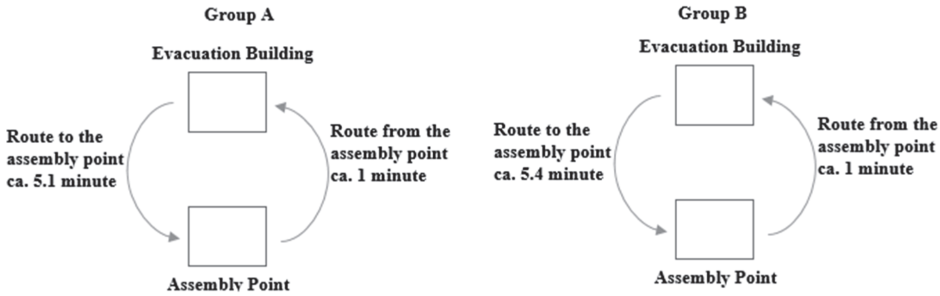
The main motivation for the submitted contribution is therefore the aforementioned rescue of nuclear power plant employees and the surrounding population, but also the provision of the maximum possible level of safety for all the units involved.

The proposal points out how the number and formation of the evacuated group affects the time of the evacuation. It is logical that the more people we put in the group, the faster the evacuation will take place. However, the number of people in the group is determined by the surrounding environment and, last but not least, by employees' regular practices. Due to the size of the group, there are other aspects that need to be monitored, such as the increasing demands on supervision by escorts in a larger group. This supervision is necessary in view of the strain on the situation associated with the emergency. As we can see from the results, the fewer people in the group, the longer the evacuation time will be. It is therefore necessary to model a group size the composition of which will not place excess demand on the necessary supervision of the group and at the same time the number of individuals in the group will be maximized.

The evacuation time is not only affected by the number of individuals in the group but also by the number of trips that firefighters have to take during the evacuation.

A clear comparison of the evacuation design of variants A and B is shown in Fig. 5.

As regards calling external rescue services, the most effective help that arrives at the destination first in our case is the Levice Fire and Rescue Brigade, which must travel along a route of 20.4 km, taking 29 minutes.



Description	Group A	Group B
D_p	0.74 [-]	0.77 [-]
v	13.7 m. min^{-1}	13.1 m. min^{-1}
X	5.1 min	5.4 min
Number of groups	20	8
Cycle there	102 minutes	44 minutes
Cycle back	20 minutes	8 minutes
Total cycle of evacuation	122 minutes	52 minutes

Fig. 5. Comparison of proposals A and B for evacuation in Mochovce NPP.
Source: own elaboration

In the case study, we start from the assumption that all examined external basic components are ready in terms of material and personnel for an emergency situation at Mochovce NPP.

The optimal way to perform this process as safely as possible in the shortest possible time could be to set up more groups of accompanying firefighters to accompany groups with fewer evacuees. However, we would then need a large number of staff members, which sometimes cannot be provided if we realize that the numbers of rescue services are limited and dependent on the travel times of external rescue services, which are also part of the work and depend on their location in the region.

The present proposal also points out how the evacuation of people from the power plant is to take place. The calculations confirmed the strengths as well as weaknesses of the evacuation removal process from the power plant area.

This knowledge and the suggestions for evacuation can be applied and adapted to similar structures and situations. At the same time, it is possible to assume that the travel times of external organizations will be an informational benefit in the creation of evacuation and rescue plans for the nuclear power plant and can also serve as a basis for providing technical assistance to units involved in dealing with emergencies at Mochovce NPP.

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Abstract

This paper examines the evacuation of people in the event of an emergency caused at a nuclear facility. The study describes the emergency preparedness of the Mochovce Nuclear Power Plant. The paper describes the proposal of the logistics solution and the implementation of protective and emergency preparation, which is determined by the internal emergency plan, based on the information flow in the event of an emergency and the activities of individual emergency response units. The above results indicate that the fewer people there are in one evacuated group, the longer the evacuation time will be. However, the reason is not the length of time to get to the assembly point itself, but the number of groups that must be created and therefore the higher number of trips that firefighters have to take. The optimal way to carry out this process safely, in the shortest possible time, could be to set up more groups of escorting firefighters, who would accompany groups with smaller numbers of evacuees. Strict preparation and adherence to pre-prepared instructions, based on logistical principles in the event of an emergency at a nuclear facility, minimizes loss of life and harm to the health of persons, and also damage to property or the environment.

Keywords:
environmental protection, nuclear power plant, emergency, logistics, evacuation