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Fire Safety in Museums: Simulation of Fire Scenarios for Development of Control Evacuation Schemes from the Winter Palace of the Hermitage

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Abstract: The manuscript is focused on the problems of evacuation in case of fire from the buildings of museums as places with a mass presence of people. Features specific to museums and how they affect safe evacuation conditions are discussed. Most attention is paid to evacuation management, since the vast majority of museum visitors are not familiar with the layout of the building. In this case, the actions of staff in evacuation management are decisive. The paper considers the development of evacuation schemes, taking into account the spread of fire hazards in the building and the development of instructions on their basis for the staff. Using the example of the Winter Palace of the State Hermitage Museum, the solution of the marked tasks with the use of computer simulation of evacuation during a fire is given. The analysis of the simulation results showed the vulnerabilities of the museum. In this work, the evacuation schemes for the scenarios are considered. The maximum number of visitors at a single time in the Winter Palace has been set at 4000. The principles of making evacuation schemes are formulated, including taking into account the peculiarities of space-planning solutions inherent in museums, such as enfilades and the connections of rooms.

Keywords: museum; computer simulation; fire safety; design; dangerous fire factors; ASET; RSET; evacuation; control

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1. Introduction

Museums, as places of mass gathering, are high-risk facilities. In the case of fire, safe evacuation conditions must be provided for all people, without exception. For museums (and any other buildings) the safe conditions are currently defined by the Inequality (1). This inequality should be true for the whole evacuation path of each person. Additionally, unobstructed evacuation is required, that is, the duration of congestion with a density that has reached a critical value should not exceed 360 s (for example, it equals 0.5 m^2/m^2 in Russia [1,2]).

$$t_{evac} < \alpha \cdot t_{block} \tag{1}$$

where t_{evac} is the time of the end of evacuation from the part of the building (which is called a required safe egress time or RSET), t_{block} is the time of reaching the critical value by some dangerous fire factor in the same part of the building (which is called an available safe egress time or ASET), $0 < \alpha < 1$ is a safety factor (for example, it equals 0.8 in Russia [1,2]). For example, the critical values of fire danger factors are given in Table 1 [2].

Table 1. Critical values of fire danger factors.

Fire Danger Factors	Critical Value
Ambient temperature, °C	70
Loss of visibility in the smoke, m	20
Carbon dioxide emission, kg/m^3	0.1
Carbon monoxide emission, kg/m^3	0.0012
Hydrogen chloride emission, kg/m^3	0.000023
Oxygen content, kg/m^3	0.226

Fires also pose a danger to the contents of museums that contain objects of world cultural heritage that are easily involved in the combustion process (old books, manuscripts, clothing, antique furniture, paintings, graphics, objects of artistic crafts, etc.) [3–7]. For example, in 2018, a fire that lasted more than five hours destroyed almost 90% of the collections at the National Museum of Brazil. In Malaysia, between 2001 and 2015, three museums experienced fires that destroyed buildings and their contents [3,6]. Museums are often located in cultural heritage sites; in which case, the goal of fire safety is also to minimize damage to the building itself. Aging and combustible materials in the load-bearing structures of buildings pose one of the main problems to solve regarding this aspect. Historic wooden buildings are the most vulnerable [5]. At the same time, the equipping of buildings with modern fire protection systems is a complex task. For example, water fire suppression is safe for people and conditionally safe for the buildings but can cause significant damage to the exhibited collections.

While fires cannot be prevented entirely, pre-planning measures can significantly help mitigate and effectively reduce their impact. This paper focuses on considering the museum as an object with a mass presence of people and the period from the time of the fire starting, during which it is possible to evacuate visitors.

Some visitors have limited mobility and require staff assistance in the case of an emergency evacuation. Museums are characterized by the constant rotation and renewal of visitors. Most often, visitors are not familiar with the plan of the building, the location of the evacuation exits, and it is up to the staff to manage the evacuation, directing visitors to a safe route. That is why the training of evacuations in museums is very important: they train the staff, develop the mechanism of coordinated work of all the museum services involved and external security services [8]. Two possible weaknesses of the management strategy may be the lack of a direct phone line to the fire department and the lack of an automatic fire suppression system in the building.

A peculiarity of museums is the fact that the positions of caretakers of the halls are often held by employees of advanced age. In the event of an emergency, they cannot be expected to be proactive and give clear instructions to visitors. Therefore, it is important to understand the location of the most key areas (nodes) of the building to form the routes of visitors during evacuation and put the most prepared staff on them to act in case of emergency. Ensuring the safety of museum values is also an important condition for emergency evacuations from the building, which is achieved by the possibility of conducting inspection procedures for visitors at the end of the evacuation.

Thus, in order to successfully solve the problem of providing safe conditions for the evacuation from a museum, it is necessary to have estimates of how fast smoke (and other dangerous fire factors: temperature, heat flow, and concentrations of O_2, CO, CO_2, HCl) spreads through the building in different scenarios, and the duration of the evacuation should be estimated as well. This information is the basis for solving the following tasks:

- to determine the allowable duration of an evacuation, which ensures safe conditions on the evacuation routes;
- to establish a limit on the number of people whose stay in the museum would be safe in the case of a fire or other emergency that requires evacuation;
- to set the maximum number of visitors with disabilities allowed to access the facility at one time; to develop strategies for accompanying them from different rooms of the

museum, taking into account the limited speed of movement and the possibility of their independent departure from the building;
- to determine the safest parts on the floors to use as safety zones for disabled persons;
- to develop different evacuation routes in the event of actual or suspected blockage of evacuation routes and/or exits due to the spread of dangerous fire factors, taking into account the applicable safety criteria;
- to identify areas of the building where congestions with critical density are formed and their duration;
- to develop instructions for staff, select the most appropriate staff for key areas of the building to manage evacuations, and plan for evacuation training.

It is necessary to consider the feasibility of the evacuation schemes—if the staff actually have the ability to provide routing (management of the flow of people) according to the developed schemes. It is also necessary to take into account the fact that the seat of fire (or other blocking factor) can occur in any part of the building and, respectively, several evacuation schemes should be provided. These facts, given the planning features of the object, the location of expositions by popularity, impose additional restrictions on the development of evacuation schemes. Thus, the task of developing an evacuation route during a fire is a multi-criteria task. This is an argument in favor of the use of computer modeling. Currently, the computer simulation of evacuation in a fire is a recognized tool for solving tasks in the field of safety, especially at facilities with mass presence of people.

A detailed building model can be made on the basis of building information modeling (BIM) [9,10]. In [11–18], the prediction of the dynamics of pedestrian flows at sports arenas is presented using modeling tools; in [19]—at a music festival; in [20,21]—at the airport and in the subway; and in [22–24]—at mass events of religious significance.

BIM can effectively provide three-dimensional geometric data to assess and plan fire safety in the organization of museums and optimize the use of exhibition space. For example, in [25], the capacity of the Castello Ursino museum (Catania, Italy) was evaluated and the effectiveness of the existing evacuation plan was tested for different configurations of accessible exits and for several speeds of the incoming flow of visitors. In [26], different evacuation scenarios are considered and recommendations for faster and safer evacuation of museum visitors (arrangement of expositions, increase or transfer of passages) are offered. In [27,28], the trajectories of visitors to the Galleria Borghese museum (Rome, Italy) were studied in order to develop strategies of occupancy and visits to the museum during the day by means of mathematical simulation of the movement of people. In [29], the dynamics of visitors in a crowded museum (Rome, Italy) were examined in order to create a mathematical model that can be used as a tool for the management and optimization of the work of this museum. In [30], scenarios of fire development and safety of evacuation of people in the palace-museum Frusione (Salerno, Italy) were considered by means of simulation; the results confirmed the effectiveness of the existing evacuation plan in limiting the number of people staying in the building simultaneously. In [31], a study of visiting historic buildings by people with different types of disabilities was conducted. In [30,31], it was noted that staff actions play an important role in ensuring timely evacuation from museums. In [32], the adaptation of a building of cultural heritage, the hydro tower building, for a new purpose (an exhibition complex and museum) was investigated and a computer simulation of fire evacuation was utilized as a creation tool.

Modern approaches to the simulation of human movement allow each person to be considered separately as an individual agent [33]. Each person may be assigned with individual properties: free movement velocity, pre-evacuation time, projection size and evacuation way. It allows the solving of a variety of pedestrian movement tasks, including fire evacuation tasks, and makes this model a powerful simulation tool.

CFD (computational fluid dynamics) modeling is used to simulate the development of a fire. CFD modeling technique is widespread and well investigated already, for example [34,35]. It provides an approximate three-dimensional solution to the equations governing fluid motion. The computational area is divided into very large number of small domains, referred to as mesh or grid cells. Complex geometries and time-dependent flows are readily handled. The solution is values of flow parameters, such as velocity, pressure, temperature and gas concentrations and optical density, calculated at each of the grid cells. It provides a complete three-dimensional, time-dependent picture of complex fluid flows.

The Sigma FS software package implements the above capabilities [36–41] and is used in this investigation. Previously, the software was used to verify the space-planning solutions and the organization of pedestrian zones for the facilities of the 2018 FIFA World Cup (FIFA CC 2017, FIFA WC 2018) and the Universiade 2019 [14–16]. The software allows a 3D model of the building to visualize the evacuation of people and the spread of fire hazards simultaneously.

This manuscript examines the use of computer simulations of evacuation in a fire to form evacuation schemes using the example of the Winter Palace of the State Hermitage Museum, one of the largest museum complexes in the world, in order to apply them to the practical actions of the staff to ensure safe conditions for evacuation.

2. Materials and Methods

2.1. Description of the Object Specifics

The Winter Palace was built by architect Francesco Bartolomeo Rastrelli in 1754–1762 in the Baroque style. It was rebuilt after a fire in 1837 and became a stone building. For 150 years, the Palace was the ceremonial imperial residence. In November 1917, the Winter Palace was declared a museum [42].

The Winter Palace is a rectangular three-story building with a basement and entresols; its area is approximately 60,000 m^2 (Figure 1). The architectural appearance has four risalites—parts of the building protruding beyond the main line of the facade in its entire height, with courtyards, as well as the central (Great) Courtyard. The main facade is divided by the entrance arch into southwest and southeast risalites. There are more than 1000 rooms in the building. The geometric characteristics of the building (length along the main facade; length along the side facade; average height) are 137, 106, and 23.5 m, respectively [42]. The Small Hermitage adjoins the Winter Palace to the east.

Figure 1. The Winter Palace of the State Hermitage Museum. Photo by the authors.

The walls are made of brick, the ceilings are of two types: brick vaults and beams (wooden or metal beams). The maximum height of the first floor is observed in the Jordan Gallery and is about 8 m; the average height of the exhibition halls is about 6.5 m; the average height of the second floor is about 7.0 m but 13–14 m in large halls; and the average height of the exhibition halls and corridors of the third floor is 6.5 m.

In the building enfilade arrangement of the rooms, some of the openings do not have doors, which is a feature of the organization of the museum space (Figure 2).

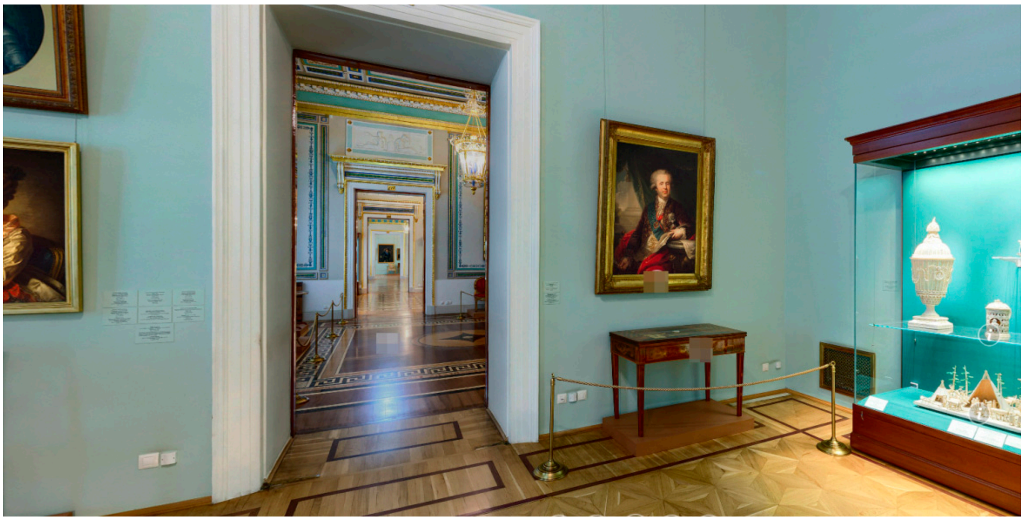


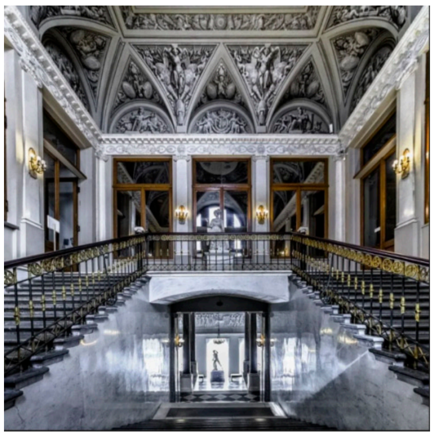
Figure 2. Enfilade arrangement of rooms in the Winter Palace of the State Hermitage Museum. Photo by the authors.

The main part of the historic building consists of spacious common areas (foyers, galleries, restrooms, exhibition halls and corridors). It is characteristic of the Winter Palace that the corridors, which are evacuation routes, are often used as exhibition areas where trellises, sculptures, and paintings are exhibited. To provide for the work of the museum complex there is a large number of service rooms, some of which have their own separate exits to the outside.

Fire detection and notification systems are provided in the Winter Palace (voice and light notification, the division of the building into fire warning zones, the feedback of fire warning zones to the fire control room, and the possibility of implementing several evacuation options from each fire warning zone [43]). Hand-held fire extinguishers are present in all rooms in the building.

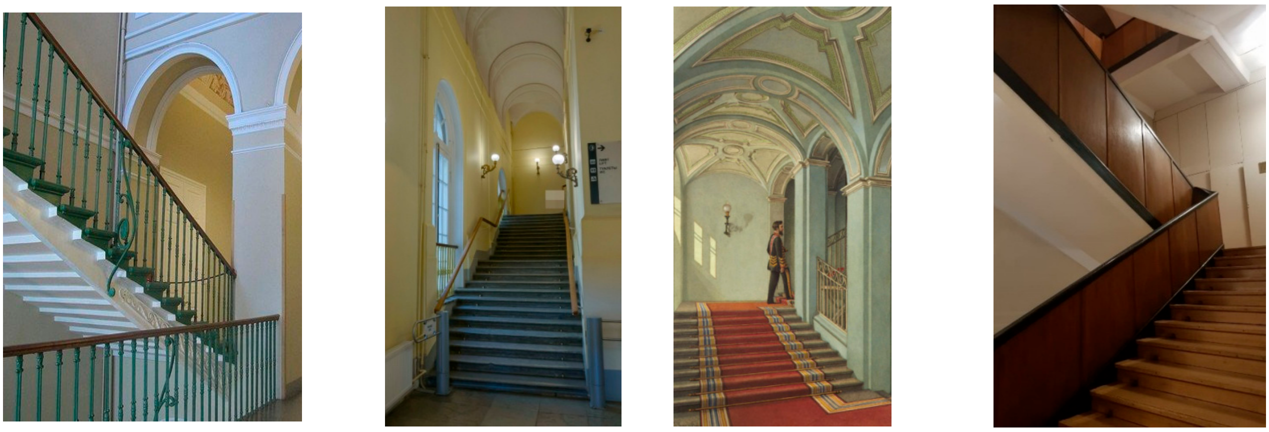
Six staircases are available to visitors for general use (there are lifts in the building, but we do not consider lifts for evacuations routs) [42]: the Jordan Staircase connecting the first and second floors; the Saltykov Staircase; the Great Church Staircase; the Commandant Staircase; the October Staircase; and the Wooden Staircase, connecting the first and third floors (Figure 3).

(**a**)



(**b**)

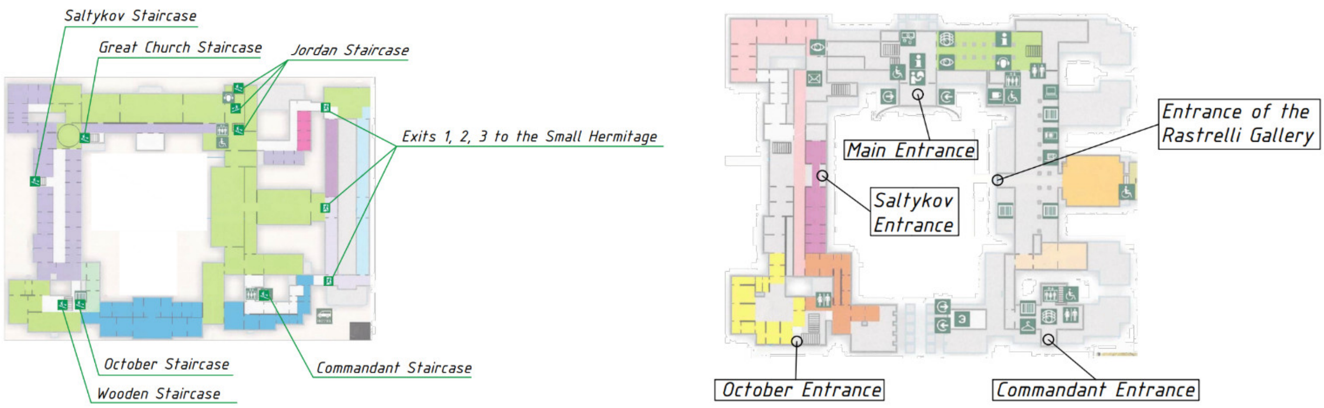
Figure 3. *Cont.*



(**c**) (**d**) (**e**) (**f**)

Figure 3. Staircases provided for the evacuation of visitors to the Winter Palace: (**a**) Jordan Staircase; (**b**) Great Church Staircase; (**c**) October Staircase; (**d**) Commandant Staircase; (**e**) Saltykov Staircase; (**f**) Wooden Staircase. Photo by the authors.

The distribution of staircases in the building is shown in Figure 4. The following evacuation exits may be used to evacuate visitors to the Winter Palace: Main Entrance, Entrance of the Rastrelli Gallery, Commandant's Entrance, October's Entrance, Saltykov's Entrance, and three exits to the Small Hermitage from the 2nd floor, located on the east facade of the building (Figure 4).



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

Figure 4. Distribution of staircases throughout the building (**a**); evacuation exits on the first floor plan (**b**).

From the point of view of museum valuables preservation, the exits to the central (Great) Courtyard of the Winter Palace have the advantage in the evacuation, since in this case it is easiest to organize the inspection procedures without using special measures to cordon off the perimeter.

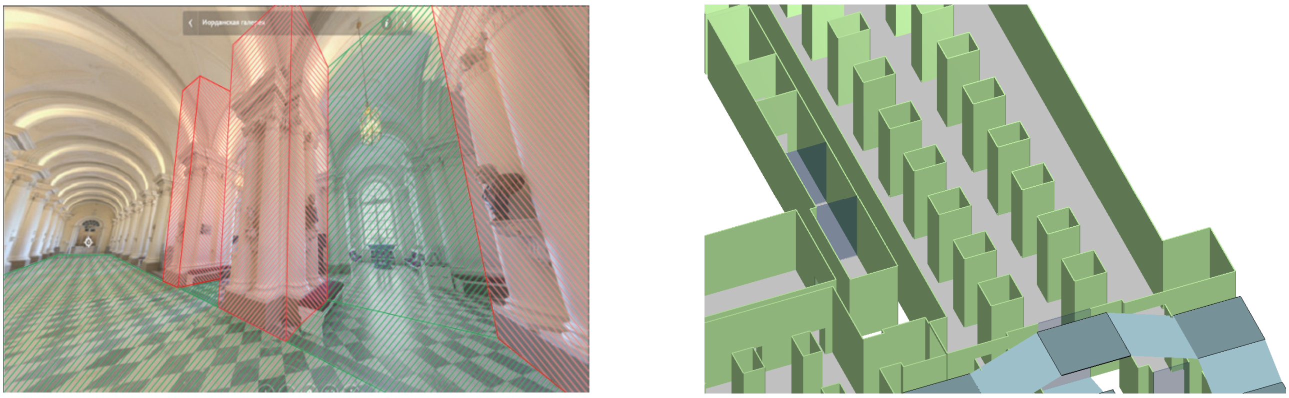
The largest exposition area and the most popular among visitors is the 2nd floor, where the art exhibits, household items, and the interiors of the rooms of the royal family are displayed.

2.2. Simulation of Evacuation and Fire Development

2.2.1. Creating a 3D Model (BIM) of the Building: Basic Principles

The BIM model of the Winter Palace building was made in the Sigma FS software package to simulate the development of the fire (and estimate ASETs for the whole evacuation paths for each scenario) and evacuation (and estimate RSETs for the same positions).

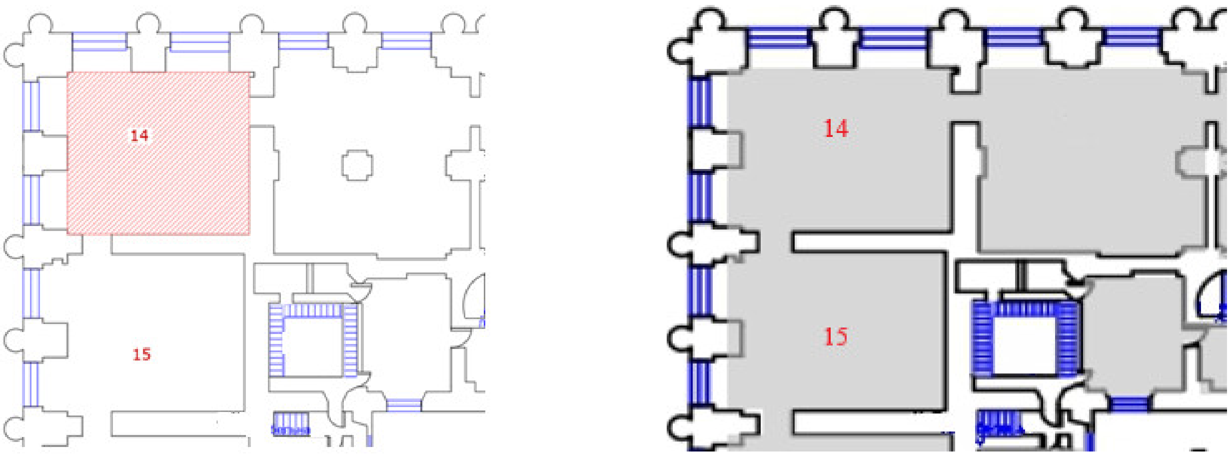
The building has a complex shape, the rooms have the decorative elements of compound columns and many rooms have a vaulted ceiling structure and deep window niches. In the model, a number of geometric simplifications are adopted, which do not reduce the length of the evacuation route and, by reducing the volumes included in the calculation area for modeling the development of the fire, contribute to obtaining lower estimations of the blocking time of evacuation routes. The complex geometric shape of the real columns at the object of study is simplified to rectangular parallelepipeds (Figure 5).



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

Figure 5. Columns in the Jordan Gallery (**a**); Columns in the Jordan Gallery in the model (**b**).

As a second simplification, window niches are excluded from the calculation area (they do not lie on the evacuation routes). The exclusion of window niches from the computational domain entails a reduction of the computational domain for simulating fire development (Figure 6).



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

Figure 6. Bronze Age Hall on the plan of the Winter Palace (**a**); in the model (**b**).

The complex architectural form of the ceilings (nerve structures, vaults) was simplified using the principle of volume reduction (Figure 7). The average height was calculated using the Formula (2):

$$H = H_{min} + \frac{H_{max} - H_{min}}{2}, \quad (2)$$

where H_{min} is the height of the bottom point of the nerve structure and H_{max} is the height of the upper point of the nerve structure.

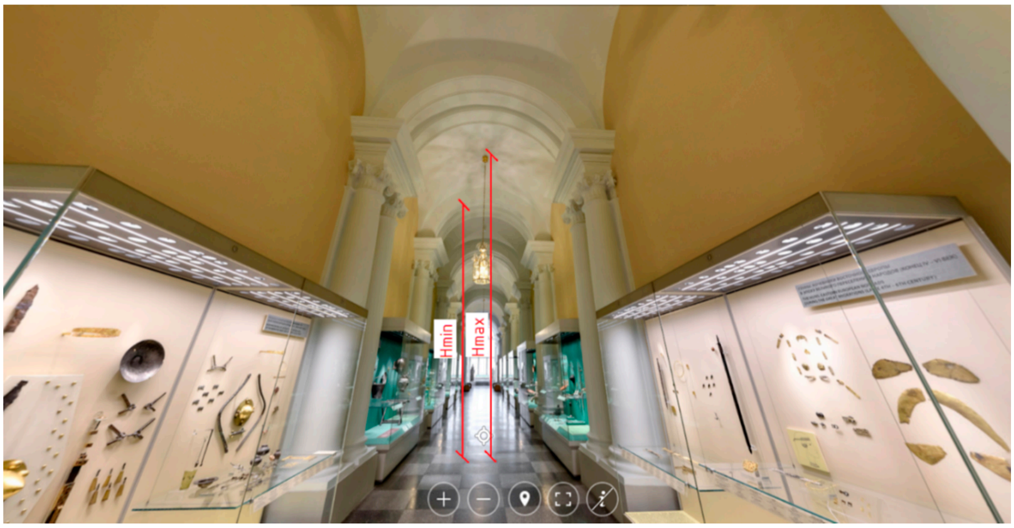


Figure 7. Calculation of average height of the room.

With the above geometric simplifications, the model of the Winter Palace was built (Figure 8).

Figure 8. 3D model of the Winter Palace.

The structure of the BIM model of the Winter Palace building is the following: the Building consists of Floors and Staircases; the Floor consists of Rooms with different types (halls, corridors, rooms) and Openings with different types (doors between the Rooms, exits, windows, other openings); and the Staircase of different types (up and down) consists of Flights and Sites.

2.2.2. Fire Seats Locations

Five locations are considered as likely locations of fires, causing difficult conditions for evacuation (the choice of fire points is conditioned, among other things, by the possibility of fire occurrence in these rooms due to the presence of a seat of fire (operated electrical appliances) and a combustible load):

- the fire in the foyer of the Wooden Staircase: Wooden Staircase and October Staircase are excluded;
- the fire in Buffet (Rastrelli Gallery): the use of the Jordan Staircase is minimized;
- the fire in the Commandant's Cloakroom: the Commandant Staircase from the 2nd to the 1st floor is excluded;
- the fire in the foyer of the Saltykov's Entrance: the Great Church Staircase from the 2nd to the 1st floor is excluded;
- the fire in the School Cloakroom: the Great Church Staircase from the 2nd floor to the 1st floor is excluded.

2.2.3. Initial Data for Fire Spread and Evacuation Simulation

In each scenario people are evenly distributed throughout the building in areas accessible to visitors with a predominant occupancy of the 2nd floor, which has more exhibition space, more popularity, and higher attractiveness of expositions (1st floor and basement—30%, 2nd floor—53%, 3rd floor—17%).

The presence of visitors with reduced physical activity (disabled persons) is an essential condition for the operation of the museum. Their speed determines when the evacuation ends. In some cases, they require an escort by museum staff.

For the calculations, the following individual characteristics of people in the ratio of 70% (healthy persons), 3% (disabled persons), and 27% (disabled persons), respectively, were taken [2]:

- speed of free movement of a person: 1.66 m/s, 0.50 m/s, 1.16 m/s;
- horizontal projection area of a person: 0.1 m^2, 0.2 m^2, 0.3 m^2.

The start time of evacuation is 60 s after the beginning of the fire [2] (it is assumed that fire detection system functioned, alarm system started, and people took some time to make a decision and start to evacuate).

During the simulation of fire development in the calculation area (mesh) the evacuation routes directly connected with the seat of fire were included, and the spread of the dangerous factors of fire through them is dangerous to people. All rooms included in the mesh are connected to each other. The computational meshes for the considered scenarios are shown in Figure 9. As boundary conditions it was accepted that heat exchange with enclosing structures is adiabatic, i.e., the heating of structures is not considered, the temperature of structures is taken to be equal to the near-wall layer during the whole period of simulation. The initial temperature in the calculation area and the outside temperature are taken as 20 °C. The specific power of combustible loads and smoke-forming capacity, respectively, are taken as the following [44]: in cloakrooms, 417 $\frac{\text{kJ}}{\text{m}^2 \cdot \text{s}}$ and 61 $\frac{\text{Np} \cdot \text{m}^2}{\text{kg}}$; in the buffet and in the foyer of the Saltykov's Entrance, 200 $\frac{\text{kJ}}{\text{m}^2 \cdot \text{s}}$ and 270 $\frac{\text{Np} \cdot \text{m}^2}{\text{kg}}$; and in the foyer of the Wooden Staircase, 259 $\frac{\text{kJ}}{\text{m}^2 \cdot \text{s}}$ and 130 $\frac{\text{Np} \cdot \text{m}^2}{\text{kg}}$. Mass load is admitted 20 $\frac{\text{kg}}{\text{m}^2}$; a square of fire area in each scenario equals the square of the room.

The combination of the accepted initial data provides the upper estimates of evacuation time and the lower estimates of time blocking of evacuation routes. In this case, the obtained results can be evaluated as results obtained with reserve.

In a fire, the building is exposed to high temperatures, which can lead to complete or partial destruction of building structures. However, the work considers the initial period of time of fire development, during which evacuation takes place and the temperature does not have a critical impact on the structures (which is also shown by calculation).

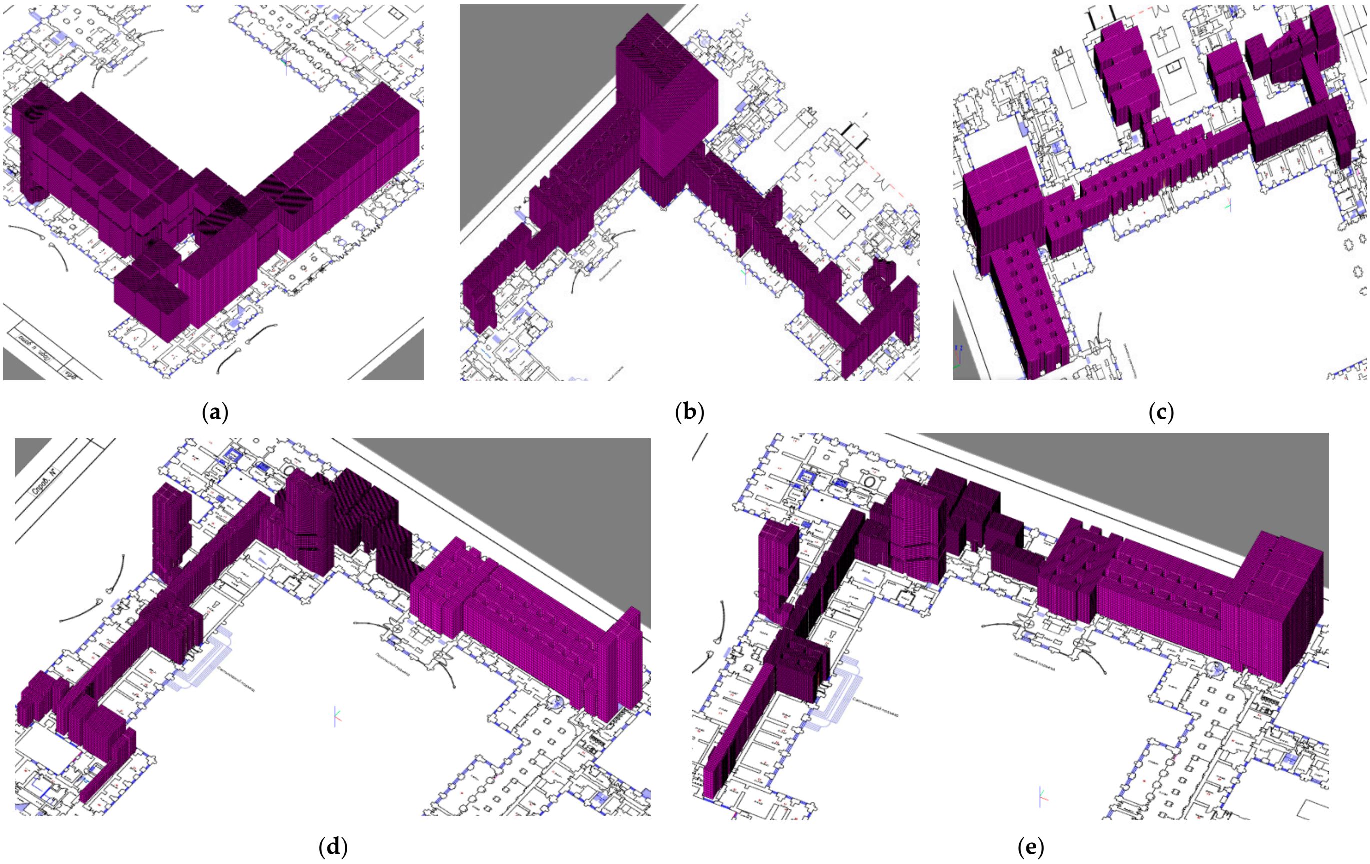


Figure 9. Calculation mesh for fire simulation in the scenario: (**a**) "The fire in the foyer of the Wooden Staircase"; (**b**) "The fire in Buffet (Rastrelli Gallery)"; (**c**) "The fire in the Commandant's Cloakroom"; (**d**) "The fire in the foyer of the Saltykov's Entrance"; (**e**) "The fire in the School Cloakroom".

3. Results

3.1. Simulation Results

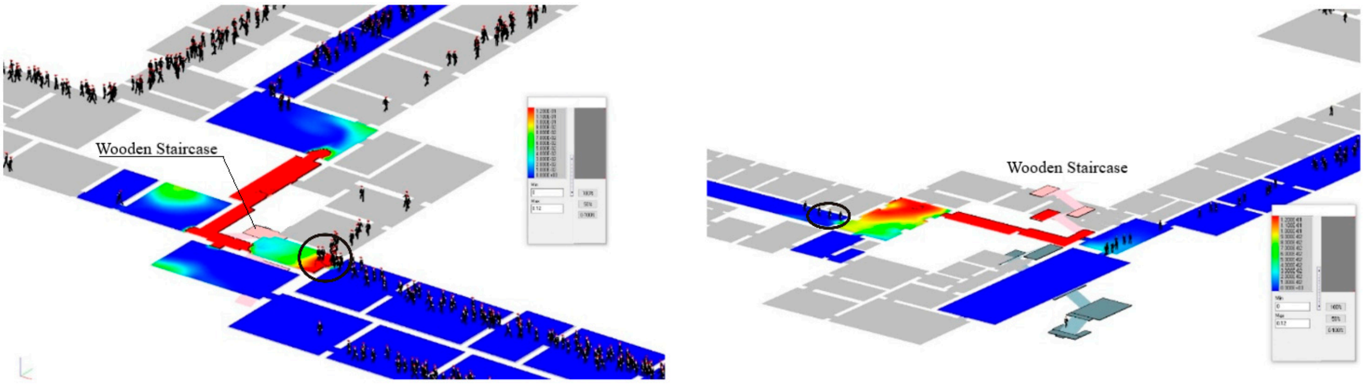
Preliminary calculations were conducted for a building occupancy of 6000 people, but safe conditions for evacuating people were not achieved. While some routes and exits were limited or rejected both criteria were not true: there were situations when the duration of congestion with a density that has reached a critical value of longer than 360 s and situations when Inequality (1) was not true (Figure 10). With a building occupancy of 4500 people congestion was solved, but there were still scenarios when Inequality (1) was not ensured (Figure 11). Among others, a reason was number of disabled persons with low speed. So, in the process of calculations, it was determined that with a single occupancy of 4000 people in the building, taking into account people with disabled persons and staff using common evacuation routes and exits, safe (that is, timely and unobstructed) evacuation from the building can be provided.

It has been found that in some places of fire it is necessary to restrict the spread of smoke (dangerous fire factors) along evacuation routes to ensure safe conditions. For the scenarios "The fire in the foyer of the Wooden Staircase", "The fire in Buffet (Rastrelli Gallery)", and "The fire in the foyer of the Saltykov's Entrance", two variants of the state of doors near the seat of fire were considered:

- in the "open" state (corresponds to the state in normal operation of the museum, in this case the doors do not restrain the spread of fire hazards through the building);
- in the "closed" state (the door leaves prevent the spread of fire hazards, but if the door is not closed tightly, the fire hazards can penetrate into adjacent rooms through the gap).

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

Figure 10. Crowding on the stairs at 200 s from the start of the evacuation: (**a**) Wooden and October Staircase; (**b**) Saltykov (**left**), and Great Church Staircase (**right**).



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

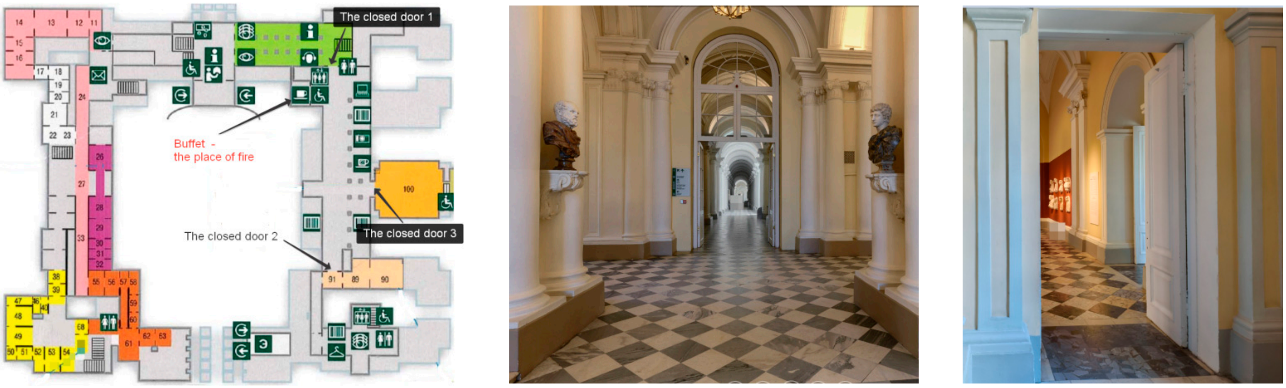
Figure 11. Horizontal slices of smoke (Np/m) at a height of 1.7 m from the floor and evacuation in the scenario "The fire in the foyer of the Wooden Staircase" (the color changes from blue (safe) to red (dangerous), the critical value of the optical density of smoke is given in the Table 1): (**a**) Equation (1) is not true for the 3d floor; (**b**) Equation (1) is not true for the 2d floor.

The calculation shows that closing the doors in order to localize the spread of fire hazards in the building can provide safe conditions for evacuating visitors for the required time. The spread of fire hazards through the building occurred, but more slowly than in the case of open doors. Due to the spacious volume of rooms, the temperature of the door's surface did not reach the value at which the destruction of the door leaf—not more than 300 °C.

The example of the "The fire in Buffet (Rastrelli Gallery)" scenario shows the effect of controlling the state of the doors near the seat of fire (Figure 12).

Doors 1, 2, and 3 after the last person leaves the Rastrelli Gallery are taken in the calculation to be closed, and the spread of fire hazards to adjacent rooms occurs only through a gap with a width of 3 cm, which simulates the leakage of the vestibule.

Table 2 presents the horizontal slices of smoke at a height of 1.7 m from the floor (the average level of human respiratory organs [2]), allowing the assessment of its dynamics in two different conditions. The color of the field changes from blue (safe) to red (dangerous), the critical value of the optical density (smoke produced by the flaming combustion of a certain amount of solid matter) of smoke is 0.12 Np/m [2].



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

Figure 12. Doors (1, 2 and 3), which are controlled (staff closes these doors) during the fire (**a**); door 1—between Jordan and Rastrelli galleries (**b**); door 2—between the Rastrelli gallery and the room of the Art of Palmira (**c**).

Table 2. Visualization of evacuation and smoke (optical density, Np/m) at the height of 1.7 m from the floor at 300, 420, 480, and 530 s from the beginning of the fire in the scenario "The fire in Buffet (Rastrelli Gallery)".

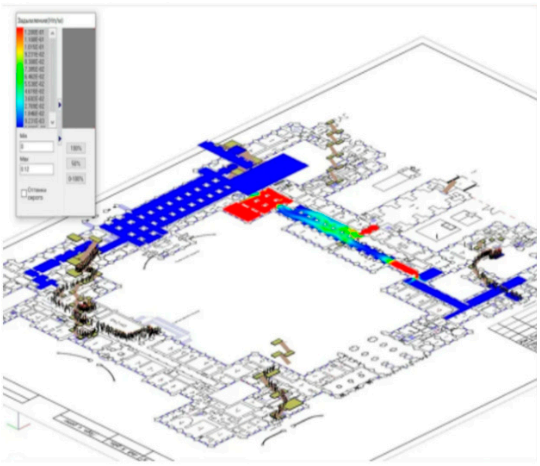
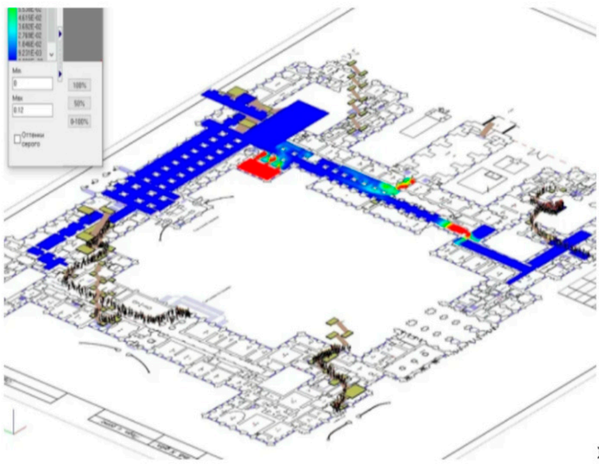
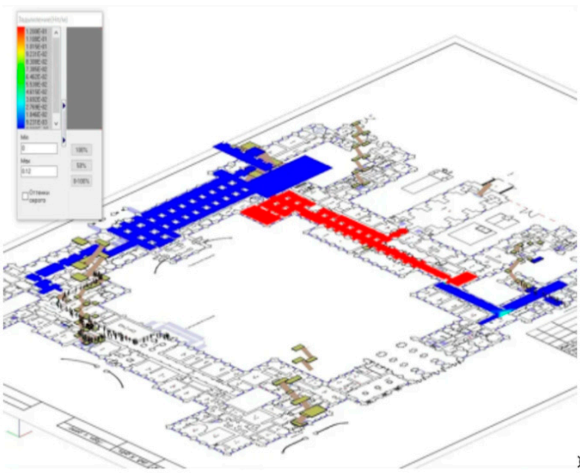
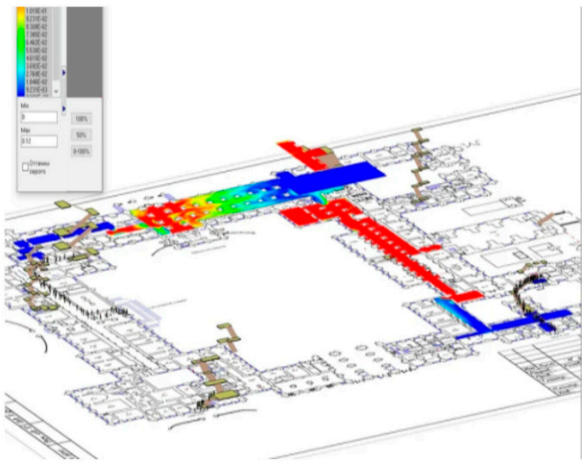
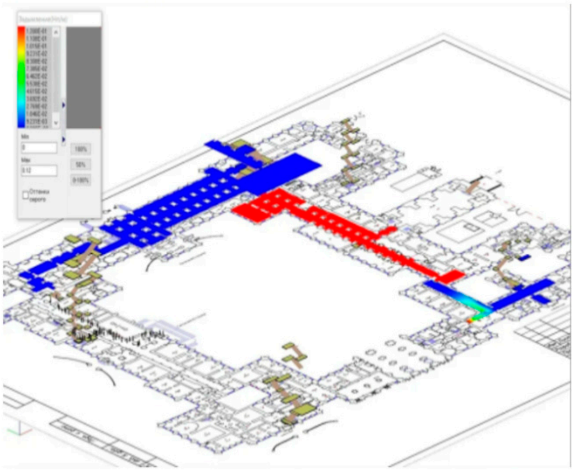
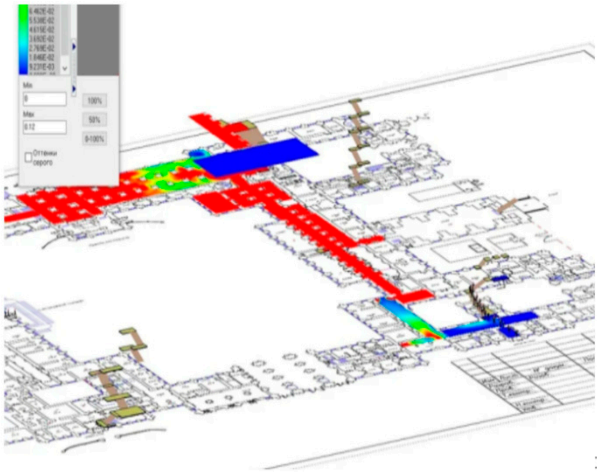
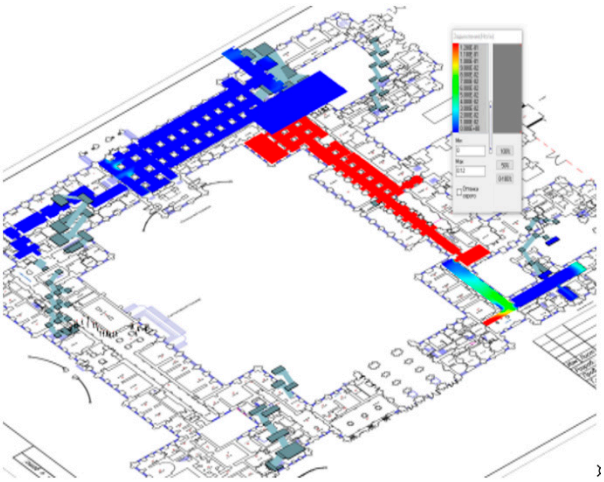
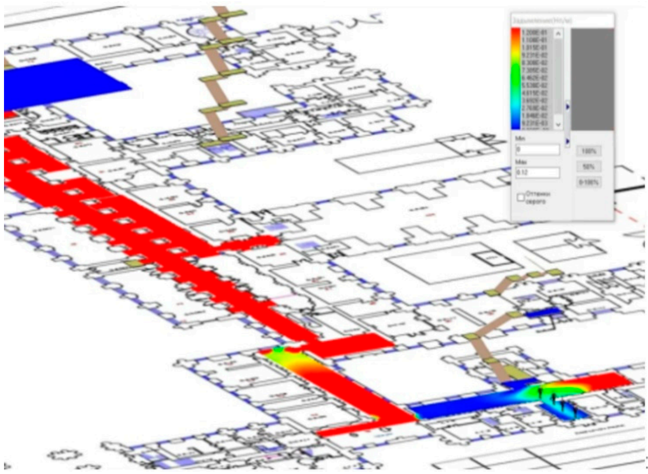
Visualization of the Smoke Field (Doors Closed)	Visualization of the Smoke Field (Doors Open)
300 s, 827 people	
	
420 s, 175 people	
	

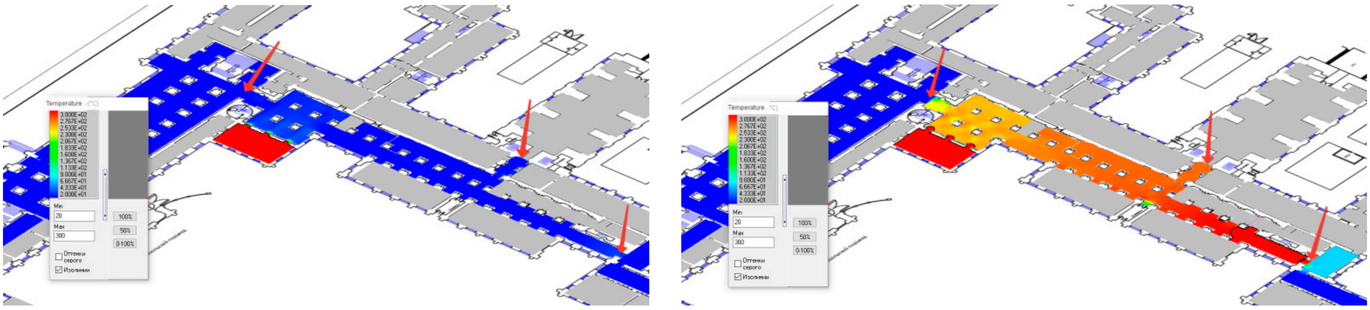
Table 2. *Cont.*

Visualization of the Smoke Field (Doors Closed)	Visualization of the Smoke Field (Doors Open)
480 s, 79 people	
	
530 s, 8 people	
	

In this scenario, the calculation shows that during evacuation it is acceptable to minimize the use of the Jordan Staircase and the Main Entrance (as the closest to the seat of fire). The exclusion of the Commandant Staircase and the Commandant's Entrance from the evacuation route is unacceptable (their exclusion leads to prolonged congestion on the remaining involved evacuation routes). In the case of open doors, visitors with reduced speed of movement (disabled persons) evacuating on the Commandant Staircase to the 1st floor (530 s) are at risk, which means that no safe conditions of evacuation are provided.

If the state of the doors between the Rastrelli Gallery and the Commandant's Corridor is controlled and set in the "closed" state, the spread of fire hazards along the Commandant's Corridor is contained (at least 9 min) and the conditions for safe evacuation are met.

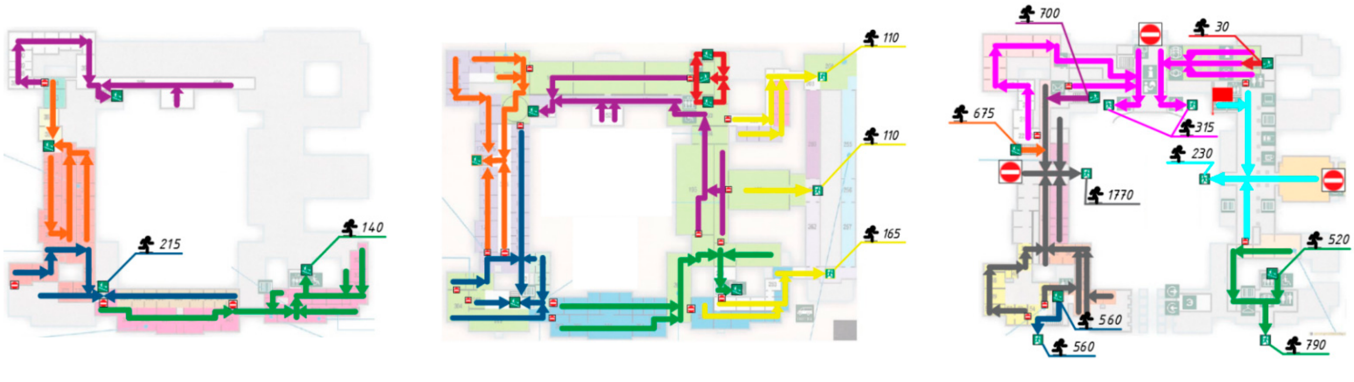
Due to the spacious volume of rooms, during the evacuation period the temperature on the door surfaces did not reach the value at which the destruction of the door may start—no more than 300 °C (Figure 13).



(**a**) 300 s (**b**) 600 s

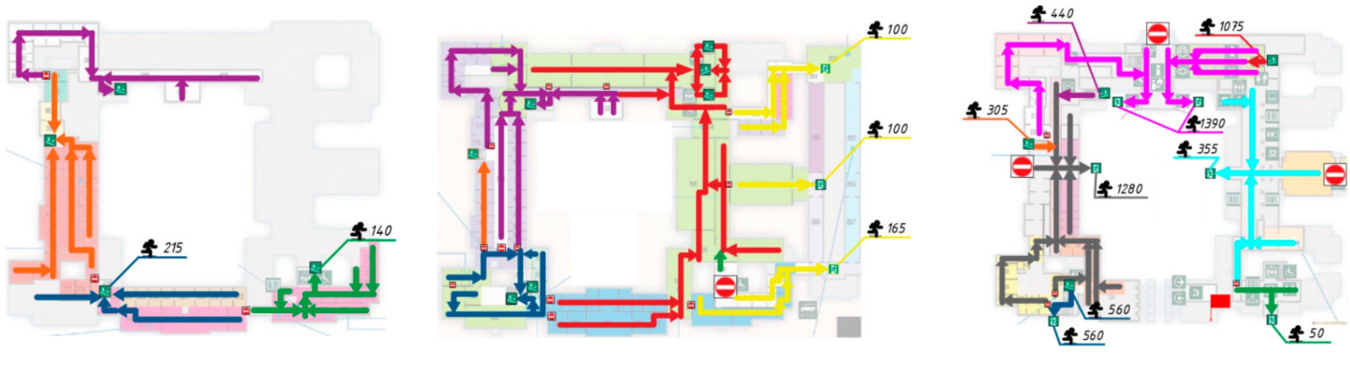
Figure 13. Horizontal slices of temperature (°C) at a height of 1.7 m from the floor in the scenario "The fire in the foyer of the Wooden Staircase", the color changes from blue (20 °C) to red (300 °C).

Similarly, the analysis of the results of calculations of other scenarios was carried out. For each scenario, evacuation schemes have been developed to ensure safe evacuation with a minimum number of people evacuating outside of the perimeter (Figures 14–18). On this basis, recommendations for evacuation management were developed. In the creation of evacuation schemes followed the principle of maximum uniformity, with the exclusion of part of the evacuation routes because they are blocked by the hazards of fire.



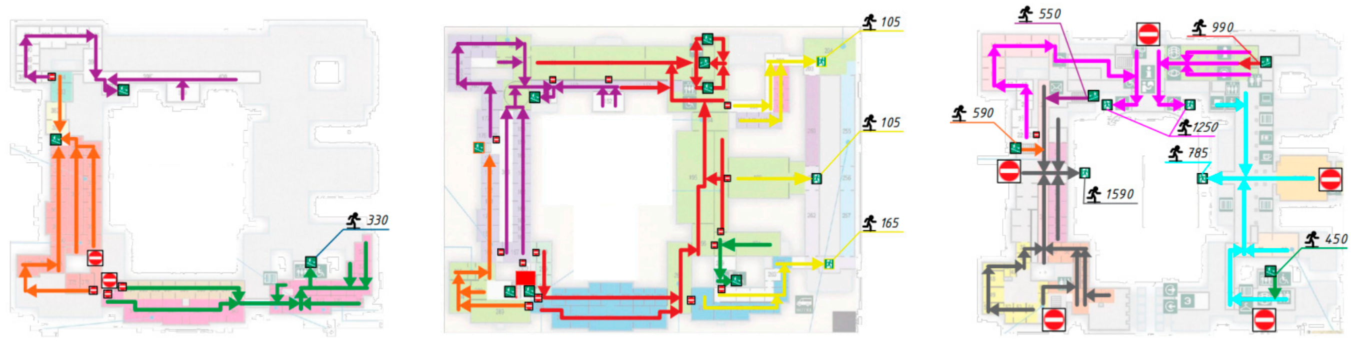
(**a**) (**b**) (**c**)

Figure 14. Scheme of evacuation of people from the Winter Palace for the scenario "Fire in buffet": (**a**) for the 3rd floor; (**b**) for the 2nd floor; and (**c**) for the 1st floor.



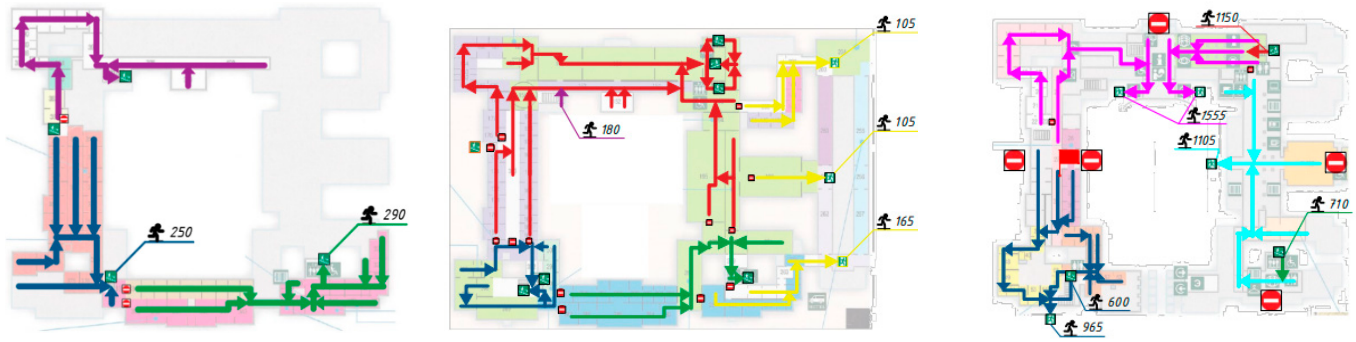
(**a**) (**b**) (**c**)

Figure 15. Scheme of evacuation of people from the Winter Palace for the scenario "Fire in the Commandant's Cloakroom": (**a**) for the 3rd floor; (**b**) for the 2nd floor; and (**c**) for the 1st floor.



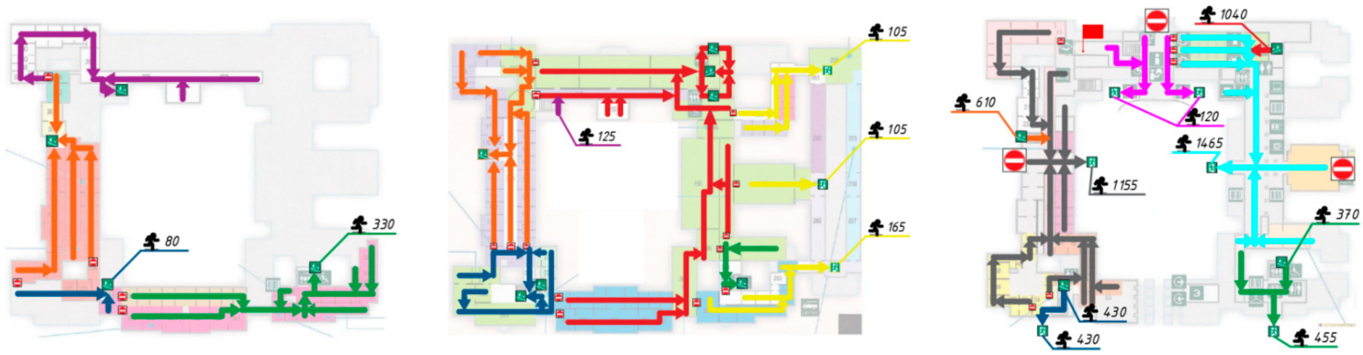
(**a**) (**b**) (**c**)

Figure 16. Scheme of evacuation of people from the Winter Palace for the scenario "Fire in the foyer of the Wooden Staircase": (**a**) for the 3rd floor; (**b**) for the 2nd floor; and (**c**) for the 1st floor.



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

Figure 17. Scheme of evacuation of people from the Winter Palace for the scenario "Fire in the Saltykov's Entrance": (**a**) for the 3rd floor; (**b**) for the 2nd floor; and (**c**) for the 1st floor.



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

Figure 18. Scheme of evacuation of people from the Winter Palace for the scenario "Fire in the School Cloakroom": (**a**) for the 3rd floor; (**b**) for the 2nd floor; and (**c**) for the 1st floor.

The analysis of the results of fire simulation in the considered scenarios showed that safe conditions are provided in some floors for a long time (up to 20 min) (dangerous fire factors do not exceed critical values or are absent at all). Thus, these parts of the building can be used as safety zones for the temporary accommodation of visitors with mobility restrictions (disabled persons).

3.2. Discussion

The calculations made it possible to estimate the capacity of the building when redistributing the load on alternative evacuation routes if part of the route is blocked by fire hazards. A quantitative analysis of the resulting evacuation schemes is presented in the distribution of people by staircase (Figure 19) and building exits (Figure 20) and the estimates of evacuation times by staircase (Figure 21) and exits (Figure 22) for each scenario. Figures 19 and 20 also show the time of blocking by the fire hazards of the corresponding area (no data means that the area is not blocked for the 20 min of fire development), from which we can see what time reserve is available for evacuation.

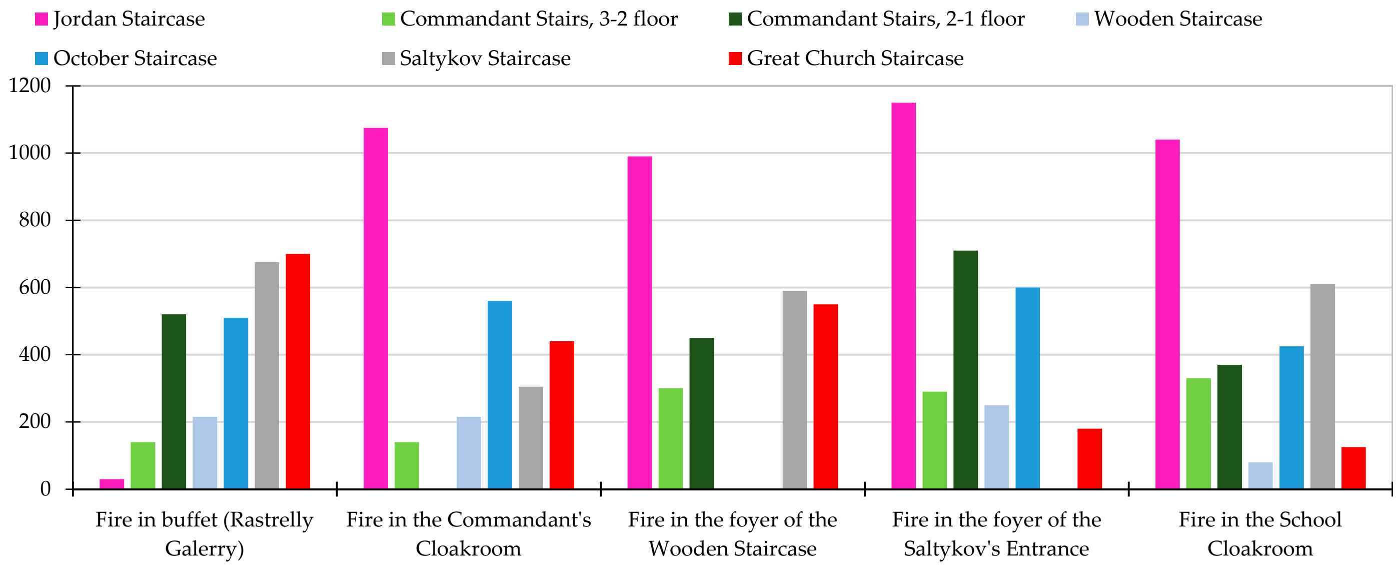


Figure 19. Distribution of people on the stairs.

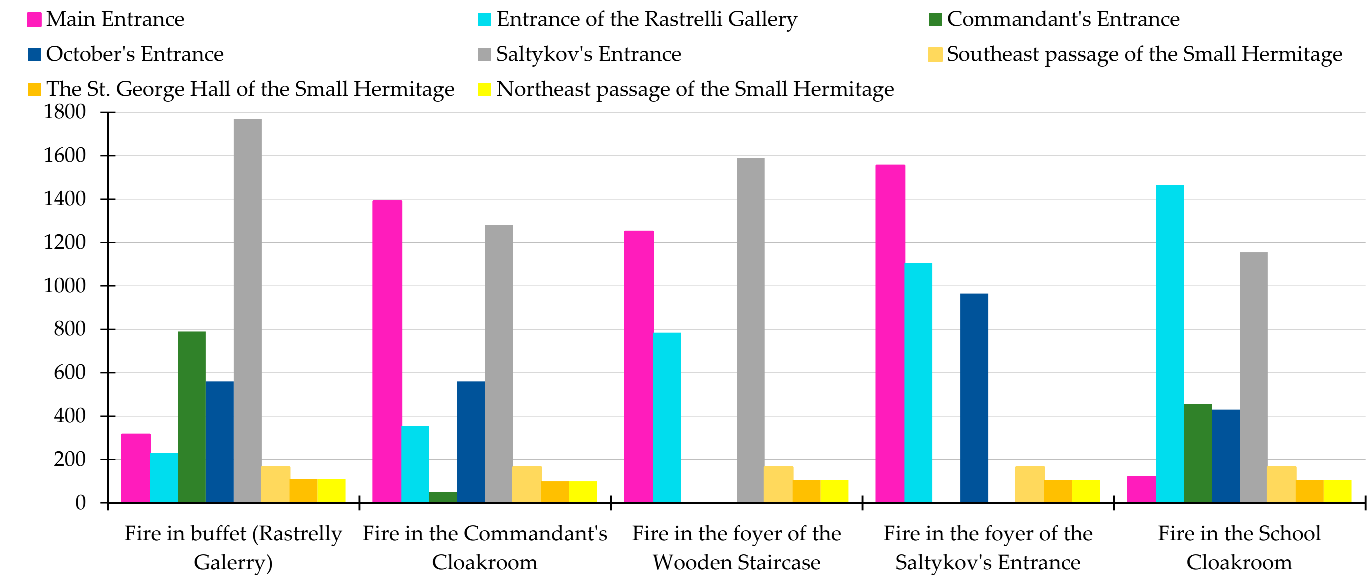


Figure 20. Distribution of people to the exits of the building.

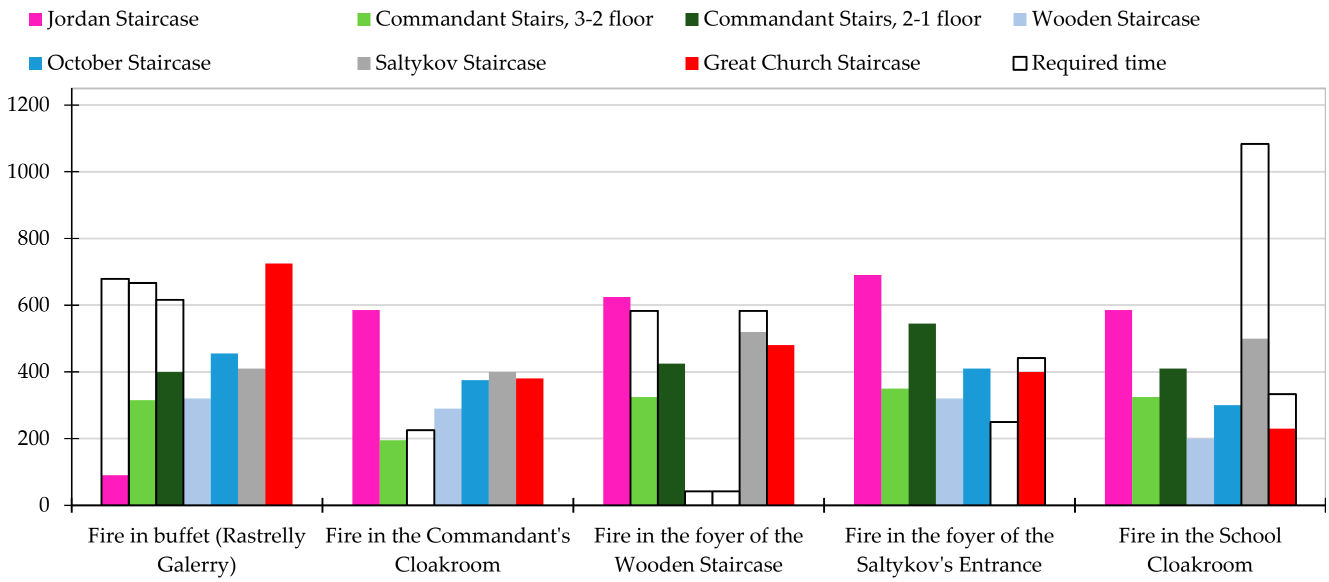


Figure 21. Evacuation time by stairs.

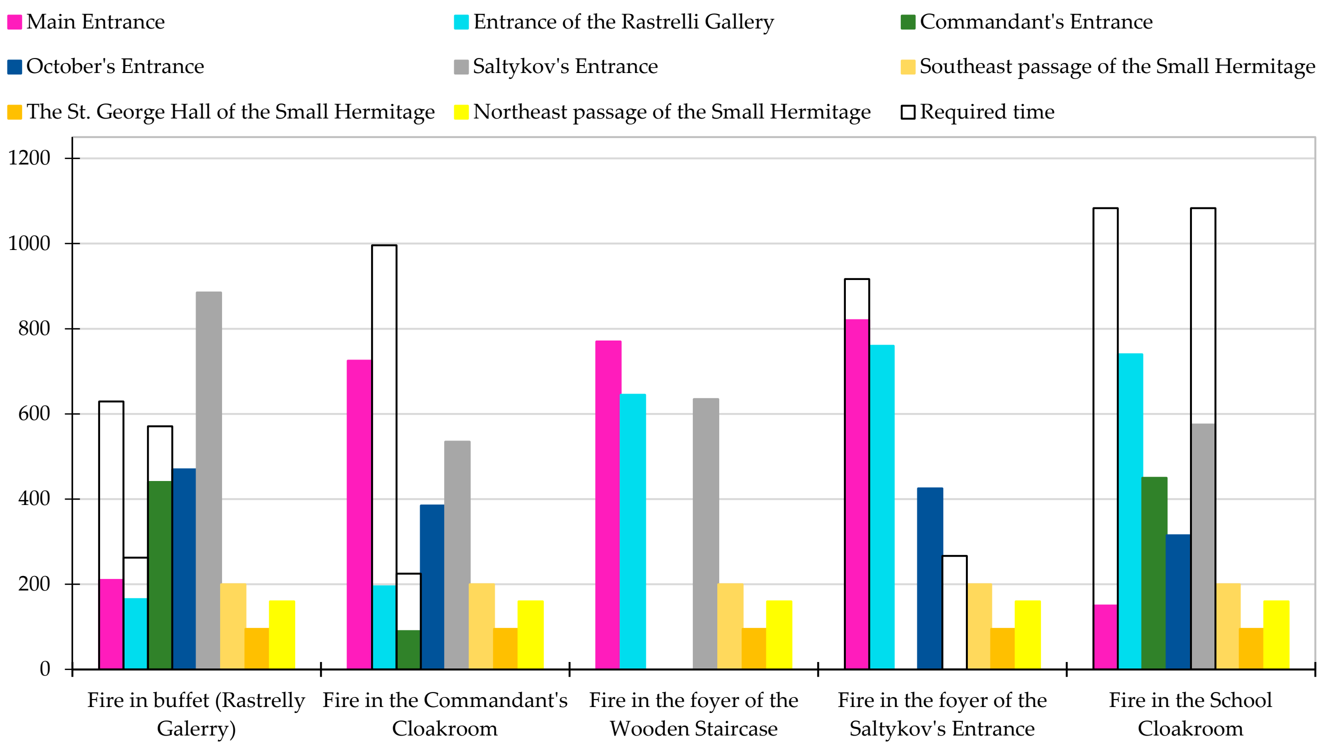


Figure 22. Evacuation time by exits of the building.

Figure 19 shows that by almost completely excluding the Jordan Staircase (which has the highest capacity) from the evacuation scheme (as is the case in the "Fire in Buffet" scenario), it is possible to distribute the load on the other staircases approximately proportionally. It is clear that with approximately equal numbers of people on the Great Church and Saltykov Staircase, the duration of evacuation on the Great Church Staircase is longer. This is due to the presence of visitors with low speed of movement (disabled persons), their evacuation route from the eastern part of the building due to the exclusion of the Jordan Staircase is significantly longer but passes through a safe environment. Scenarios that use the Jordan Staircase estimate an increase in total evacuation time due to this redistribution of about two minutes but still provide safe evacuation conditions.

It is also acceptable to minimize the use of the Main Entrance, as seen in Figure 20: scenarios with seats of fire in the Buffet and the School Cloakroom. The exclusion of the October and Commandant's Entrances that extend beyond the building perimeter from the evacuation scheme is acceptable, as seen in the "Fire in the foyer of the Wooden Staircase" scenario. Additionally, it is worth noting that the total evacuation time in this case is not superior to other variants of the use of exits from the building.

For the first time, the following was carried out for the Winter Palace:

- the analysis of the features of the space-planning solution of the building;
- BIM model of the Winter Palace building and fire evacuation simulations;
- the comparative analysis of the simulation results of the spread of the dangerous fire factors and evacuation;
- the maximum number of visitors for a safe single stay has been set at 4000, including disabled persons with very restricted mobility of about 3%;
- the "critical" points in the evacuation management have been identified;
- evacuation schemes for considered scenarios are created.

These results are used for:

- the basic instructions for staff to act in times of fire and evacuation control for each workplace;
- distribution of the areas of responsibility between staff, including the location of nodal points of routing the flow of visitors during evacuations in different scenarios;
- solving the logistical tasks of the staff schedule of the Security Service of the museum;
- determining parts of the building which can be used as safety zones for the temporary accommodation of visitors with disabilities;
- tuning of the evacuation control system.

All these results are derived only from using computer simulations of evacuations under fire conditions in different scenarios.

4. Conclusions

The need to manage evacuations in a museum is an undeniable fact [3–8,31–33]. The conducted research has shown, using example of the Winter Palace building, that the task of developing an evacuation route in case of fire in museum buildings is multi-criteria. It is shown that the use of the simulation of evacuation in a fire allows the encapsulation of these criteria and provides a fundamental opportunity to solve the task of developing the optimal schemes for evacuation. The decision is based on following issues which could be derived through simulations:

- to determine the allowable duration of an evacuation, which ensures safe conditions on the evacuation routes;
- to establish a limit on the number of people whose stay in the museum would be safe in the case of a fire or other emergency that requires evacuation;
- to set the maximum number of visitors with disabilities allowed to access the facility at one time;
- to determine the safest parts on the floors to use as safety zones for disabled persons;
- to develop different evacuation routes in the event of actual or suspected blockage of evacuation routes and/or exits due to the spread of danger fire factors, taking into account the applicable safety criteria;
- to identify areas of the building where congestions with critical density are formed and their duration.

An important aspect is the realizability of the developed route—that is, the routing (management of people flows) according to the developed scheme could be realized in real life. It is also necessary to consider the fact that the seat of fire (or other blocking factor) can occur in any part of the building; accordingly, employees should have several evacuation schemes. In order to be fluent in these schemes and to use the right one correctly in a limited time, the schemes must be as uniform as possible. These features, together with the planning features of the site also impose certain restrictions on the development of evacuation schemes (in addition to the criteria of the safety of people and the preservation of museum values).

It is very important to develop evacuation schemes which can be realized within the practical activities of the museum. For the first time in this work, the following principles for their creation have been formulated:

- evacuation schemes for different scenarios differ only in the extent of necessity and the location of the seat of fire (or other blocking factor);
- from one hall (room), all people go the same route;
- the main routing (management of traffic direction) mechanism is the closing of doors for unambiguous route formation;
- visitors to enfilades (systems of rooms separated by open doorways) are directed in one direction;
- exclusion of oncoming and intersecting flows;
- based on the analysis of the dynamics of fire development and the identified temporal characteristics, select safe, although longer, routes to accelerate evacuation in the most vulnerable parts of the building;
- ensuring the safety of people is the primary task, taking priority over ensuring the safety of museum objects and valuables.

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