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CONSTRUCTION OF A VISUAL MODEL OF PEOPLE'S MOVEMENT TO MANAGE SAFETY WHEN EVACUATING FROM A SPORTS INFRASTRUCTURE FACILITY

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By applying the probabilistic method and optimization synthesis of flexible technological lines, topological models have been built of safety-oriented management of human flows and evacuation time using the «Arena Lviv» stadium as an example. They are necessary to calculate the time of evacuation of people to a safe zone. When people leave the stadium sectors on the promenade, their flow is significantly modified. Therefore, the calculation of the time of evacuation of people requires the use of different procedures depending on the type of human flow in order to obtain more accurate results. There may be several such cases on one evacuation route and significantly more during the evacuation of people from all sectors and premises of the stadium administrative building as a whole. Thus, a lot of time is spent on choosing the right procedure and initial data for calculation if we use existing classical verbal models, which is their disadvantage. Verbal models have a large volume, they need to be repeatedly re-read in order to determine the numerical values of factors affecting the flow of people while topological models are much more compact. Topological models make it possible to visually present more complete information about the evacuation process, and this makes it possible to quickly select the initial data for calculating the time of evacuation of people at the next evacuation site.

The time of evacuation of people from the «Arena Lviv» stadium was calculated; the evacuation system happened to not comply with the accepted standards. In particular, the time of evacuation of people from the structure exceeded eight minutes. Using the critical path method, bottlenecks of the stadium evacuation system were identified, and human flows were redistributed, which made it possible to reduce the total evacuation time to acceptable indicators

Keywords: evacuation of people, object of sports infrastructure, ensuring the safety of people, safety-oriented management, topological models

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1. Introduction

There is a constant need to restore a large number of infrastructure facilities for various purposes. No exception in this list are sports infrastructure facilities (SIF), which are characterized by the presence of a large number of people. The operation of such facilities requires the creation of safe conditions for people to stay during their operation. Therefore, there is a need to implement projects to ensure the safety of people at sports infrastructure facilities. World experience in the operation of sports facilities with a mass presence of people has shown that the solution to this problem is laid at the design stage of the facility. The most effective way to ensure the safety of people at objects with their mass presence is to conduct timely and unhindered evacuation of visitors to a mass event to a safe zone outside the building. Visitors to the sports infrastructure facility include spectators, officials, participants in the competition, referees, guests of honor, journalists, staff, etc. Thus, there is a need for a detailed study of the process of evacuation of people from SIFs, taking into account the current regulatory framework of Ukraine and the world since international sports events taking place at these sites must also comply with international standards. An example is the holding of the European Football Championship in Ukraine in 2012, the final leg of the international football tournament «Champions League» in 2018 at the NSC «Olimpiyskiy», and others.

Therefore, scientific research into the construction of new methods and models for the safe evacuation of people from structures for various purposes is relevant.

2. Literature review and problem statement

Paper [1] provides a detailed analysis of the unannounced evacuation of people from the premises of buildings put into operation (hotels, restaurants, health care facilities, etc.) and their behavior in fire conditions. The data obtained as a result of this study indicate that the time of evacuation from the recreation area was characterized by a longer time of the first evacuation site and a relatively shorter time of movement in other areas. While the evacuation time in the more densely populated functional area of the room was characterized by a shorter time of the previous evacuation area, but a longer time of human movement as part of the evacuation flow. The article highlights important problems of designing and managing the evacuation of people under the influence of alcohol and examines the impact of intervention by service personnel using addressable voice communications. The differences in response behavior between two separate areas of the premises are highlighted and discussed. However, the cited paper considers public buildings, which has a different impact on the modification of human flow in comparison with sports infrastructure.

In work [2], it was investigated that when leaving buildings, theaters, and stadiums where there are a large number of people, exit points can be bottlenecks, leading to crowded exits and reduced flows. Most flow studies have been conducted in bottlenecks (doors) or funnel-shaped bottlenecks, with the latter investigating bottlenecks located in the middle of the track. The article explores the flow of crowds through funnel-shaped bottlenecks located in the corner of the track and compares them with similar bottlenecks of the same length, entry and exit widths located in the middle of the track. Ninety-four participants of different ages passed through escape routes of various configurations. The results showed that using funnel-shaped bottlenecks in the middle of the track significantly increased the flow rate compared to corners in long bottlenecks. This contradicts what some other researchers have found for bottlenecks located in the middle and corner of the wall. The study of the configuration of funnel-shaped bottlenecks of human flows is more complex, so more work is needed. Despite this, the results obtained are considered valuable for consideration when designing exit points and corridors in complex buildings such as stadiums, metro stations, railroad stations, etc.

In work [3], the peculiarities of the pedestrian flow in bottlenecks, that is, exits from rooms, are investigated using experiments on humans, taking into account the different sizes and location of doors. All evacuation time indicators showed that a larger door width demonstrated higher exit efficiency. Studies have shown that time intervals between two consecutive pedestrians showed a difficult distribution in all scenarios studied. Meanwhile, regardless of physical settings, higher flow rates and significant gap dimensions were found as the door width increased. In addition, the influence of the boundary layer, as well as the effective width on the dynamics of the movement of the flow of people, is clearly traced. The results of the work also demonstrated that the position of the doors also affects the flow of pedestrians in bottlenecks. In narrow-door scenarios, specific throughput has steadily decreased from mid-exit scenarios to corner exit scenarios. As the width of the door increased, this gap gradually disappeared.

With the aging of the world population and the consequent increase in disability, the characteristics of the pedestrian flow mixed with wheelchair users are receiving increasing attention. In study [4], funnel-shaped bottleneck experiments were conducted to examine the effect of bottleneck shapes and the number of wheelchair users on crowd dynamics. It was found that an increase in the number of wheelchairs in a crowd leads to a decrease in movement efficiency and an increase in congestion, which affects evacuation time and time-space ratio. At low mixing rates (<2.35 %), the least congestion occurred at a bottleneck with a rotation angle of 45 degrees among the four angles tested (0°, 15°, 30°, 45°). However, the angle preference disappears when the mixing ratio becomes higher. The findings of the cited study are significant for guiding the evacuation of people through bottlenecks with the presence of wheelchair users.

Studies [2–4] focus only on solving the problem of delayed movement of human flow and do not take into account the process of calculating the time of evacuation of people in general.

A number of crowd accidents in recent decades have attracted scientists' interest in studying self-organized crowd behavior under extreme conditions. The faster-slower effect is one of the most mentioned behaviors in pedestrian dynamics. However, this behavior has not yet been experimentally tested. Therefore, in [5], a series of experiments with mice in a state of panic in two-dimensional space was conducted. Mice were taught to know escape routes. Different numbers of sticks were used to create different levels of stimulus to encourage mice to escape. The evacuation process was filmed for further analysis. The experiment found that escape time increased significantly with stimulus levels due to stronger competition from selfish mice in a state of panic. The effect of «faster – slower» has been experimentally tested. The probability distributions of time intervals showed a power law, and flash sizes showed exponential behavior. The cited study reveals the impact of panic on the evacuation process and does not provide data on the use of the procedure to calculate the evacuation time.

The role of data-driven approaches in crowd behavior research has received unprecedented recognition. As a result, the amount of empirical literature on the dynamics of human flows has increased rapidly. Paper [6] analyzes a significant number of scientific papers reporting experimental studies into the dynamics of human flows. The author of the cited article notes that laboratory mass experiments turned out to be the most popular method among all empirical methods, covering a wide variety of topics and constituting almost half of the empirical literature. On the other hand, he notes that the use of mass experiments on animals/insects is decreasing. Studies of virtual reality of the evacuation process have retained their popularity. Pedestrian flow in bottlenecks, pedestrian behavior, and route selection remain the main traditional themes. However, new research topics have appeared or acquired a significant scope. This includes evacuation of vulnerable groups (i.e., the elderly, children, persons with mobility disabilities, and people with major signs of obesity), vertical evacuation, evacuation under conditions of limited visibility, social groups, and evacuation training. While the most popular conventional topics are mostly explored through crowd lab experiments, evacuation exercise procedures and virtual/augmented reality are proving more important to explore the most common topics. This highlights the complementary relationship between different experimental approaches in this field. The cited paper notes that more work is needed to establish the possibility of transmitting experimental results by different methods, geometric schemes, contexts, and demographics, which indicates the need for more research into the subject area. Study [7] includes an analysis focused on determining the main parameters of human movement and the experimental results of their movement under different conditions, which focuses on three key parameters: speed, distance between people (density), and motor behavior (intensity). Based on this study, a parametric model for motion forecasting is presented and a roadmap is proposed that outlines appropriate steps for future studies of human flow movement and human behavior in a dangerous situation.

In [8], the authors proposed a classification of complex systems in the management of projects and programs of the civil protection system. A comparative analysis of methods and algorithms for the use of simulation modeling in projects of this type was made, as well as the peculiarities of using simulation models to describe the process of evacuating people to a safe zone. In the cited paper, an example of using simulation modeling of the evacuation process is given, which is not convenient in terms of quick calculations and does not take into account various procedures for calculating the time of evacuation of people.

Paper [9] reports the results of experimental studies into the parameters of movement of children of primary school age in horizontal areas during evacuation from schools with inclusive classes. The dependence of the speed and intensity of evacuation flows on their density was established.

Work [10] describes the development and evaluates an inclusive emergency evacuation system, which enables people with disabilities to independently find a safe way out in case of an emergency. This feature is implemented through a mobile application that makes it possible to find the optimal evacuation route from the building, taking into account the parameters of a fire or an emergency event in real time. After receiving an emergency notification, the system provides the user with access to a specially designed mobile application on his/her smartphone, which in turn has access to threat information in real time. After that, the user simply follows the step-by-step navigation instructions on the screen in order to exit to the nearest safe exit. Analysis of the practical application of such an application showed that this solution is effective not only in terms of reducing evacuation time but also in providing instructions. Such recommendations lead users to choose deterministic, shorter, and safer routes to the most appropriate escape exit for them.

Studies [9, 10] consider the evacuation of low-mobility groups of the population, which should have their own individual evacuation route from sports infrastructure. The evacuation parameters of such segments of the population as part of the movement of human flow differ from the classical example and require more detailed study.

Study [11] aims to quantify and better understand the parameters underlying the development of a new predictive microscopic model of human movement to accurately reflect the complexity of flow dynamics. The work reports the results and analysis of two experiments with the same initial data intended to quantify physical space. It takes into account the degree of human step movement (maximum step size) and the minimum distance between human contact points (contact buffer) over the entire range and walking speed. The experiments successfully used high-resolution optical motion capture and advanced video analysis to quantify dynamic changes in motion and spatial parameters. The procedure of calculating the evacuation time presented in the cited paper is designed for small groups of people, so its use in crowded objects requires additional research.

In [12], using the method of system analysis and synthesis, the parameters affecting the process of evacuation of people were determined. Methodological principles for managing the flows of people based on the use of the critical path method were used. The analysis of existing mathematical models describing the movement of flows of people on objects of their mass stay showed that the flow of users of the airport is modified and its mathematical description requires the synthesis of several mathematical models. Accordingly, a method for calculating the time of evacuation of airport users is proposed, in which the results of other experimental studies are used as an information base. Using the models and methods developed by the author, the evacuation time of people was calculated, and evacuation plans for Danylo Halytskyi International Airport «Lviv» were developed.

Improving the efficiency of the program for creating and developing a security system at sports and entertainment facilities requires the use of methods and models built on the basis of the use of information technology, a systematic approach, and project-oriented management [13, 14].

Works [12–14] give an example of calculating the time of evacuation of people from the object of their mass congestion using safety-oriented management. The articles provide an example of calculating the capacity of the airport evacuation system using the method of individual movement of a person as part of the flow of people. However, at sports facilities there is a need for a combination of different procedures since the composition and characteristics of human flow are modified, which requires additional research into the subject area.

Evacuation training is usually the main mechanism for improving or measuring the safety of people at facilities in the event of emergencies, the level of which is difficult to measure. However, innovations in technology (e.g., augmented/virtual reality, the latest sensors, and mobile technologies) open up significant opportunities for the «next generation» of science-based evacuation exercises. Article [15] reports the results of a transnational research project regarding:

– devising an evidence-based methodology for evaluating evacuation training;

– application of new objective and automated approaches to data collection/analytics;

– development of guidelines for regulatory authorities regarding the positive and negative aspects of each approach to different training scenarios.

According to the classification, sports infrastructure facilities are divided into categories, according to which sports and cultural events of various levels of significance can be held there. Therefore, there are different requirements for the parameters of space-planning solutions and other characteristics that are taken into account at the stage of design, operation, development. The study of the stage of effective functioning of objects included in the system of sports and entertainment type is possible under the conditions of studying existing mechanisms and programs for their development, as well as a result of analyzing the best world practices for the implementation of projects for the safe operation of sports infrastructure [16, 17].

Works [15–17] do not provide methods and models for calculating the time of evacuation of people. These works reveal the methodologies of an integrated approach to ensuring safety at objects of mass presence of people, which can be used only at the stage of planning and construction of structures of this type.

Understanding the impact of the geometric characteristics of escape routes on human exit behavior is a widespread phenomenon in the safe and effective management of human flows. Work [18] investigates how funnel-shaped bottlenecks with different angles affect the microscopic and macroscopic properties of the pedestrian exit flow. As a result, the influence of length, large width, and slope was investigated.

Thecited study does not reveal the problems of rapid and automated calculations regarding the determination of the time of evacuation of people from structures for various purposes.

Works [19, 20] reveal approaches to ensuring the safety of people at sports infrastructure facilities during the organization and holding of mass events. In particular, it is proposed to take a fixed number of people per unit width of the evacuation passage, which it can pass within one minute. The peculiarity lies in the fact that the entire evacuation route with this approach should not reduce its capacity. The use of this procedure during the examination of the evacuation system requires the use of numerous calculations, so it is necessary to automate the use of this procedure.

From the above review of scientific papers [2, 7, 12, 20] it follows that there are several methods for determining the time of evacuation of people from structures of various purposes. However, each of these methods involves analyzing space-planning solutions inside a building or structure in order to determine the optimal evacuation route. The movement of people in the composition of the stream is influenced by many factors that often lead to a modification of its movement and composition. Therefore, the calculation of its time characteristic often requires the compilation of several methods for calculating the time of evacuation of people. Thus, it is advisable to create a visual model of people's movement along the optimal evacuation route, which would show what factors influence the movement of people in the flow at a certain evacuation area. This will make it possible to choose the optimal procedure for calculating the time of evacuation of people in a particular evacuation area.

3. The aim and objectives of the study

The aim of our work is to build visual models of people's movement along the optimal evacuation route. This will optimize the evacuation process from the structure to the safe zone according to the time criterion.

To accomplish the aim, the following tasks have been set:

– to analyze the movement of people during evacuation as part of the stream and determine the factors that influence its modification;

– to build topological models of human flows during evacuation from a sports infrastructure facility;

– to calculate the time of evacuation of people from the sports infrastructure facility;

– to optimize the process of evacuation of people from the sports facility according to the time criterion.

4. The study materials and methods

The object of research is the process of evacuation of people from crowded facilities. To study the subject area of evacuation of people from structures of various classes of purpose, an information analysis of world requirements for ensuring the safety of people, scientific papers on the subject area was carried out and the problems of this study were formed. The use of factor analysis made it possible to determine the parameters affecting the flows of people during their evacuation from structures to a safe zone. To visualize the factors influencing the process of evacuation of people, the method of synthesis of flexible technological lines and topological modeling were used. The evacuation time was calculated in accordance with the methodology for determining the estimated duration of evacuation of people from the premises of buildings and structures using a simplified analytical model of human flow movement given in DSTU 8828:2019. Calculations of the evacuation time of people from a stadium to a safe zone can be carried out using Excel, or by developing specialized software. Optimization of evacuation time was carried out using the critical path method. To reflect the results of the study in practice, the «Arena Lviv» stadium was chosen.

5. Results of the study of safe evacuation of people from sports infrastructure

5. 1. Investigation of factors influencing the process of evacuation of people

The implementation of project actions often entails certain consequences, which can be both positive and negative. In order to minimize negative consequences, safety-oriented evacuation management should be carried out within the permissible limits stipulated by the regulatory framework. Accordingly, each executive action in such a project should be planned and implemented in accordance with the requirements. Otherwise, during the implementation of a people safe evacuation project (PSE project), unforeseen circumstances may arise, which often require additional resources.

Such a project is focused on creating conditions for timely and unhindered evacuation of people from the structure to a safe zone. An important condition for the implementation of such a project is the timeliness of their implementation. Therefore, they provide for the development of an evacuation system that is able to ensure the movement of people through the building so that all visitors can leave it in time within 8 minutes. To do this, it is necessary to determine the relationships between the factors influencing the success of a PSE-from-SIF project.

For a better understanding of the influence of various kinds of factors on the process of evacuation of people, this study should be considered on a specific example. Therefore, for the factor analysis, the existing SIF with a mass presence of people was chosen – the «Arena Lviv» stadium, which was built in the framework of Ukraine's preparation for Euro 2012. The stadium is designed for 33,400 visitors, who are comfortably accommodated in the stands of the upper and lower tiers and the administrative building. On the western side of the stadium there is a four-level administrative building (western stand), which is designed to accommodate football teams, VIP guests, media, support staff, etc. At the mark of 10,000 m, a promenade with a total area of 16,355 m^2 was built along the perimeter of the stadium, which is accessed by spectators from the sectors of the upper and lower tiers of the stadium and provides the main movement around the building. You can go down from the promenade to the zero level and go to the outskirts of the stadium (free territory) by nine flights of stairs, which are located along the perimeter of the promenade and four staircases located in the administrative building.

Taking into account the results of the information analysis of regulatory documents and experience in the construction and operation of SIFs, it can be noted that a fairly close relationship exists between the following factors:

– width of evacuation routes;

– length of evacuation routes;

– the direction of movement of the flow of people (down or up stairs, horizontally);

– the height of the steps of staircases and the angle of inclination of the stairs;

– the number of people in the stream;

– area of horizontal projection of a person;

– cluttering of evacuation routes;

– navigation signs (safety signs indicating the direction of travel);

– the quality of work of service personnel.

A significant impact on the movement of people in the structure is exerted by the geometric dimensions of evacuation passages and exits. The greater the width of the aisles and exits, the greater the number of people can pass through the evacuation exit per unit of time. The capacity of passages and exits from the sector is also affected by the horizontal projection area of a person, which can vary within permissible values. The smaller the projection area of a person, the less space s/he occupies on the evacuation route and, accordingly, the greater the number of people able to evacuate.

Reducing the width of the escape route from a SIF sector can lead to a decrease in the speed of movement of people's flows up to their delay, and a decrease in the width of doorways or evacuation hatches can lead to a decrease in their capacity and crowding at the exit. In the case when the total number of people in the sector is not able to leave the building within the regulated time and it is not possible to increase the width of the escape route, it is necessary to reduce the capacity of people in the sectors. It is necessary to reduce the capacity to such a value at which the timeliness of their exit from the structure is achieved. An important role in projects for the safe evacuation of people from SIFs is played by the length of the evacuation route. The larger it is, the more time a person needs to go through it. Therefore, it is necessary to plan the evacuation system in such a way that the path to the exit of people in case of an emergency is the shortest. When planning the movement of people through the building, it is also necessary to take into account the direction of movement, which is characterized by different speeds.

The flow rate of people decreases in any direction of movement with increasing density value. The movement of people acquires a lower value when they move down the stairs and the least – when climbing up. The intensity is reversible and tends to increase. When moving people up or down, staircases are used, which must be designed for SIFs in accordance with the requirements. The optimal size of the staircases will contribute to the rapid movement of human flows and the minimum time spent on overcoming part of the evacuation route.

An important aspect of evacuation is the SIF navigation system, which is a set of certain safety signs that provide publicly available information about evacuation routes for the movement of people in the event of an emergency. Also, the navigation system can indicate the location of fire alarm equipment, fire extinguishing equipment, etc. Navigation signs are symbols in the form of an arrow or other animations that indicate a specific action in places of uncertainty and are located in a place of good visibility. Providing such information will speed up the safe evacuation of people from the structure.

Another important characteristic affecting the speed of the evacuation process is the quality of the stewards' work. Practice shows that a significant proportion of SIF visitors who have received a message about the danger and the need to leave the building, first observe the behavior and actions of other people. And they pay special attention to the staff, which includes stewards. That is, we can say that people expect confirmation (reliability) of the information provided and then independently decide on the advisability of evacuation. It is at the initial stage, when people are waiting for further instructions, that there should be active work of stewards, which should be aimed at quickly evacuating people to a safe place. Therefore, when detecting or receiving information about the danger, the steward must independently decide on the organization of evacuation of people.

5. 2. Development of topological models of human flows during evacuation

The process of evacuation of people from any object should be considered as a technological line since the entire evacuation route of each person as part of the movement of the flow of people is divided into certain peculiar evacuation areas. Therefore, the success of a people safe evacuation (PSE) project depends on the degree of optimization of the technological line of the process of evacuating people to a safe zone. For a better understanding of the process of evacuation of people as a technological line, it is advisable to give the following definitions:

Definition 1. The technological line of the evacuation process (TLEP) is a set of technological operations to calculate the time of evacuation of people from individual sections of the structure to a safe zone, carried out in a certain sequence.

Definition 2. The block of the technological line of the evacuation process (TLEP block) is some indivisible element from the point of view of the overall functioning of the system, which reflects the process of evacuation of visitors to the building on its separate section. It is used as an elementary component of the evacuation system, ensuring the implementation of one technological operation.

Definition 3. Sequential topological model-diagram of the technological line of the evacuation process (sequential TLEP TM) is a set of interconnected blocks of the technological line that characterize the process of evacuation of visitors to the building to a safe zone. In addition, each of them in the course of its operation uses the results of the work of the previous block, and between the entrance and exit from the technological line there is only one way of connecting these blocks.

Definition 4. Parallel topological model-diagram of the technological line of the evacuation process (parallel TLEP TM) is a set of interconnected blocks of the technological line, in which each of its blocks characterizes the process of evacuation of visitors to the structure to a safe zone in a certain part of it. In the course of its operation, the unit works independently of each other, and between the entrance and exit from the technological line there are several alternative ways of connecting such blocks.

Definition 5. The tree-like topological model-diagram of the technological line of the evacuation process (tree TLEP TM) is a set of interconnected blocks of the technological line, in which there may be two or more blocks that reflect the process of evacuation of visitors to the structure at the initial stage. The entrances of these blocks are the inputs of the technological line, and several blocks with their exits are, in turn, the outputs of the technological line. At the same time, from each input of the technological line to each of its outputs there may exist several alternative ways of connecting such blocks.

Consequently, each block of the technological line of the evacuation process is designated as Z_i and H_i, which are characterized by a set of input and output parameters.

The set X of input parameters, which includes the block of the technological line of the evacuation process (Fig. 1) can be divided into two subsets: X_1 and X_2. A subset of X_1 includes known initial data such as the width σ_i, length l_i of the section of the general evacuation route, the area of horizontal projection of a person f_i, the number of people in the flow N_i, the direction of movement F_i (upwards, down, horizontally), and the number of turns of flows of project stakeholders, etc. The set X_2 includes data that are determined at a separate stage based on the initial data of the subset X_1: density D_i, intensity q_i, and the velocity movement of people v_i, the time of evacuation from the previous evacuation site t_i, etc.

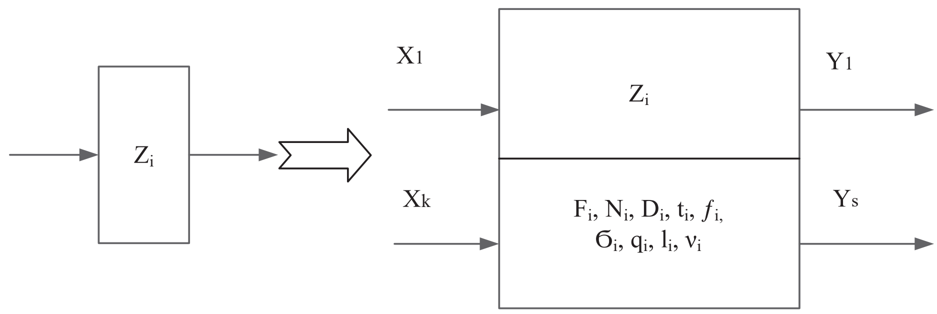

Fig. 1. Model of the technological line block of the evacuation process of people

In reality, the TLEP of visitors from the stadium to the safe zone has a very large number of blocks and, accordingly, an even greater number of integrated connections, of which there may be several between the two blocks.

Definition 6. Integrated is a connection between two blocks that contains one or more connections of the output parameters of one block with the input parameters of another block of TLEP. That is, integrated links record the presence of at least one connection between two blocks of the technological line.

Based on the use of the above theoretical basis in combination with the analysis of space-planning solutions of the «Arena Lviv» stadium, topological models of safety-oriented evacuation management of people were built. First, let's take into account the sectors with the largest capacity of visitors to the building since, based on logical considerations, evacuation from them would take the longest.

It should be noted that the time of evacuation from a SIF is the time interval from the moment of announcement of the need for evacuation to the exit of the last person from the structure. Usually, the last to leave the building are people who were at the time of notification of the need to evacuate in the place farthest from the exit. At the «Arena Lviv» stadium, these are spectator seats in the stands:

– in the sector of the upper tier – the last spectator seat of the last row, which is located in its upper part;

– in the sector of the lower tier – the first or last spectator seat of the first row, located in its lower part, closest to the playing field.

Analyzing the space-planning solutions of the structure, we determined possible routes of movement of people from the most remote spectator places of the most loaded sectors in case of emergencies, which are shown in Fig. 2, 3. The arrows in the figures show the route of movement of people in the sector.

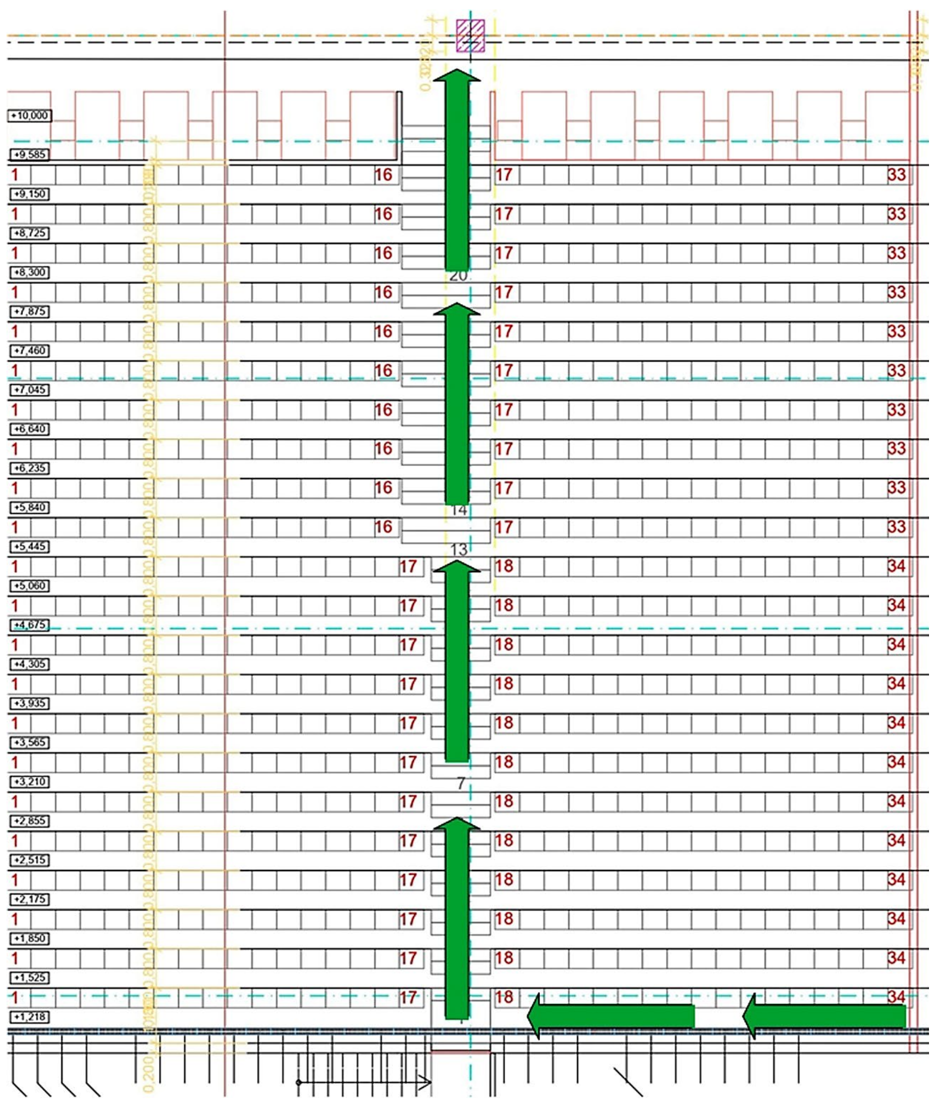

Fig. 2. Plan-scheme of exit from the most crowded sector of the upper tier of the «Arena Lviv» stadium to a safe zone

Fig. 3. Plan-scheme of exit from the most crowded sector of the lower tier of the «Arena Lviv» stadium to the safe zone

The above schemes reflect the evacuation routes of movement of visitors to the stadium from the sector to the promenade. In some cases, the place itself on the promenade can be considered a safe zone for humans in case of fire or emergency. However, in most cases, free space on the promenade is often used for the construction of trade kiosks, which in turn create a significant fire load. As a result, staying on the promenade is considered dangerous during emergencies and there is a need to evacuate visitors outside the building to a free territory (safe zone).

Using the probabilistic method and optimization synthesis of flexible technological lines, the evacuation of stadium visitors to a safe zone will be represented in the form of topological models of safety-oriented management of human flows. The general view of the verbal-topological model of the process of evacuation of people from the stadium sectors to the safe zone is shown in Fig. 4. The model is formed as a result of combining serial and parallel schemes of TLEP of people from the SIF since such a process takes place simultaneously and independently of each other from all sectors and premises of the structure. Therefore, the blocks describing the movement of stadium visitors in TLEP form a «tree-like» topological model.

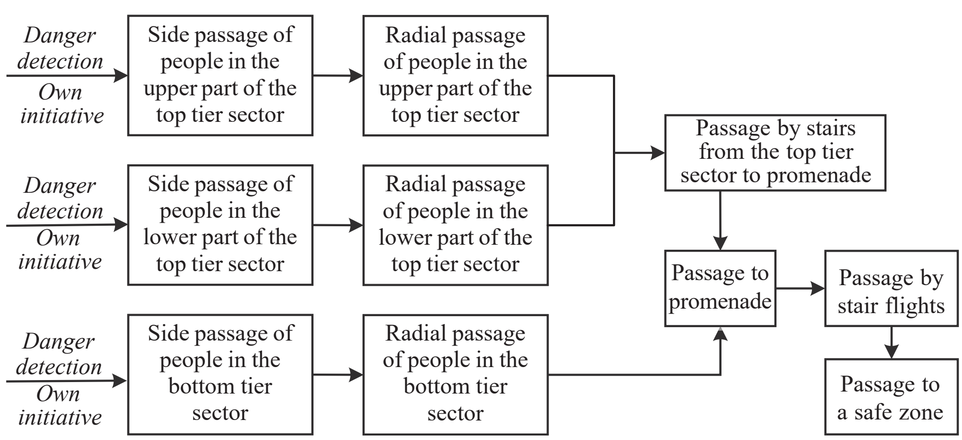

Fig. 4. General «tree-like» verbal-topological model of safety-oriented management of evacuation of people from a sports infrastructure facility

The yopological models of safety-oriented management of evacuation of people from the «Arena Lviv» stadium from the most loaded sect tors of the lower and upper tiers to the safe zone are shown in Fig. 5, 6.

In the sector of the upper tier of the stadium (Fig. 2), the most remote spectator seats are in its upper part – displayed by blocks Z1, Z2; lower part – Z11, Z14; block Z16 – movement of people along the promenade; Z17 and Z18 – movement on flights of stairs to a free territory (Fig. 6).

Our topological models have made it possible to analyze the movement of people around the building, synthesize the evacuation system of the stadium taking into account the regulatory framework, and identify the most loaded evacuation areas (critical paths), bottlenecks, and buffer zones. In such problem areas, it is necessary to take into account the safety-oriented distribution of human flows to ensure timely evacuation of people from the stadium to a safe zone.

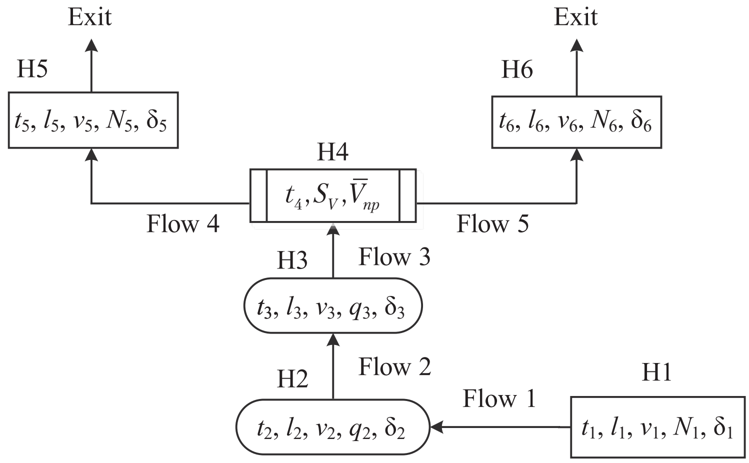

Fig. 5. Topological model of safety-oriented management of evacuation of people from the most crowded sector of the lower tier of the «Arena Lviv» stadium to a safe zone: N_1 — number of visitors who are in block *H*1, persons; *H*1, ..., *H*6 — blocks of the topological diagram of the technological line of the process of evacuation of visitors from the lower sector of the stadium to a safe zone

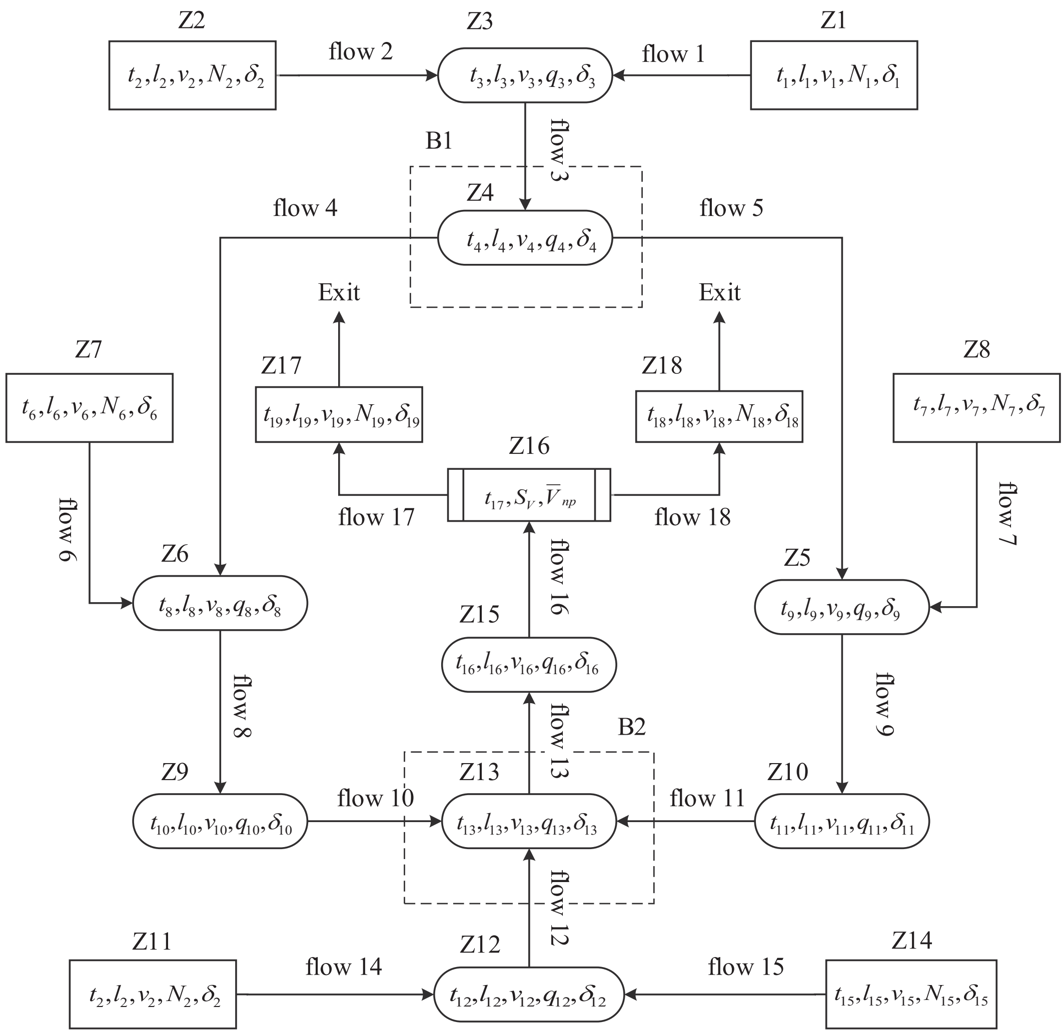

Fig. 6. Topological model of safety-oriented management of evacuation of people from the most crowded sector of the upper tier of a sports infrastructure facility to a safe zone: *Z*1, ..., *Z*18 — blocks of the technological line of the process of evacuation of people from the upper tier to a safe zone; t_1 — duration of human flow on the first (initial) section of the evacuation route, min.; *B*1 — bottleneck of the evacuation route, distribution of human flow; *B*2 — bottleneck of the evacuation route, the unification of human flow; zones *B*1 and *B*2 require special attention when evacuating people

5. 3. Studying the evacuation time of people from sports infrastructure facilities

The limited capacity of turnstiles, stairs, aisles, doorways complicates the movement and evacuation of stadium visitors on certain sections of the evacuation route. Given this, it is necessary to manage the flows of people in order to rationally distribute visitors to evacuation passages and exits. This distribution must be carried out in such a way as to avoid accumulation and delay in the movement of people and, ultimately, to ensure their timely exit to the safe zone. During the evacuation from the «Arena Lviv» stadium, most people pass through the designed nine main evacuation exits from the promenade, which are located around the perimeter of the structure, which allows for an even distribution of human flows. Visualization of evacuation exits from the promenade to the safe zone is shown in Fig. 7. Each evacuation exit is characterized by some parameters, namely:

– width of the passage;

– bandwidth for a period of 8 minutes;

– the number of visitors evacuated through the specified exit;

– degree of workload of the evacuation exit;

– the number of visitors as a percentage of their total number.

Table 1

Characteristics of evacuation exits from the promenade at the «Arena Lviv» stadium

Evacuation exit number	Width (m)	Throughput (limited to 8 minutes)	Number of evacuated visitors (persons)	Evacuation exit load (%)	Visitors (% of total)
E1	8	4200	2577	61.36	7.79
E2	9.6	5070	3502	69.07	10.59
E3	7.2	3800	3528	92.84	10.67
E4	7.2	3800	3393	89.29	10.26
E5	9.6	5070	5194	102.45	15.71
E6	7.2	3800	4067	107.03	12.30
E7	7.2	3800	3052	80.32	9.23
E8	21.5	11180	5591	50.01	16.91
E9	8.2	4264	2164	50.75	6.54
E_{total}	–	–	33068	–	100

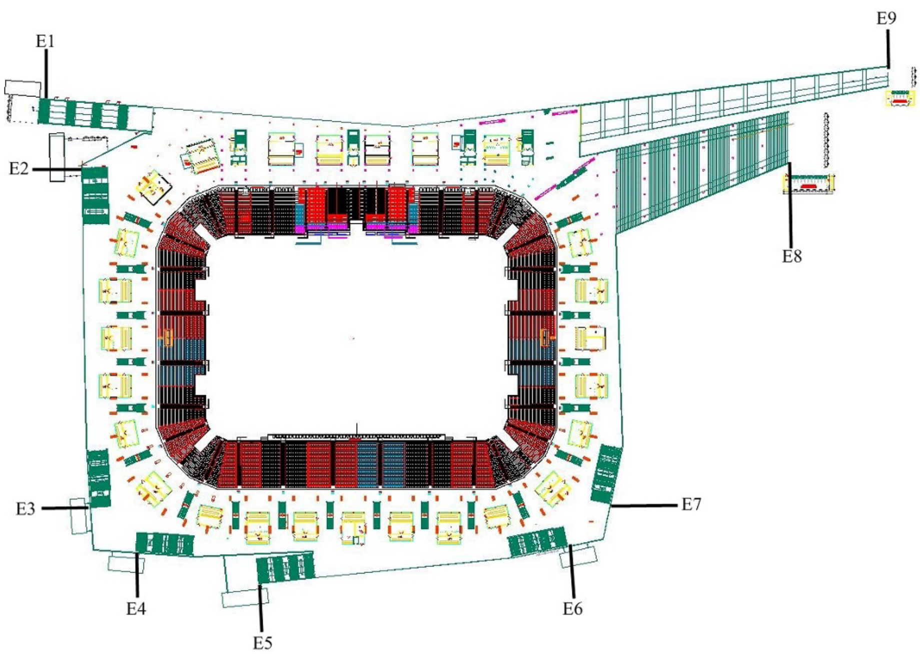

Fig. 7. Layout of evacuation exits from the promenade at the «Arena Lviv» stadium

These indicators are decisive for the safety-oriented management of flows of people on the promenade during the evacuation process. Calculations of evacuation time according to DSTU 8828:2019 showed that the evacuation system of the «Arena Lviv» stadium is not able to provide evacuae tion of its visitors up to 8 minutes. The calculations given in Table 1 revealed that the evacuation system at the «Arena Lviv» stadium is not balanced and needs to be optimized. This is due to the fact that evacuation exits E5 and E6 are not able to allow such a number of people in the time allotted by the requirements.

Taking into account the psychophysiological properties of people, most of them, in case of danger to their lives, will try to leave the dangerous place at the shortest evacuation exit. As a result, some evacuation exits may not be able to allow an excessive number of people to pass in the required amount of time. That is why the system of evacuation exits should be clearly thought out and balanced. That is, after the completion of the stage of construction or reconstruction of SIF, it is necessary to conduct an examination of the evacuation system and optimize it.

5. 4. Optimizing the time of evacuation of people from the sports facility

Improving the work of TLEP requires its analysis in order to determine the main optimization criteria.

Since the evacuation of people takes place within a strict time frame, the main criterion for optimizing such a line will be the total time T of evacuation of people from the SIF to a safe zone.

The main task of the evacuation process is to remove people from a dangerous place as soon as possible, so this criterion should be minimal.

A similar criterion is the time t_i of the i-th technological operation (unit) – evacuation of people from a separate section of the SIF.

In order to determine the total time T of operation of the production line, it is not enough to have the entire set of times of operation of individual technological operations because the evacuation of people from the SIF takes place simultaneously from all sectors and premises.

Therefore, it is necessary to analyze the topology of connections of blocks (individual evacuation areas) in which technological operations are performed and select those that are interconnected with each other and form a serial or parallel connection, describing the evacuation process. Minimizing the execution time of operations in TLEP blocks can be represented as the following dependence:

$$\{t_i\}|_{\forall i(i=1\ldots n-1\ldots n)} \overset{P}{\Rightarrow} \{T\} \to \min, \quad (1)$$

where P is the operator of selection of technological operation, taking into account the topology of connections between them.

Often, and this is especially true for structures with a mass presence of people to which SIFs belong, there is a delay in the execution of technological operations t_z. Therefore, the movement of people along the SIF should be planned in such a way as to avoid delaying the flow of people on the evacuation routes or minimize it as much as possible in time. Therefore, to a certain extent, the criterion t_z is derived from t_i.

Thus, the downtime of the entire technological line T, which also needs to be minimized, in general terms can be expressed as:

$$\{t_z\}|_{\forall i(i=1\ldots n-1\ldots n)} \overset{P}{\Rightarrow} \{T_z\} \to \min. \quad (2)$$

Another important criterion for optimizing the production line is the number of people N_i involved in the evacuation process. Reducing the evacuation time for an existing structure can be achieved by reducing spectator seats in the SIF stands. In this case, the number of people in a separate evacuation area will form a flow of lower density, which will provide a higher speed and, ultimately, reduce the time of evacuation from the SIF.

The total number of people N_{total} involved in the evacuation process is:

$$N_{total} = \Sigma N_i \to \min. \quad (3)$$

Since in the process of optimizing the TLEP of people from the building it is necessary to take into account all three criteria, we get the following dependence:

$$\{t_i, t_z, N_i\}|_{\forall i(i=1\ldots n-1\ldots n)} \overset{P}{\Rightarrow} \{T, T_z, N_{total}\} \to \min. \quad (4)$$

Taking into account the relationship between optimization criteria, we shall subsequently take into account the most important criterion for the technological process – evacuation time.

Thus, it is necessary to exert some physical impact on factors that are related to the time of evacuation until it meets the required normalized value.

The main practical methods of safe management of human flows include:

– physical reduction in the number of seats in rows and sectors in general;

– increase in the geometric parameters of evacuation passages (if possible);

– increase in the parameters of evacuation routes (if possible);

– installation of distribution railings;

– management of human flows with the help of specially trained service personnel (stewards);

– installation of navigation signs;

– video and sound alerts of the population about the procedure (exit) in case of emergency.

Using the above theoretical tools for safety-oriented management of evacuation of people from structures, it is advisable to devise practical recommendations for optimizing evacuation routes at the «Arena Lviv» stadium. Scheduled evacuation of visitors to the stadium is carried out after the match.

The peculiarity of such evacuation is that all spectators under normal conditions leave the spectator area and enter the free exit zone. The choice of exit route is arbitrary, the evacuation time is unlimited.

The route of movement of visitors during evacuation is determined by dependence on their location at the SIF. For the «Arena Lviv» stadium, this is the distance from the location of the spectator in the sector on the stand to the exit outside the building (to the safe zone). To determine the critical evacuation routes, a detailed analysis of the space-planning solutions of the «Arena Lviv» stadium, a mathematical description of the process and simulation of evacuation time were carried out.

The peculiarity of this work was the analysis of spectator flows in order to assess the ratio of the area required for movement, the accumulation of spectators in the aisles and in front of their exits. This value is compared with the size of the waiting areas.

After analyzing the movement of flows of people at the SIF, taking into account their space-planning decisions, parameters have been established that affect the movement of flows of people in their individual evacuation areas and the process of its modification when entering the promenade. As a result, it was established that the evacuation route from the stadium sectors for calculating the time of movement of spectators from the building to the safe zone should be divided into the following evacuation areas:

– exit of people from the sector of the upper tier of the SIF: lateral passage in the sector, radial passage, passage down stairs from the sector, passage along the promenade, descent of staircases to the free territory (safe zone);

– exit of people from the sector of the lower tier of the SIF: lateral passage in the sector, radial passage in the sector, passage along the promenade, descent of staircases to the free territory (safe zone).

Radial passage is a stepped or inclined path for traffic through the spectator area, which passes between the ledges of the terrace or rows of chairs.

Side passage is a horizontal path for people to move through the spectator area, which runs parallel to the ledges of the terrace or rows of chairs.

The promenade is a specially made platform at a certain height, which ensures optimal movement of flows of people through the building.

When determining the time of movement of people, the width and length of each site is taken in accordance with the design or the actual values of the parameters of the existing structure. The length of the staircase or ramp is equal to the length of the march, and the length of the path in the doorway is zero. If the opening in the wall exceeds 0.7 m, then it must be considered as a horizontal escape route.

In accordance with [19, 20], it is also necessary to provide for the possibility of evacuation from individual sectors, that is, partial evacuation. Taking into account the peculiarities of the planning of the structure, it can be divided into four zones (Fig. 8):

– zone A (north stand);
– zone B (east stand);
– zone C (south stand);
– zone D (west stand).

The exit of people from their spectator seats outside the «Arena Lviv» stadium can be predicted along the routes indicated in Fig. 9, 10:

1. The exit of people who are at the initial stage of the evacuation process in zone A takes place in the following order:

– from the sectors of the lower tier: a lateral passage between the rows of chairs, along the radial passage in the sector, passage through the promenade, passage by staircases E2, E3 from the promenade outside the stadium towards Stryiska or Kiltseva Streets;

– from the sectors of the upper tier: a side passage between the rows of chairs, along the radial passage in the sector, descent by stairs to the promenade, passage by promenade, stairways E2, E3 from the promenade outside the stadium towards Stryiska or Kiltseva Streets.

2. The exit of people who are at the initial stage of the evacuation process in zone B takes place in the following order:

– from the sectors of the lower tier: a lateral passage between rows of chairs, along the radial passage in the sector, passage through the promenade, passage of staircases E4, E5, E6 from the promenade outside the stadium towards Vernadsky Street;

– from the sectors of the upper tier: a side passage between the rows of chairs, along the radial passage in the sector, descent up the stairs to the promenade, passage along the promenade, along the flights of stairs E4, E5, E6 from the promenade outside the stadium towards Vernadsky Street.

3. The exit of people who are at the initial stage of the evacuation process in zone C takes place in the following order:

– from the sectors of the lower tier: a side passage between rows of chairs, radial aisles in the sector, passage through the promenade, passage by stairways E7, E8 from the promenade outside the stadium towards Vernadsky or Stryiska Streets;

– from sectors of the upper tier: a side passage between rows of chairs, a radial passage in the sector, a descent by stairs to the promenade, a passage through the promenade. From the promenade, people move along the flights of stairs E7, E8 outside the stadium towards Vernadsky or Stryiska Streets.

4. Evacuation of people from zone D provides for the exit of stadium spectators from the sectors of the lower tier and from each level of the administrative building. The route of movement of people during evacuation from the sectors of the lower tier will be as follows: a lateral passage between the rows of chairs, then along the radial passage in the sector, passage along the promenade. From the promenade, go by flights of stairs E9, E8, E1 outside the stadium towards Kiltseva or Stryiska Streets.

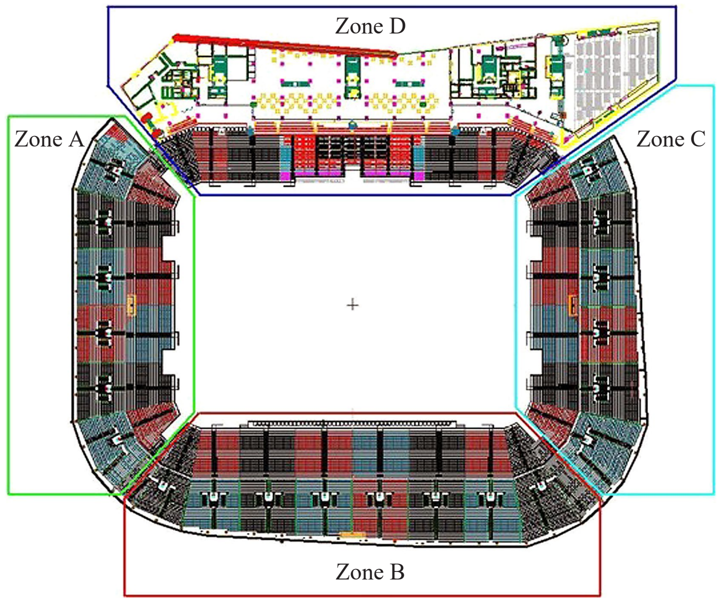

Fig. 8. Conditional division of the «Arena Lviv» stadium into evacuation zones

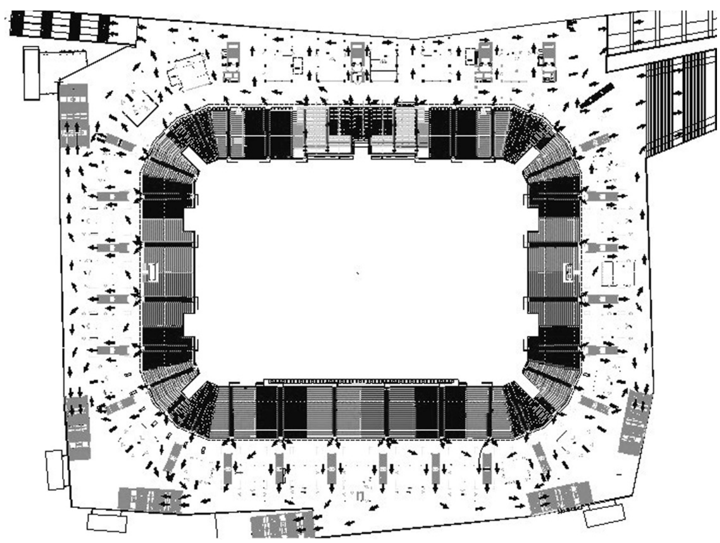
Fig. 9. Optimized model-scheme of safety-oriented management of flows of people during evacuation from the «Arena Lviv» stadium

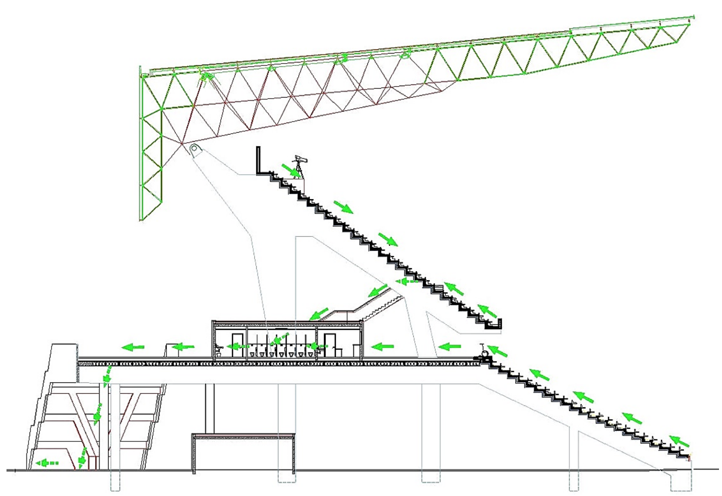
Fig. 10. Model-diagram of safety-oriented management of flows of people during evacuation from sectors of the stadium beyond its borders in cross-section

6. Discussion of results of investigating safety at a sports infrastructure facility

Our information analysis of the process of evacuation of people from structures of different classes of purpose made it possible to determine the factors that influence the movement of people in the flow (Fig. 1). Analysis of scientific papers [1–7, 9, 12, 20] showed that these factors can vary depending on the type of structure under study, that is, its purpose. Therefore, it is not advisable to calculate the time of evacuation of people from structures of different classes of purpose using the same method. That is, there is a need for an individual approach to such calculations, as shown in works [15–17, 19, 20]. The need to determine the parameters of evacuation is due to the fact that they are the initial data for the application of procedures for determining the total time of evacuation of people from the structure to the safety zone beyond its borders, as the main indicator of safety.

For visual representation of the factors influencing the evacuation process in its sections, the theories of analysis and synthesis of flexible technological lines and topological modeling were used. For this purpose, an analysis of all evacuation routes from the sports infrastructure facility («Arena Lviv» stadium) was carried out. As a result of this analysis, the total evacuation route of the most remote place for a person from the largest sector in terms of number was divided into separate evacuation areas. Such sites were created depending on factors that influenced the evacuation flow of people. As soon as one of the factors changed its value or its presence changed, another topological block of the technological line was built. Thus, a separate section of the evacuation route was considered as a separate block (Fig. 1). Synthesis of all blocks of the evacuation route made it possible to form a general topological model of evacuation of people from the structure (Fig. 4). Since the stadium sectors are different in their design (Fig. 2, 3), topological models for the upper and lower tiers are presented in the current paper (Fig. 5, 6). To describe the parameters that affect the evacuation process, other scientists use verbal models in their research [9]. This is appropriate when it comes to small objects. Verbal models have a completely different meaning when considering the process of evacuation of people from crowded objects, where there are several dozen evacuation routes and hundreds of evacuation areas. In this case, verbal models become quite massive and the search for a specific factor influencing the evacuation in a certain area takes a lot of time and is a difficult task since you can fill the correctness of the selected required area. Since the presence of certain factors affects the choice of the methodology by which evacuation time will be calculated, the analysis of all factors in each evacuation section of alternative evacuation routes becomes a very difficult task. Therefore, topological models have an advantage over verbal ones because they are compact compared to others, show the sequence of the evacuation process, clearly reflect the better change of factors in accordance with the previous evacuation route. Therefore, these models can be considered a universal tool for visualizing the parameters of the evacuation process.

Using our topological models of safe movement of human flows and the method of calculating the time of evacuation of people from structures, which is given in DSTU 8828:2019, calculations were made to determine the time of evacuation of people from different places of stay at the «Arena Lviv» stadium. The estimated duration of evacuation of people from a sports facility was determined using a simplified analytical model of human flow, which is given in this regulatory document. Such a model takes into account the results of the studies reported in [1–7]. The data obtained as a result of calculations (Table 1) showed that evacuation exits E5 and E6 are filled by 102.45 and 107.03 %, respectively. That is, in these areas there is a delay in the movement of people. This suggests that the evacuation system under such conditions is not able to provide evacuation of people up to 8 minutes, as required by world standards in the construction of stadiums.

Information analysis of successful practices of operation of sports infrastructure has shown that the main safety criterion is evacuation time. Therefore, the optimization of the movement of human flows was carried out according to the time criterion. To this end, the critical path method was used. Based on the obtained calculation data (Table 1), problem areas during evacuation were identified. A systematic analysis of evacuation sites has established that it is necessary to minimize the evacuation time on a particular evacuation route section (1) and the delay in the movement of people in the area where it is observed (2). In the case when the total time of evacuation from the structure exceeds the permissible values, it is necessary to reduce the total number of seats in sectors to an acceptable value (3). Therefore, the stadium was divided into zones (Fig. 8) according to common sectors from which people are evacuated through common exits. Thus, expression (4) lists factors that must be minimized in practice to ensure safety in the stadium. The practical implementation of the process of optimizing the movement of human flows during evacuation is carried out by parallelizing them. Therefore, evacuation flows of people going to exits E5 and E6 were redirected to other less congested exits E4 and E7. The redirection of human flows was carried out through the installation of additional restrictive handrails and explanatory work of stewards. The optimized process of general evacuation of people from the «Arena Lviv» stadium is shown in Fig. 9.

Our study has a prospect of development since the devised topological models of safety-oriented management of evacuation of people are specifically for the «Arena Lviv» stadium. It should be noted that such models need to be developed for each evacuation route, of which there may be several within one object. Therefore, it is advisable to develop a technique for building dynamic topological models of safety-oriented management of human flows. This technique of model development would be a universal tool for determining the factors influencing the process of evacuating people from structures of various kinds. It will simplify the modeling of evacuation routes, will automate the calculation of evacuation time, which will ensure a quick examination of the evacuation system of the structure.

7. Conclusions

1. Information analysis of the movement of flows of people allowed us to determine the factors that influence the process of safe and timely evacuation of people to a safe zone. Such parameters should include evacuation time, number of people, density of human flow, area of horizontal projection of a person, geometric parameters of evacuation routes, and design features of structures.

2. Topological models of safety-oriented evacuation management of people have been built, which take into account

the factors influencing the evacuation process on a separate section of such a route. This makes it possible, unlike other models, to use different procedures for calculating the evacuation time of people, which gives a more accurate result.

3. Using the topological models of safety-oriented human flow management and the procedure for determining the evacuation time given in DSTU 8828:2019, the total time of evacuation of people from the «Arena Lviv» stadium was calculated. The calculation results showed that the total evacuation time from the structure exceeds 8 minutes; this indicator does not meet international requirements. It was found that it is necessary to optimize the movement of human flows since there is an overload of evacuation exits E5 and E6 by 3 % and 7 %, respectively. That is, there is a delay in the movement of people at evacuation exits E5 and E6, as a result of which the recommended value of evacuation of people in the interval of up to eight minutes is not achieved.

4. The assessment of the evacuation system at the «Arena Lviv» stadium showed weaknesses in the building. It was found that the most problematic are evacuation exits E5 and E6 since they account for the largest number of people during evacuation. This is due to the fact that these exits are located at the shortest distance from the busiest sectors of the stadium. Therefore, the most effective practical way to unload these exits is to create conditions for the redirection of human flows. This can be implemented in practice by installing certain handrails that will delimit the flows of people. You can also differentiate flows with stewards who can provide the necessary recommendations verbally or using sign language.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

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