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Advanced Methods and Approaches in Fire Safety of Buildings

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Case Study

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Abstract

The paper deals with the advanced of progressive computer-aided modelling tools in the practice of fire protection. The main of the implemented study was to solve a specific fire scenario, simulating the real conditions of the environment and fire and its spread, based on the practical application of computer-supported modelling in the PyroSim program, to point out the possibilities of applying these tools in the practice of fire protection. In this case, it was a fire on the 6th floor of block A in the main building of the Technical University in Zvolen. The fire scenario itself was created based on knowledge and experience gained from a tactical training with the same subject, which was connected also by declaring a practice fire alarm at the Technical University in Zvolen and evacuating the entire main building. Based on the knowledge and experience from the tactical training, which were also confirmed by the results of modelling and simulation of fire behaviour, risks were identified and measures were proposed for activities in terms of three aspects of ensuring the safety of persons in the event of a fire: penetration of information about the occurrence of a fire and subsequent measures of employees; declaration of alarm, evacuation, escape and verification of completeness of evacuees; construction-technical solution and condition of the object.

Keywords: fire safety of buildings; PyroSim; school facility; training fire alarm.

1 Introduction

The behaviour of fires in indoor areas is subject to fire engineering, which is also related to determining the degree of fire safety in buildings as well as in the design of fire safety equipment (systems). Of course, it all depends on the expected fire behaviour, which is in correspondence with material and constructions fire properties as well as environment conditions. The dynamics of indoor fire are also related to computer modelling of fires, which is currently used. There are several types of computer models, the most complex of which are CFD models. Modelling also plays an essential role in the current trend of integrating access into the fire engineering [1-9]. Computer-aided modelling is now an integral part of investigative procedures.

Modelling, but also describing the development of fire in fire dynamics, is based on data on the rate and amount of energy released, energy transfer mechanisms and environmental parameters. For the correct calculation (estimation) of the rate and amount of energy released, the decisive characteristic is the amount of combustible substance (fuel). To obtain input data, we can also use the results of experimental fire tests of flammable substances. In addition, for some types of flammable liquids, flammable polymeric solids and some products, accurate data on the heat released, the rate of combustion, the rate of formation and concentration of flue gases and others are available in various databases. Where such data are used, the availability and rate of oxygen access and ventilation conditions as well as escape routes for the evacuation of disabled persons shall be considered in a particular case. When modelling the behaviour of an indoor fire, when changing the parameters of a fire environment, computational fluid dynamics (CFD) systems are most often applied in practice, based on the application of field models, in this case specifically Fire Dynamic Simulator (FDS) and its graphical interface PyroSim. The SmokeView as well as Smartfire and Pathfinder environments are used to assess options for controlled evacuation of persons from the fire-threatened area.

PyroSim was developed by the American company Thunderhead Engineering (USA) in 2008. The basic functions of PyroSim include interactively creating a complex geometry of the space in which fire is modelled (creating models of buildings using floor plans, creating repetitive objects, curved walls, and other complex elements of buildings, such as a staircase, etc.), importing existing input FDS files and, to some limited extent, models created in the AutoCAD (Computer Aided Design software application developed for 2D, and 3D design). In addition to the geometry editor for FDS, the current version of PyroSim integrates the FDS system itself and the SmokeView visualization program, which is part of the FDS [10].

FDS is generally a complex program system that simulates the flow of fire-induced gases, the spread of heat by radiation, burning, estimating the concentration of substances released during a fire. It can simulate fires in various objects, such as buildings, garages, tunnels, technical equipment (e.g., cars). It does not need to model fire to deal with gas dynamics, so it can also deal, for example, with the movement of toxic gases in fireless areas. All input data is entered using a single text input file, and the most difficult part is often to define the geometry of the modelled space. For the simulation of a fire to be as accurate as possible, it is necessary to define the geometry and properties of all, for fire and its propagation of the inevitable, bodies and holes in each space. These can then, according to their chemical and physical properties, act as an obstacle to the spread of fire and gas flow, conduct or emit heat, or burn. They can also attenuate the intensity of a fire or be inert to it (they are not affected by it and have no effect on the fire).

At the same time, for a fire model, it is necessary to enter the actual amount of material by determining the thickness of the material. To represent the inclined surfaces of bodies in a rectangular lattice, there is a technique of "smoothing" the surface, in which the system performs calculations as with an uncooled surface, but the removal of turbulences that arise near the inclined surfaces represented in the rectangular lattice is programmed. The inclined surface in this case is visualized as a smooth surface. Among the necessary input parameters for body surfaces that need to be determined are the properties of the material. In FDS, devices for measuring fire parameters such as heat released, temperature of walls, bodies, or gases at points of space or in sections, gas concentration can also be included in the simulation. One of the most important input parameters in modelling is the maximum rate of release of heat produced from 1 m^2 in fuel-controlled fires.

This paper deals with the issue of fire behaviour modelling and the possibilities of applying computer-aided modelling tools to the practice of fire protection. Based on the practical application of selected computer models to solve specific fire scenarios simulating real environmental conditions and fire and its spread, the intention of the conducted study was to point out the possibilities of applying these tools in the practice of fire protection. In this case, it was a fire on the 6th floor of block A in the main building of the Technical University in Zvolen. In addition, the task was to find out the basic parameters for the development and spread of fire and smoke, to determine the parameters of the time required for the safe evacuation of persons from the fire-threatened area.

A similar issue was addressed by Xiao et al. [11] used the PyroSim software to numerically simulate a fire situation based on the size and volume of a prefabricated building construction site to ensure the safe construction of prefabricated buildings and improve the efficiency of the safe evacuation of construction personnel after a fire caused by improper operation during construction. The variation rules of smoke visibility, CO concentration, and ambient temperature in the construction site of prefabricated buildings were analysed and the available safe evacuation time was determined. Moreover, the Pathfinder software was used for simulation in combination with the physical attributes of personnel, evacuation speed, and personnel proportions. The time required for safe evacuation was determined and the factors influencing the evacuation time, such as the quantity and location of stacked prefabricated components, machinery, and appliances, and the number of on-site construction personnel, were analysed.

2 Material and Methods

In this section, the subject and object of research are characterized, the methodology used for processing the study is described.

The object of the research was to find out the basic parameters of the development and spread of fire and smoke, which originated on the 6th floor in the main building of the Technical University in Zvolen (TUZVO), to determine the parameters of the time required for the safe evacuation of persons from the fire-threatened area using progressive tools of mathematical and computer-aided modelling of fire development and controlled evacuation procedures.

The object of research was the 6th floor in block A of the main building of TUZVO.

The main building of TUZVO is located on T. G. Masaryka Street 24, 960 01 Zvolen, Slovakia. It is used for teaching full-time and part-time students, but also for the implementation of scientific and research activities by professional employees of TUZVO.

TUZVO main building consists of 3 blocks with a different number of floors. Block A consists of 8 above-ground floors, block B 7 floors and block C 6 floors. At the same time, the main building has 1 underground floor. The structural system has been assessed as non-combustible in accordance with Article 2.6 of STN 92 0201-2 [12]. In accordance with Art. 2.2.6 STN 92 0201-2, the fire height (h) was set at 25.5 m. The legislation currently in force dealing with the fire safety of buildings does not apply to the TUZVO building, as it was built before the regulations currently in force were issued.

A total of 6 escape routes lead from the building to the open air, the number of which varies depending on the floor, which creates difficult conditions for evacuation. From the 7th and 6th floors there are 2 unprotected escape routes. From the 5th to 1st floors there are 4 unprotected escape routes. The route of unprotected escape routes leads through corridors and staircases. The building has 2 main staircases located at the interface of blocks A/B and B/C. Main staircase A/B runs from the basement to the 7th floor, between the basement and the 6th floor it has a width of 2.5 escape lanes, from the 6th to the 7th floor it has a width of 2 escape lanes. The main staircase B/C leads from the basement to the 5th floor with a constant width of 2.5 escape lanes. At the end of block A there is a backup staircase connecting the ground floor with the 7th floor with a width of 1.8 escape lanes. At the end of block A there is a second backup staircase connecting the ground floor with the 5th floor with a width of 1.6 escape lanes. From the ground floor and its classrooms, a greater number of escape routes lead to the open air in different directions.

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The following materials were used in the structures and premises of the offices and laboratories located on the 6th floor of the main building of TUZVO, block A. Vertical structures (walls) are concrete, plastered with lime cement plaster. On the floor of the laboratory there is ceramic tile. The interior of the laboratory is equipped with furniture (chairs and tables) and built-in wardrobes made of chipboard. The windows are filled with glass filling. The glass used for filling window frames is an insulating double-glazed window achieving class 2 acoustic insulation parameters and with a heat transfer coefficient of Ug=0,1 W/(m^2·K). This is a product made of two simple drawn flat panes of glass with a thickness of 4 mm. The internal dimension of the gap between the glasses is 16 mm, and the gap is filled with inert gas with argon. All entrance doors are made of chipboard, while the thickness of the door is 50 mm. The floor in the hallway is made of PVC. The floor in the offices located on the 6th floor is made up of PVC covered with carpet.

In the case of a fire simulated, we entered the heat release rate of concrete at 1,000 kW/m^2 and the plaster at 100 kW/m^2 [13]. Glass belongs to fire response class A1, i.e., non-combustible. In the simulation, we specified its heat release rate at 500 kW/m^2 [13]. For chipboard used as cladding of built-in cabinets, as well as wooden furniture located in the laboratory, we used a heat release rate value of 2,250 kW/m^2 [2] in the modelling and simulation of fire in the PyroSim.

As part of the processing of the study, the documentation (including graphic changes in the project in the AutoCAD environment) and the calculation of all parameters necessary to ensure the fire safety of the object, i.e., the main building of TUZVO, were updated. This state was also used in the process of creating a 3D model of construction in the ANSYS environment (3D model Spaceclaim and conversion to STL format, which the PyroSim program works with).

2.1 Fire model and fire scenario

Modelling and simulation of fire and smoke propagation during a fire that originated in a laboratory located on the 6th floor in block B of the main building of TUZVO were carried out in PyroSim ver. 2014.4.1105, licensed by the Department of Fire Protection, which is also the graphical user interface of the Fire Dynamics Simulator (FDS) fire model. An important input into modelling was the input of heat release rate (HRR) values for all flammable elements of structures and interior equipment. The simulation duration was set at 3.5 min, which is the maximum permissible evacuation time according to STN 92 0201-3 [14].

The fire scenario was chosen in accordance with the theme of the tactical training itself associated with the training fire alarm, which preceded the modelling process itself and the knowledge of which we used in its creation. The fire originated in the laboratory of the Department of Wood Technology, which is located near the door leading from the corridor of the 6th floor of block A to the main staircase located between blocks A/B. The fire initiating source was turned on hot air oven, which, due to a technical error, did not turn off, overheated, while its surface temperature reached 1,000 °C for 60 s. The HRR data of other combustible materials in the room have been set in accordance with [2].

The monitored parameters were the transfer of combustion (smoke) and later fire products to the corridor and to neighbouring rooms within the standard time, i.e., 3.5 min, which is necessary to ensure the safe evacuation of persons from the fire-threatened area.

2.2 Theme of the tactical training associated with the practice fire alarm

The tactical training of Fire and rescue Service officers with the management staff, which took place on 03/09/2021 from 9.00 AM, with a focus on practicing how to deploy, manage forces and resources in fire destruction and evacuate persons from the premises of the main building of TUZVO and especially the 6th and 7th floors, was also attended by TUZVO employees.

The performed tactical training had several objectives:

- Practicing the method of deploying forces, managing forces and resources in extinguishing a fire in the premises of the TUZVO building on the 6th floor of block A.
- Practicing fire management and evacuation of persons with the establishment of a control headquarters and its simultaneous functioning with TUZVO employees included in the fire-alarm directives.

- Practicing the activities of commanding and intervening Fire and Rescue Service officers from several fire stations.
- Practicing cooperation in the deployment of forces and assets of the components of the Integrated Rescue System and related to the practice of the actionability of fire brigades, equipment as well as cooperation of Fire and rescue Service officers and members of the municipality volunteer fire brigades.
- Practicing the cooperation of Fire and rescue Service officers and employees of TUZVO.
- Practicing and mastering the operational-tactical peculiarities of fire and evacuation of persons from high-rise buildings.
- Verification of the deployment of mobile altitude equipment and climbing equipment.

The tactical training focused on:

- Evacuation of persons and destruction of fire.
- Activities of the management staff of the district headquarters of Fire and Rescue Service in Zvolen.
- Cooperation with TUZVO employees.
- Cooperation, deployment of municipality volunteer fire brigades.
- Possibilities of using boarding areas.

2.3 Training fire alarm at the Technical University in Zvolen

The training fire alarm began on 03/09/2021 with the detection of the EPS smoke sensor in the laboratory of the Department of Wood Technologies, which is located on the 6th floor of the main building of TUZVO, block A.

It was signalized on the electric fire alarm (EFA) control panel, which is located on the main gatehouse of TUZVO. The gatekeeper deactivated the sensor, closed the gatehouse and the main entrance to TUZVO, and went to check the situation by the main staircase between blocks A/B. After noticing smoke, which had already penetrated the stairs and the 5th floor in the meantime, she reported the fire to the emergency call line. She briefly announced the location of the fire, what and where it was burning, the extent of the fire and smoke Subsequently, she declared a fire alarm by calling *F I R E* and using electronic fire alarms. Subsequently, he also reported the fact by telephone to the fire reporting office.

After the alarm was sounded by the call *F I R E*, there was a gradual evacuation of persons mainly from the 7th - 5th floors of blocks A and B and subsequently the entire main building of TUZVO. Meanwhile, the attending porter returned to the main gatehouse, opened the main entrance for the purpose of entering the intervening firefighters, gave them information, and then personally and manually opened the side escape exits from the main building. The evacuees gathered in the open air near the fountain, where their presence was to be checked according to the status recorded in the attendance system. In the meantime, an inspection of the abandoned premises of the main building was carried out to search for disabled persons or persons to whom information about the fire did not penetrate.

In this case, although it was supposed to be a controlled evacuation, it was gradual but spontaneous, since the change in legislation created a situation where fire patrols in workplaces were abolished, since their existence is not required by the current legislation.

2.4 Draft measures in relation to improving the level of fire safety of the main building of the Technical University in Zvolen

The measures that were proposed pursued the objective of reducing the fire risk and thus the degree of fire safety by dividing the structure into several fire compartments, since today this structure forms one fire compartment, which means that in the structure the fire and combustion fumes will spread rapidly to all its premises, since there are no elements or fire-dividing structures that would prevent the spread of fire and combustion products to other parts for the required time, which is necessary to ensure the safe evacuation of persons and, where appropriate, also property.

Optimization of procedures for the controlled evacuation of persons was carried out using the tools of mathematical modelling and at the same time compliance with the conditions set by the relevant fire standard.

3 Results and Discussion

We divided the results of the study into 3 main parts. First, we present the results of the modelling and simulation of the fire from the PyroSim, although this was realized only after the implementation of the tactical training and based on observations, identified shortcomings, and updating data on the construction solution of the structure and its and their detailed examination. Subsequently, there are introduced the findings of performed tactical training, which took place in the main building of TUZVO in September 2021. Lastly, we propose the content of the new documentation of fire safety of the structure, i.e., the main building of TUZVO, considering the most serious shortcomings that prevent the safe and timely evacuation of persons from the area threatened by fire and combustion products.

3.1 Results of fire scenario modelling and simulation

In PyroSim, we performed a simulation of the fire that originated in one of the laboratories of the Department of Wood Technologies, in the main building of TUZVO on the 6th floor of block A (Fig. 1).

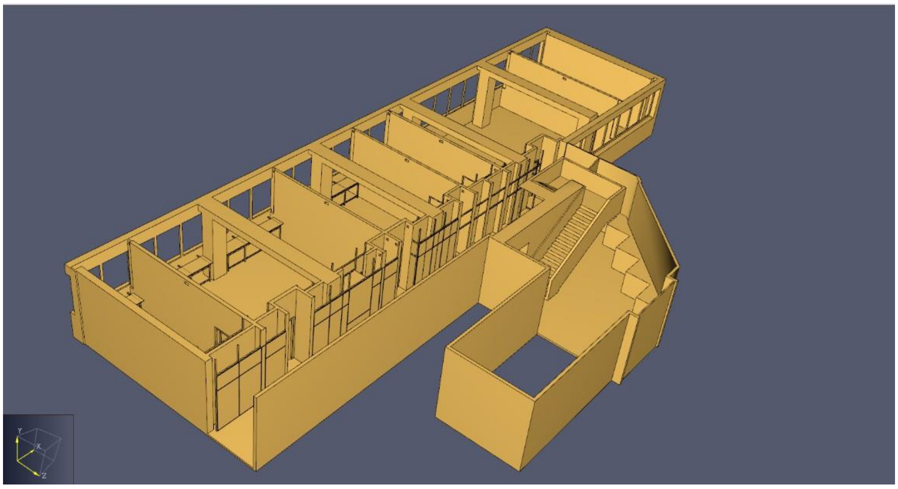

Fig. 1 3D model 3D model of the 6th floor spaces

The duration of the simulation was set to 3.5 min, which is the maximum permissible evacuation time according to the standards. The fire spread to the hallway / escape entry and was detected in the hallway / escape entry at 3.2 minutes (Fig. 2).

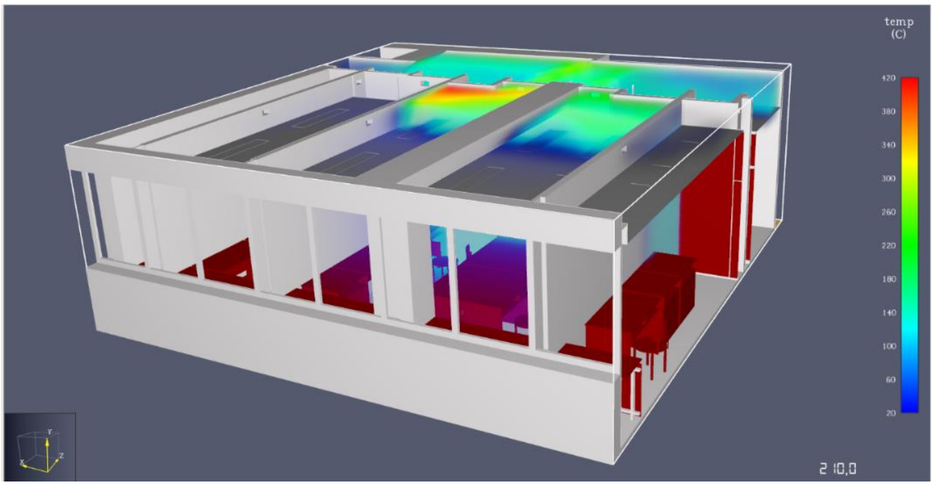

Fig. 2 Temperature zones of the fire spreading from the laboratory space to the hallway

Significant smoke and the gradual transfer of smoke to adjacent rooms were noticeable (Fig. 3, 4).

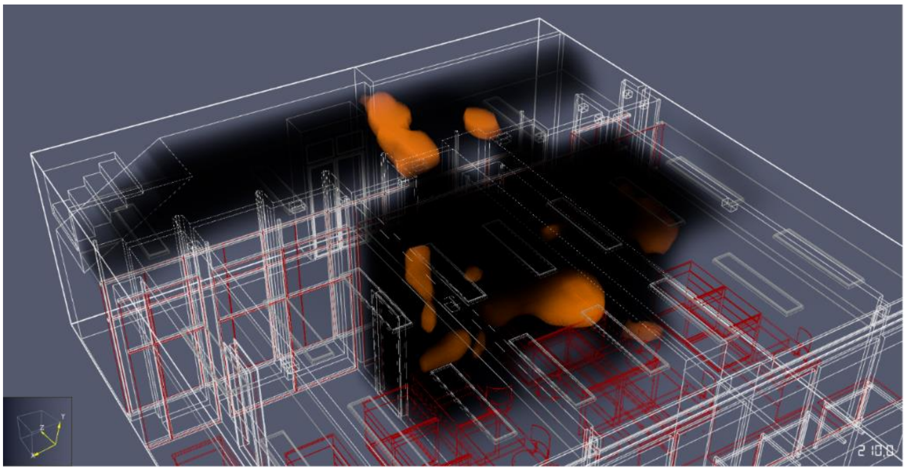

Fig. 3 Spread of smoke and fire from the laboratory to nearby rooms

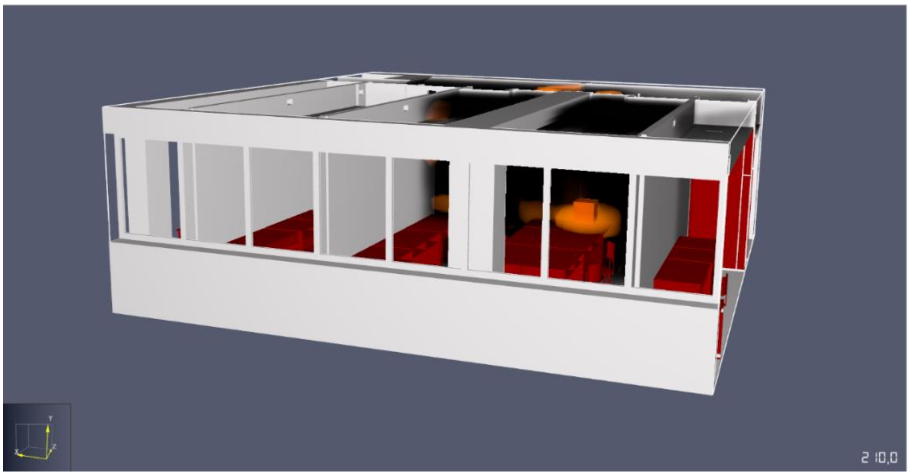

Fig. 4 Smoke transfer to other rooms

Fig. 5 shows the course of a curve representing the heat release rate (HRR) in space over the entire duration of the fire observed.

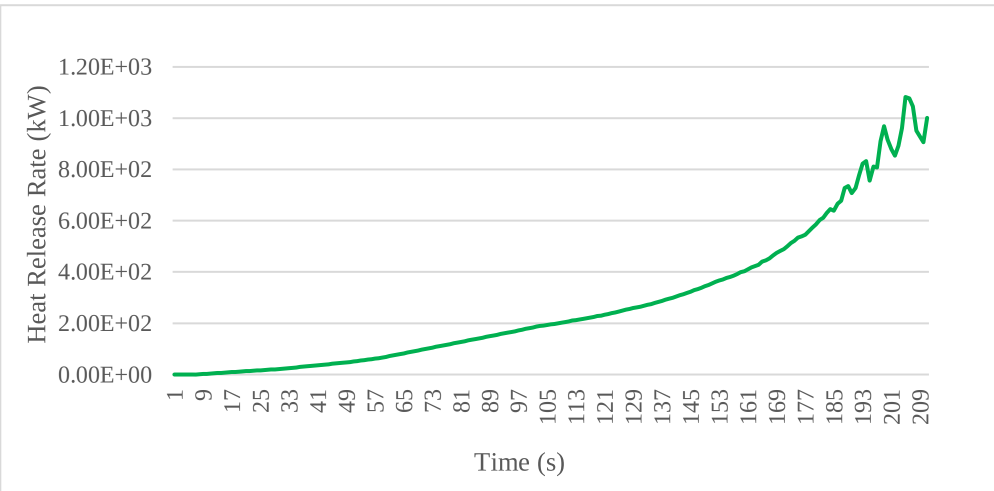

Fig. 5 The course of the heat release rate in an interval of up to 210 s

As seen from the course of the HRR curve, in the standard maximum time for the evacuation of persons from the fire-endangered area, i.e., 3.5 min (210 s), there is a significant increase in the rate of heat release, heating of surrounding combustible materials, increasing the values of total heat released (Fig. 6), the release of volatile substances and the subsequent spread of fire from source to surroundings. Of course, this is also related to the increasing formation of combustion products, which are toxic to the persons found in this environment.

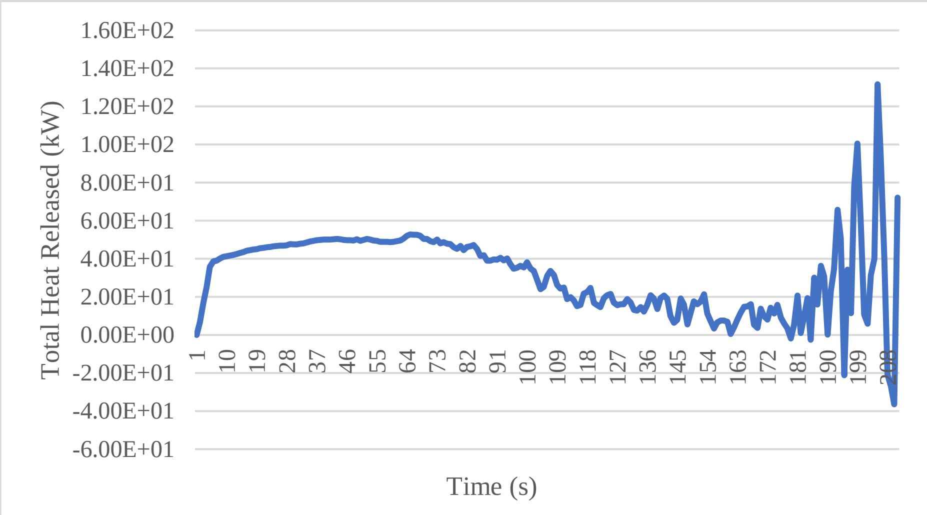

Fig. 6 Total heat release up to 210 s

In general, the heat release rate varies with time depending on the heat of fuel gasification and is directly proportional to the rate of burning.

The course of fuel burning rate values is shown in Fig. 7.

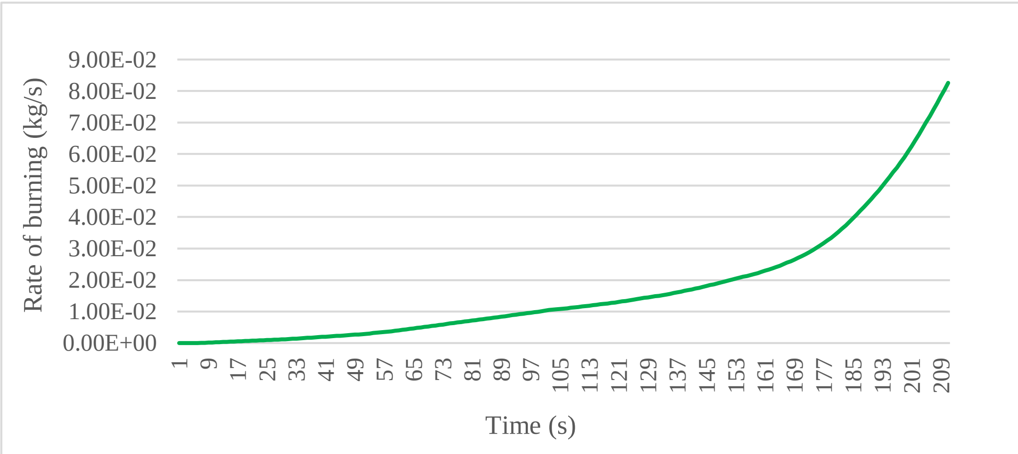

Fig. 7 Fuel burning rate up to 210 s

Fig. 8 presents the course of enthalpy values over time. These values follow the shape of a curve representing the course of the heat released rate, while these values increased significantly from approximately 193 s.

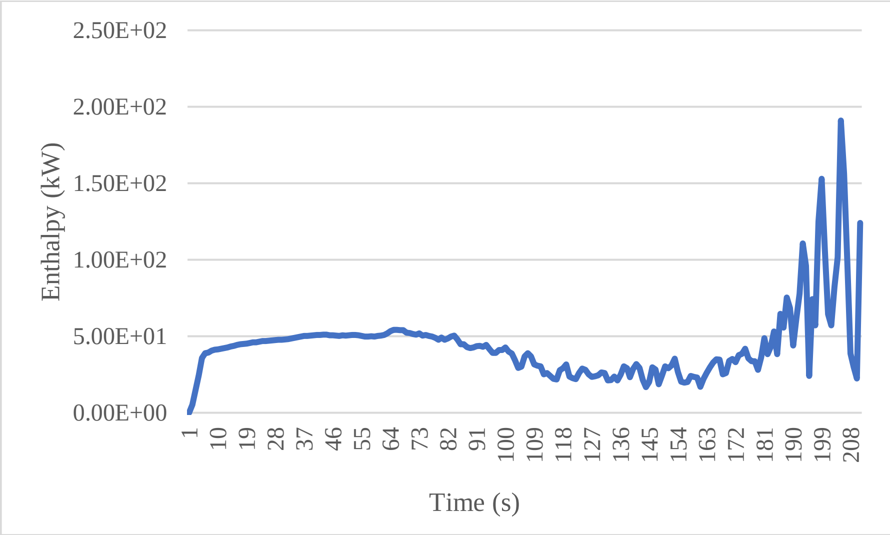

Fig. 8 Enthalpy values course

The results of the simulations presented here relate only to a time interval of 121 s (3.5 min), which is critical to ensuring the safe evacuation of persons. When observing the further development of the fire, we would also obtain additional information that is necessary for understanding the behaviour of the fire, the spread of combustion products in the space. These are more important at any given moment for the needs of designing the fire safety of buildings, for the identification of weak points in the construction, the design of suitable and effective fire-separating structures, shutters. From the point of view of evacuation, it is assumed that persons will already be evacuated from the area at a given time. At this point, the fire extinguishing work begins. Modelling the behaviour of fire after this interval also makes sense from the point of view of the safety of the intervening fire brigades, especially in terms of their potential intoxication with fire-produced combustion products.

3.2 Findings from the performed tactical training

The tactical training of officers of the Fire and Rescue Service with the management staff establishment took place on 03.09.2021. The focus was concerned to practice how to deploy, manage forces and resources when extinguishing fire and evacuating persons from the premises of the Technical University in Zvolen. The employees of TUZVO were also active participants of this training.

In this section, we present the findings of the performed tactical training, in the form of identified risk situations/states and the proposal of measures aimed at improving the current situation.

3.2.1 Getting of information about the fire and its further distribution

The subject of the training fire alarm assumed the detection of the fire by the smoke sensor of the electric fire alarm (EFA) with subsequent signalizing to the main gatehouse of TUZVO (also the fire alarm office) and the subsequent procedure of the gatekeeper in accordance with TUZVO internal fire safety documentation.

The following situations have been identified as risks related to the distribution of fire information:

- Absence of an operator at the workplace – toilet, inspection of the building, etc.
- Sighting of a fire by a natural person not using a detector but directly reporting it to the emergency call line.
- Occurrence of a fire in a place unprotected by EFA.

Based on the findings of the performed tactical exercise, the training alarm in the main building of TUZVO, the following measures were proposed.

- Re-assess the current form of safety and the subsequent internal processes after the sighting/reporting of a fire, focusing on the complexity of the measures, with particular regard to sufficient staffing of the initial measures – immediately after receiving the report, processes should be started by several routes so that they are not tied to a single person, e.g. the porter / operator receives the report, immediately informs 3-4 other persons with specific tasks (e.g. open escape exits, provide lifts, inform the competent persons in the management) only then go to check the reported fire, after confirmation of the fire, followed by the declaration of an alarm for evacuation and the initial extinguishing intervention by designated employees.

- Extended EFA interface – e.g., opening of escape exits, illumination of the light signalizing of escape exits and direction of escape, activation of the sound of the internal radio using a sound loop, etc.

3.2.2 Put on the alarm, evacuation, escape and verification of the completeness of the evacuees

The alarm put on is realized only by shouting "F I R E" without the use of technical means with the absence of light signalizing.

Additional risks in this regard can be identified as:

- Information about the occurrence of a fire, put on the alarm with the need for evacuation does not reach all persons in the premises.
- Some of the persons ignore the alarm and remain in the object.
- There is no information about the number of persons located in the premises.
- In locked offices it is impossible to conduct a survey without forcibly entering.
- Private passenger cars parked on the so-called boarding areas and access roads for firefighting equipment form an obstacle.

Several measures have been proposed to improve the current situation:

- Reconsider the current form of putting on alarm using several forms, including sound and optical technical means (e.g., internal radio allowing controlled evacuation, light signalizing of the direction of escape and escape exits).
- Increase the intensity of staff training with an emphasis on evacuation under the new rules, including a reassessment of the modification of the job description, focusing on specific responsibilities and substitutability.
- Introduce a registration system of the number of persons in the building, including monitoring of individual entrances but also escape exits (e.g., infrared sensor at individual entrances and exits ensuring continuous monitoring of the number of persons in the building with the exit to several workplaces of superiors – no identification of an individual is required, an indication of the number of persons in the object expressed by an absolute number is sufficient).
- To conduct a regular training of fire alarm associated with the evacuation of all employees.
- Propose parking rules for private passenger cars with unambiguous user identification so that keys or a driver can be obtained if parking is necessary.
- Escaping persons should be concentrated in an area not restricting fire-extinguishing intervention so that when coordinating the evacuation, the space is individually determined by the evacuated sectors.

3.2.3 Constructions, technical solution, and condition of the building

The building consists of a single fire compartment with an extremely high number of cavities, heat transfers and combustion products as well as hidden paths of spread of fire and especially smoke.

The following situations are evaluated as a risk:

- Fire, and in particular combustion fumes, may spread uncontrollably throughout the building.
- Escape routes do not provide protection against fire, the capacity of escape routes does not correspond to the current number of persons in the building.
- Elevators do not have the character of fire or evacuation lifts and in the event of a power outage or deliberate shutdown without prior control, there is a risk of persons being trapped in the cabins.
- High fire loads on escape routes encouraging the spread of fire,
- High fire loads or impossibility of entering alternative escape options.

To improve the status quo, it is necessary:

- Reconsider building modifications aimed at creating protected escape routes on staircases and creating separate fire compartments on individual floors.
- Reconsider the possibilities of increasing the capacity of escape routes.
- Reconsider the possibilities of reconstructing elevators into fire or evacuation elevators.
- Reconsider the possibilities of reducing the fire load on escape routes (hallways, corridors).
- Reconsider building modifications reducing the number and interconnectedness of cavities by changing building materials and sealing penetrations with the required fire resistance.
- Free up all areas usable as replacement escape options (balconies, loggias, etc.).

It is necessary to deal with individual areas in interconnectedness, however, any area solved individually represents an increase in the safety of persons in the building, and for this reason we recommend the immediate adoption of measures depending on the implementation possibilities of TUZVO.

3.3 Proposal for measures to ensure the fire safety of the structure and the safe evacuation of persons

The content of this sub-chapter only provides an assessment of the current state of the main building of TUZVO with a proposal for possible measures to correct the identified shortcomings.

3.3.1 Fire compartments

The TUZVO building currently represents one fire compartment covering all above ground and underground floors. The legislation currently in force dealing with the fire safety of buildings does not apply to the TUZVO building, since it was built before the current regulations were issued. However, from the point of view of safety, the current state of the building is unsatisfactory.

Therefore, based on the findings of the conducted tactical exercise associated with the training fire alarm and the evacuation of persons from the main building of TUZVO, as well as calculations (evacuation time and permissible size of fire compartments), in accordance with the current legislation, in order to ensure the greatest possible safety of the structure, it is necessary to divide the structure into several fire compartments, where each floor and each staircase would constitute a separate fire section.

Recommended division of the structure into fire compartments:

Fire compartment N7.01 – 7th floor (8th above ground floor)
Fire compartment N6.01 – 6th floor (7th above ground floor)
Fire compartment N5.01 – 5th floor (6th above ground floor)
Fire compartment N4.01 – 4th floor (5th above ground floor)
Fire compartment N3.01 – 3rd floor (4th above ground floor)
Fire compartment N2.01 – 2nd floor (3rd above ground floor)
Fire compartment N1.01 – 1st floor (2nd above ground floor)
Fire compartment N0.01 – ground floor block A (1st above ground floor)
Fire compartment N0.02 – ground floor block C (1st above ground floor)
Fire compartment N0.03 – classroom B4
Fire compartment N0.04 – classroom B5
Fire compartment N0.05 – classroom B6
Fire compartment N0.06 – classroom B7
Fire compartment N0.07 - 7.07 – Protected escape route block A (alternate staircase block A)
Fire compartment N0.08 - 7.08 – Protected escape route block ABC (main staircases between blocks A/B and B/C including corridor on the ground floor)
Fire compartment N0.09 - 5.09 – Protected escape route block C (alternate staircase block C)
Fire compartment of elevator shafts

3.3.2 Fire risk

The fire risk in a non-production structure is expressed by the calculation fire load within the meaning of § 33 Decree of the Ministry of Interior of the Slovak Republic No. 94/2004 Coll. [15]. Due to the current state – the entire TUZVO building is one fire compartment, the fire risk was calculated at 36.9 kg/m^2. For the designed fire compartments, the calculation fire load would be as follows:

p_v (Fire compartment N7.01) = 21.99 kg/m^2
p_v (Fire compartment N6.01) = 26.36 kg/m^2
p_v (Fire compartment N5.01) = 28.86 kg/m^2
p_v (Fire compartment N4.01) = 36.19 kg/m^2
p_v (Fire compartment N3.01) = 37.13 kg/m^2
p_v (Fire compartment N2.01) = 37.58 kg/m^2
p_v (Fire compartment N1.01) = 35.60 kg/m^2
p_v (Fire compartment N0.01) = 33.75 kg/m^2
p_v (Fire compartment N0.02) = 28.27 kg/m^2
p_v (Fire compartment N0.03) = 37.36 kg/m^2
p_v (Fire compartment N0.04) = 38.36 kg/m^2
p_v (Fire compartment N0.05) = 39.79 kg/m^2
p_v (Fire compartment N0.06) = 40.83 kg/m^2

For protected escape routes, it is necessary to ensure that the accidental fire load is not more than 15 kg/m^2.

3.3.3 Size of fire compartments

The permissible area of the fire compartment is determined in accordance with § 4, par. 1, letter b) and par. 4, Decree of the Ministry of Interior of the Slovak Republic No. 94/2004 Coll. [15], according to equation 36 and Article 4.1.1 in STN 92 0201-1 [12]. For the entire building, the permissible size of the fire compartment is as follows:

$$S_{max} = 2{,}120\ m^2 \leq 12{,}490\ m^2$$

The permissible size of the fire compartment does not suit. Therefore, it is necessary to divide the structure into smaller sections. In the case of the proposed division, the condition is met, since the maximum area of the floor is 2,044 m^2, which is less than the maximum permissible area.

3.3.4 Determining the degree of fire safety of the building

The degree of fire safety of the fire compartment was determined in accordance with § 37, par. 5, Decree of the Ministry of Interior of the Slovak Republic No. 94/2004 Coll. [15], Article 3.3 and Table 3 in STN 92 0201-2 [12]. The fire compartment of the entire building is currently classified in the 3rd degree of fire safety (DFS). In the case of the recommended division of the structure into fire compartments, the stages are as follows:

Fire compartment N7.01 – 2nd FSD
Fire compartment N6.01 – 2nd FSD
Fire compartment N5.01 – 2nd FSD
Fire compartment N4.01 – 3rd FSD
Fire compartment N3.01 – 3rd FSD
Fire compartment N2.01 – 3rd. FSD
Fire compartment N1.01 – 3rd FSD
Fire compartment N0.02 – 2nd FSD
Fire compartment N0.03 – 3rd FSD
Fire compartment N0.04 – 3rd FSD
Fire compartment N0.05 – 3rd FSD
Fire compartment N0.06 – 3rd FSD
Fire compartment N0.07 – 7.07 – 3rd FSD
Fire compartment N0.08 – 7.08 – 3rd FSD
Fire compartment N0.09 – 5.09 – 3rd FSD
Fire compartment of elevator shafts – III. FSD

3.3.5 Determination of requirements for structural elements in the building

In Tab. 1, there are introduced the minimum requirements for constructions, which the building should meet.

Tab. 1 Minimum requirements for structural elements in the building

Item	**Structural element**	**Type of structural element and lowest fire resistance (min)according to FSD**	
		2nd	3rd
1	**Fire walls and fire ceilings:**		
	(a) on underground floors	60/D1	90/D1
	(b) on above-ground floors	45	60
	(c) on the last floor	30	45
2	**Enclosure walls:**		
	(a) ensuring the stability of a structure or part thereof:		
	1. in underground floors from the inside of the wall	60/D1	90/D1
	2. on the above-ground floors	45	60
	3. on the last floor	30	45
	(b) not ensuring the stability of the structure or part thereof	30	45
3	**Roof cladding:**	30	45
4	**Fire stoppings for openings:**		
	(a) on underground floors and on all floors between structures	45/D1	45/D1
	(b) on above-ground floors	30	45
	(c) on the last floor	30	30
5	**Supporting structures of staircases inside the fire compartment which are not part of the protected escape routes:**	15	30/D2
6	**Shafts and channels:**		
	(a) Fire compartmentation structures:		
	1. Shaft of evacuation and fire elevators	According to item 1	
	2. Shafts of other lifts	30/D1	45/D1
	3. Plumbing shafts and channels	45/D1	60/D1
	fire stoppings for openings in fire compartmentation structures:		
	1. Shaft of evacuation and fire elevators	According to item 4	
	2. Shafts of other lifts	30/D1	30/D1
	3. Plumbing shafts and channels	45	60/D1
7	**Load-bearing structures of roofs without fire subdivision function:**	30	45
8	**Load-bearing structures inside the structure, which ensure the stability of the structure:**		
	(a) on underground floors	60/D1	90/D1
	(b) on above-ground floors	45	60
	(c) on the last floor	30	45
9	**Load-bearing structures inside the fire compartment not ensuring the stability of the structure:**	30/D2	45/D2
10	**Load-bearing structures inside the fire compartment ensuring the stability of the structure:**	30	45

It is necessary to carry out an inspection of the ceiling structures and project precautions to prevent smoke and fire from passing between floors when a fire.

3.3.6 Spacing distances

Spacing distances are determined in accordance with § 80, par. 1 and par. 2 of the Decree of the Ministry of Interior of the Slovak Republic 94/2004 Coll. and pursuant to Art. 5.3.1 in STN 92 0201-4. Due to the current situation, where TUZVO has only one fire compartment, the separation distance from the main building along the entire height of the structure is 22.5 m. This is a large area that covers parking places around the building, adjacent grassy areas, technical areas, and park. Therefore, it is very likely that the fire will be extended to those adjacent areas.

However, if the structure were to be divided into fire compartments along the floors, the spacing distances would be reduced to 6 m for the entire 7th to 5th floors and 7 m for the entire 4th to 1st floors. The spacing distance for the ground floor is set up to 10.5 m due to the danger of falling particles.

3.3.7 Ensuring the evacuation of persons, determining the requirements for escape routes

The description of the escape routes that we considered when assessing the current state of evacuation has already been described in section Material and Methodology. Here we only provide descriptions of the necessary measures that must be implemented to to safely evacuate persons in the fire situation.

The number of persons who can be inside the building during the week, i.e., the workdays, is based on the current staffing and the capacity of the classrooms.

Ensuring the evacuation from the 1st to 7th floors is a key requirement. From the ground floor there are several possible evacuation routes, therefore the presence of persons on the ground floor is not considered in the calculation of the evacuation time of the TUZVO main building.

The calculation of the evacuation time is based on STN 92 0201-3, and a partial method of calculations upstairs was used. The number of persons to be evacuated from the considered floors is 1,433, which represents the maximum capacity of the school during teaching and the maximum occupancy of all lecture rooms and offices.

The first to count was the time of evacuation of persons from individual floors to the entrance to the staircase. Subsequently, the evacuation of persons from the building by individual staircases was gradually calculated. The resulting evacuation time is expressed by the sum of the worst evacuation time from each floor and the time of evacuation by staircase.

The 1st floor turned out to be the worst, since the most persons (339 persons) can be located there, due to the large number of classrooms. The resulting evacuation time was 2.52 min. The results of calculations related to evacuation by the staircases is shown in Tables 2-5:

Tab. 2 Calculation of evacuation time when using staircase A – current situation

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
7th – 6th floor	42	1.8	10.9	25	30	1	**0.44**	0.78
6th – 5th floor	95	1.8	10.9	25	30	1	**0.44**	1.76
5th – 4th floor	169	1.8	10.9	25	30	1	**0.44**	3.12
4th – 3rd floor	213	1.8	10.9	25	30	1	**0.44**	3.95
3rd – 2nd floor	243	1.8	10.9	25	30	1	**0.44**	4.50
2nd – 1st floor	270	1.8	9.8	25	30	1	**0.39**	5.00
1st – Ground level	334	1.8	10.7	25	30	1	**0.43**	**6.18**
Ground level	334	1.8	2.0	30	40	1	**0.07**	4.64
			Total evacuation time (min)				**9.25**	

Tab. 3 Calculation of evacuation time when using staircase A/B – current situation

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
7th – 6th floor	47	2	8.7	25	30	1	**0.35**	0.78
6th – 5th floor	120	2.5	13.4	25	30	1	**0.54**	1.60
5th – 4th floor	252	2.5	13.4	25	30	1	**0.54**	3.36
4th – 3rd floor	355	2.5	13.4	25	30	1	**0.54**	4.74
3rd – 2nd floor	420	2.5	13.4	25	30	1	**0.54**	5.61
2nd – 1st floor	485	2.5	13.4	25	30	1	**0.54**	6.46
1st – Ground level	646	2.5	11.4	25	30	1	**0.46**	**8.61**
Ground level	646	3.72	18.0	30	40	1	**0.60**	4.34
			Total evacuation time (min)				**12.70**	

Tab. 4 Calculation of evacuation time when using staircase B/C – current situation

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
5th – 4th floor	48	2.5	14.9	25	30	1	**0.60**	0.64
4th – 3rd floor	135	2.5	14.9	25	30	1	**0.60**	1.80
3rd – 2nd floor	195	2.5	14.9	25	30	1	**0.60**	2.59
2nd – 1st floor	254	2.5	14.9	25	30	1	**0.60**	3.39
1st – Ground level	352	2.5	12.9	25	30	1	**0.52**	**4.69**
Ground level	352	2.9	35	30	40	1	**1.17**	3.03
			Total evacuation time (min)				**8.76**	

Tab. 5 Calculation of evacuation time when using staircase C – current situation

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
5th – 4th floor	12	1.6	10.6	25	30	1	**0.42**	0.24
4th – 3rd floor	23	1.6	10.6	25	30	1	**0.42**	0.49
3rd – 2nd floor	53	1.6	10.6	25	30	1	**0.42**	1.11
2nd – 1st floor	76	1.6	10.6	25	30	1	**0.42**	1.58
1st – Ground level	97	1.6	10.5	25	30	1	**0.42**	**2.02**
Ground level	113	1.6	2	30	40	1	**0.07**	1.76
			Total evacuation time (min)				**4.20**	

Where:

E – number of persons,
u – number of escape lanes on the escape route in accordance with STN 92 0201-3,
l_u – length of the evacuation route (m),
v_u – speed of movement of persons ($m \cdot min^{-1}$) in accordance with STN 92 0201-3,
K_u – capacity of the escape lane in accordance with STN 92 0201-3,
s – coefficient of evacuation conditions in accordance with STN 92 0201-3,
l_u/v_u – time of movement of persons (min),
$E*S/K_u*u$ – expected delay of persons due to evacuation conditions.

The A/B staircase proved to be the least suitable for the needs of evacuation of persons, as it accounts for the largest number of evacuees (646), since it covers the block A, the 7th floor and is the only staircase for the 6th floor of block B, too.

The resulting evacuation time is the sum of evacuation times up staircase A/B and evacuation from the 1st floor, i.e., 12.7 + 2.52 min = 15.22 min. This time is unsatisfactory, because the standard STN 92 0201-3 allows an evacuation time of only 3.5 min under these conditions.

Since the construction is built as one fire section, the critical situation that can occur is the shutdown of the A/B staircase due to severe smoke. Thus, block A would be reliant only on the alternate staircase, which would significantly prolong the evacuation, which could have fatal consequences. The estimated evacuation time without using the A/B staircase is 3.42 + 17.62 = 21.04 min. While the critical point is the 1st floor again, where there is no other escape option on the alternate staircase in block A, persons could stay up to 14.56 min. Critical place is also the 6th floor of block B, where persons on this floor would be forced to use an alternative escape option, which would have to be additionally created by Fire and Rescue Service forces on the spot.

Even in the case of modification of evacuation plans, it is not possible to carry out evacuation from the building within 3.5 minutes. The permissible evacuation time can be increased by building protected escape routes. Within the TUZVO building, it is possible to build protected escape routes of type A from all staircases. The backup staircases lead almost to the open space, the problem is the main staircases that lead to the ground floor of block B. Thus, the culmination of the protected escape routes could be carried out using the secondary entrance at classroom B3 and through the main entrance at the gatehouse.

Such an arrangement of escape routes makes it possible to increase the maximum permissible time for evacuation in accordance with STN 92 0201-3 to 13.5 min, of which 3.5 min falls on the evacuation of individual floors and 10 minutes for the evacuation of persons down staircases.

Considering current building arrangement, the time required for evacuation from individual floors to the entrances to the staircase is observed, since the maximum time is 2.52 min. However, the maximum permissible evacuation time up staircase A/B, where the time is increased by 2.7 min compared to the permissible value, is not observed. The time of evacuation up the A/B staircase is the highest, as the main strain is placed on it. The evacuation time can only be reduced by lightening the A/B staircase so that the load on the staircases is equalized as far as possible. This was achieved by arranging the movement of persons so that block A uses staircases A and A/B. Block B would primarily use staircase B/C and block C would use the alternate staircase C. The resulting evacuation times can be seen in Tables 6-9:

Tab. 6 Calculation of evacuation time when using staircase A – proposal

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
7th – 6th floor	41	1.8	10.9	25	30	1	**0.44**	0.76
6th – 5th floor	94	1.8	10.9	25	30	1	**0.44**	1.74
5th – 4th floor	169	1.8	10.9	25	30	1	**0.44**	3.13
4th – 3rd floor	225	1.8	10.9	25	30	1	**0.44**	4.17
3rd – 2nd floor	264	1.8	10.9	25	30	1	**0.44**	4.89
2nd – 1st floor	293	1.8	9.75	25	30	1	**0.39**	5.43
1st – Ground level	349	1.8	10.7	25	30	1	**0.43**	**6.46**
Ground level	349	1.8	2	30	40	1	**0.07**	4.85
Time of movement of persons (min) / Total evacuation time (min)							3.06	9.53

Tab. 7 Calculation of evacuation time when using staircase A/B – proposal

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	E*s/K_u*u
7th – 6th floor	48	2	8.7	25	30	1	**0.35**	0.80
6th – 5th floor	121	2.5	13.4	25	30	1	**0.54**	1.61
5th – 4th floor	222	2.5	13.4	25	30	1	**0.54**	2.96
4th – 3rd floor	273	2.5	13.4	25	30	1	**0.54**	3.64
3rd – 2nd floor	305	2.5	13.4	25	30	1	**0.54**	4.07
2nd – 1st floor	340	2.5	13.4	25	30	1	**0.54**	4.53
1st – Ground level	437	2.5	11.4	25	30	1	**0.46**	**5.83**
Ground level	437	3.7	18	30	40	1	**0.60**	2.94
Time of movement of persons (min) / Total evacuation time (min)							4.08	9.91

Tab. 8 Calculation of evacuation time when using staircase B/C – proposal

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	E*s/K_u*u
5th – 4th floor	59	2.5	14.9	25	30	1	**0.60**	0.79
4th – 3rd floor	141	2.5	14.9	25	30	1	**0.60**	1.88
3rd – 2nd floor	189	2.5	14.9	25	30	1	**0.60**	2.52
2nd – 1st floor	243	2.5	14.9	25	30	1	**0.60**	3.24
1st – Ground level	388	2.5	12.9	25	30	1	**0.52**	**5.17**
Ground level	388	2.9	35	30	40	1	**1.17**	3.34
Time of movement of persons (min) / Total evacuation time (min)							4.07	9.24

Tab. 9 Calculation of evacuation time when using staircase C – proposal

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	E*s/K_u*u
5th – 4th floor	30	1.6	10.6	25	30	1	**0.42**	0.63
4th – 3rd floor	106	1.6	10.6	25	30	1	**0.42**	2.21
3rd – 2nd floor	164	1.6	10.6	25	30	1	**0.42**	3.42
2nd – 1st floor	218	1.6	10.6	25	30	1	**0.42**	4.54
1st – Ground level	259	1.6	10.5	25	30	1	**0.42**	**5.40**
Ground level	259	1.6	2	30	40	1	**0.07**	4.05
Time of movement of persons (min) / Total evacuation time (min)							2.18	7.58

Through the redistribution and arrangement of the movement of persons, it was possible to reduce the evacuation time through the protected escape route to less than 10 min. Thus, the resulting evacuation time of the building was reduced to 3.42 + 9.91 = 13.33 min.

The area of the protected escape routes allows all evacuees pertaining to the escape route to stay simultaneously in the escape route area, thus ensuring their protection.

To create protected escape routes, it is necessary to carry out certain structural modifications in the spaces of the landings on each floor, namely the delimitation of staircases and stair landings, to achieve the fire resistance of the structures bounding the EI 60 protected escape routes. Fire doors with resistance EI-CSa 30/D1 or EI-CSa 45/D1 shall be installed at the entrances to protected escape routes.

It is also necessary to provide artificial ventilation, which will ensure the supply of fresh air to the protected escape route in the opposite direction of the escape route for at least 20 min.

On individual floors it is necessary to install equipment to coordinate the evacuation of persons.

In conclusion, it should be noted that standard STN 92 0201-3 states that structures with a fire height of more than 22.5 m must have at least one protected escape route type B. This type of protected escape route would require extensive structural modifications to be carried out in the construction and is difficult to implement for the needs of TUZVO. Regardless, four protected escape routes are quite sufficient and will significantly improve the conditions for evacuation from the building.

4 Conclusions

The paper deals with the issue of the application of computer-aided modelling tools in the practice of fire protection.

The main purpose of the implemented study was, based on the practical application of selected computer models for solving specific fire scenarios, simulating fire and its spread under real conditions, to point out, in a selected case, the possibilities of applying these tools in the practice of fire protection. In this case, it was a fire on the 6th floor of block A in the main building of the Technical University in Zvolen. In addition, the task was to determine the basic parameters for the development and spread of fire and smoke, to determine the parameters of the time required for the safe evacuation of persons from a fire-endangered area.

For the purposes of modelling and simulating the spread of fire in the space, the PyroSim licence was purchased, in which a fire simulation was carried out, the extinguishing of which and the simultaneous evacuation of persons from the area threatened by fire was the subject of a tactical exercise, which was carried out together with a practice fire alarm and the evacuation of the main building of TUZVO on 03/09/2021 from 9.00 AM. The knowledge gained from this tactical exercise, which used smoke detectors to simulate the spread of smoke in the interior of block A of the TUZVO main building, was also used in the creation of a fire scenario simulated in PyroSim.

The theme of the tactical exercise, its preparation and evaluation were part of the implemented study.

Based on the knowledge and experience from the tactical exercise, which were also confirmed by the results of modelling and simulation of fire behaviour, risks were identified, and measures were proposed for activities in terms of three aspects of ensuring the safety of persons in fire situation:

• Distribution of information about the fire and subsequent measures taken by employees,
• Putting on alarm, evacuation, escape and verification of number of evacuees,
• Construction-technical solution and condition of the building.

At the same time, as part of the study, the fire safety documentation of buildings was prepared, in which the main building of TUZVO is no longer a single fire section, but is divided into several fire sections, which made it possible to shorten the time for the safe evacuation of persons and also to reduce the size of spacing distances, which it is of great importance, especially from the point of view of identifying places suitable for the temporary concentration of evacuees.

The results of the study bring several practical solution topics in relation to ensuring the fire safety of buildings. The tools of computer-supported, but also mathematical modelling is a progressive tool enabling low-cost creation of fire scenarios, their modelling, analysis of results in relation to the basic parameters of fire dynamics, which enable understanding of fire behaviour and the search for suitable preventive measures or solutions from the point of view of fire safety design of buildings, especially of school facilities.

However, the results presented here are also applicable in the field of determining the causes of fires.

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