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Analysis of Exits in Fire Evacuation and Crowd Management in Multi-Functional Sports Halls

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ABSTRACT

Crowd management and fire evacuation for assembly buildings are complex design processes in terms of design and construction. It should be designed as the main purpose of the safety of life and property to route the crowd to the nearest exit without creating congestion. This study aims to investigate the effect of exits in sports halls, which can respond to different functions from assembly buildings, for fire evacuation, and crowd management. In evacuation analyses, the effects of existing and alternative exits on the total evacuation time are investigated through Pathfinder evacuation simulations. For this purpose, a typical college sports hall was considered and possible exits were evaluated. Single and double blocking of exits in scenarios that may occur at different points were examined and total evacuation times were analyzed. In the study, it was found that spectators create congestion in sports halls (density of more than 3 people/m^2) and are decisive in total evacuation time. It was determined that an exit at a distance from the spectator area could not provide an effective evacuation. Exits close to the spectator area were found to be effective in reducing the total evacuation time and could reduce the total evacuation time by 30 seconds. In conclusion, it is emphasized that the number of exits and exit locations in multi-functional sports halls should be made with rational and performance-based analysis. The importance of preventing congestion and positioning the exits to direct the crowd in an effective fire evacuation and crowd management is explained.

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1. Introduction

The safe evacuation of occupants in assembly buildings is a complex design process, both in terms of design and construction. Crowd evacuations require extensive preparation and coordination. Well-designed buildings are needed that can accommodate the intense movement of the crowd under planned evacuation conditions and allow an acceptable and unimpeded escape speed (Guanquan et al., 2012; Li et al., 2022). Buildings that are not simple and intuitive to use contribute to panic, fear, anxiety, and overall expected negative psychology in unplanned evacuation conditions (Deng et al., 2022; Wang et al., 2016). According to the National Fire Protection Association (NFPA) definition, assembly buildings are buildings where 50 or more people gather for conference, religious, entertainment, eating, drinking, demonstration, waiting, transportation, and other purposes. Multi-functional assembly buildings are buildings that can serve different purposes periodically (NFPA 101; 2024). In the design of multi-functional assembly buildings, fire evacuation scenarios should be organized according to the functions that can be used and a safe evacuation environment should be created.

Failure to provide the necessary escape opportunities for crowd management and insufficient safe exits are seen as an important problem in creating safe evacuation conditions (van der Wal et al., 2021). Assembly buildings adopt the aim of fitting a certain number of occupants into the facility and designing the spaces to serve the maximum number of occupants. Moreover, it is necessary to develop, adopt and construct a holistic, multi-layered crowd safety paradigm for dense and crowded occupants, and to create improved communication and interaction between the various stakeholders of crowd management (Haghani et al., 2023). For this purpose, buildings are often designed according to specific building codes, guidelines, and regulations. Such regulations can be classified as prescriptive, performance-based, and target/goal-based regulations. These regulations define minimum requirements to provide the safety of all building occupants in the event of an emergency (Alvarez et al., 2013; Hadjisophocleous et al., 1998; Meacham, 2010). Within the regulations, the actual cause of the emergency (earthquake, fire, explosion, etc.) should be manageable and non-safety threatening most of the time during periods of high occupancy. However, it is unfortunate that a poorly executed evacuation scenario can lead to loss of life immediately afterward. In particular, sports halls conference halls, and multi-purpose halls as assembly buildings are at risk (Simsek and Catıkkas, 2020). Sports halls are one of the most important building types of the historical process. They represent the first examples of architecture with the Ancient Greek Stadiums, the Colosseum in Ancient Rome, and the Munich Olympic Park. Until today, they have been designed in many different forms and spatial organizations (open-closed, special spaces for athletes, special spaces for athletes and spectators, and technological spaces) (Selo and Erdönmez, 2018). Today, college sports halls, which are used for educational purposes and can serve many different functions, have also taken their place in architectural design.

The number of structural fires is increasing day by day and fires cause loss of life and property. According to The International Association of Fire Services (*Comité Technique International de prevention et d'extinction de Feu* - CTIF), the average number of fires per 1000 inhabitants in 2018-22 varies greatly between countries. The highest rates were 7,63 in Cyprus, 6,95 in Barbados, 6,57 in Uruguay, 6,40 in Austria, and 6,35 in Israel. In the same statistical analysis, when the average number of fire deaths per 100 fires is analyzed, it is determined as 9,57 in Belarus; 7,15 in Nigeria; 6,63 in Moldova; and 4,79 in Nepal (CTIF, 2024). Especially in these statistical results, it is possible to state that fire risks are high in developing countries. Moreover, in Great Britain (England, Scotland, Wales), the total number of fires that occurred in the financial year 2022-2023 and to which the fire departments responded reached 759618 cases. This region has had the highest number of fires in the last decade. Additionally, a statistical survey in the UK found that the number of fire-related deaths in the 2021-22 financial year was 274; in the 2022-23 financial year, the number of fire-related deaths was 265; and in the 2023-24 financial year, the number of fire-related deaths was 251 (Government Digital Service, 2024). Unfortunately, no comprehensive fire statistics are available for the Republic of Turkey. Some municipalities share some of their statistical results with fire departments. The statistics obtained by the research show the results of all structural fires. To explain the importance of the topic, fires occurring in buildings for assembly purposes are analyzed in detail. There have been many incidents in which people have been injured and lost their lives while evacuating assembly buildings. Such incidents vary according to location, time, and context. In 1985, 50 people were killed and more than 265 injured in the Bradford City stadium fire in England (Sivaloganathan and Green, 1998a; Sivaloganathan and Green, 1998b). In 1997, the Uphaar Cinema fire in Delhi, India resulted in the death (suffocation) of 59 people (Sunder, 2023). In 2010, there was a stampede in Phnom Penh, Cambodia during the celebration of the Water Festival (Bon Om Touk), killing 347 people (Hsu and Burkle, 2012). In 2015, 769 people lost their lives in a stampede during the pilgrimage in Mina, Saudi Arabia (Khan and Noji, 2016). In 2017, a sports center fire in Korea killed 29 people and injured many others, disrupting the torch relay at the Pyeongchang Winter Olympics (Zhu, 2021). The common point of all these and hundreds of other incidents throughout history is the lack of proper guidance in crowded areas and the failure to provide the necessary evacuation conditions and safe exits. One of the main risk factors in indoor and outdoor spaces in providing safe exits is the possible fire factor. The high number of occupants in assembly buildings and the high fire load with the building materials and equipment in the space increase the risk of evacuation during fire. Moreover, there are many components that affect fire evacuation risks, such as building familarity, awareness during fire, and training (Bodur, 2021; Shokouhi et al., 2019).

Turkey's Regulation on Fire Protection (TRFP), an important part of structural fire safety precautions in the Republic of Turkey, came into force in 2007 (TRFP, 2007). This regulation aims to ensure the safety of buildings by setting standards specifically related to fire safety. TRFP has been revised several times since its entry into force. While the regulations generally apply to certain building groups, different regulations are envisaged for special-use areas such as subways, marinas, helipads, tunnels, stadiums, and airports. This means that if there are not enough provisions in the regulation for these areas, other rules that are decisive regarding fire safety can be applied. In this context, in designing the TRFP as a regulation, the prescriptive-based regulation has to a certain extent limited the use and dissemination of performance-based approaches (Yaman and Kurtay, 2021). Thus, the regulation encourages action in line with the standards set, but at the same time imposes some limitations in terms of providing flexibility. This may make evaluating and adapting fire safety practices in a broader framework difficult. The TRFP also provides requirements for fire safety precautions for assembly buildings. However, it does not provide alternative recommendations for performance-based solutions and evacuation simulations. This situation shows that there is a need for evacuation simulations and calculation of evacuation times based on the practice methods of developed countries in the field of fire safety such as the USA. Apart from the TRFP, in 2021, the Ministry of Youth and Sports prepared the Ministry of Youth and Sports Fire Prevention and Extinguishing Directive to cover all its facilities and buildings under the guidance of the TRFP. In addition to the regulations and directives, various universities/ colleges also have various directives for the operation of sports halls. However, it should be recognized that the TRFP is the most decisive among all these legal guidelines and codes, and design processes should be carried out in accordance with it.

Depending on the occupancy status of the building, layout plans, and problems in fire safety design and fire hazards in multi-functional assembly buildings, the following fire safety objectives are defined: all occupants are safely evacuated within the required time regardless of function (i), fire is controlled within a single compartment (ii), conditions inside the building are adequate for firefighters to safely perform firefighting and rescue services (iii), and fire safety design can effectively reduce fire hazards and control property loss (iv). The most basic requirement of these steps is the evacuation of occupants to a safe area. This paper aims to analyze the effect of exits located at different points on the determination of total evacuation times in multi-functional sports halls. For this purpose, the study focuses on the fire evacuation risk scenarios (different exits) of multi-functional sports halls and evaluations were made for exits. In the cross-sectional study representing multi-functional sports halls, the study considers different exits as independent variables and the total evacuation time of the building as independent variables. The blocking of each of the existing exits and two of them in different variations (fire, smoke, etc.) and their effects on the total evacuation time are investigated. In addition, the effects of the alternative exits on the total evacuation time are observed. The effect of alternative exits on the evacuation process is explained in the analysis of the exits. The research focuses on Goal 11 (Sustainable Cities and Communities) of the Sustainable Development Goals (SDGs). It focuses on the research problem of making user settlements inclusive, safe, resilient, and sustainable.

2. Materials and Methods

Today, it has been explained that fire safety precautions must be taken in sports halls used for many different functions on high school and university/colleges campuses. For this purpose, research on fire safety precautions and evacuation scenarios was conducted through a cross-sectional study that could represent college sports halls. A multi-functional sports halls designed for a standard college building in Turkey was investigated as a cross-sectional study. In the research, it was determined that the hall is a typical sample of a sports hall, the number/profile of occupants is approximately the same as the other samples, and the finishing materials are the same as the other halls. Firstly, the necessary information about the building was provided. Total occupant load was calculated in the building. Turkey's Regulation on Fire Protection (TRFP) Annex 5/A principles have been adopted in occupant load calculations (TRFP, 2007). Evacuation analyses of the cross-sectional study were carried out through the Pathfinder computer simulation program. Pathfinder is evacuation assessment software that is simple to use, good to visualize, and easy to implement. Pathfinder uses ABM (Agent-Based Modeling). This approach allows simulation of the behavior and interactions of evacuees and modeling the behavior of large groups (Pathfinder, 2017). In the simulations, progress was made through the analysis of an evacuation and the analysis of possible scenarios during any fire. It is designed based on possible scenarios where exits are blocked and occupants turn to other exits. The existing exits are the main entrance door (Exit A) and the doors directly connected to the main hall (Exit B, and Exit C). The width of all exit doors is 180 cm. As a result of the simulations, total evacuation times and flow rate evaluations were examined. Additionally, exit alternatives were created in building fire safety analyses to improve the evacuation conditions of the sports halls. Exit alternatives are the door directly connected to the main hall (Exit-1) and the door at the top of the seating area (Exit-2) All exit alternatives doors are 180 cm. The effects of exit alternatives (Exit-1 and Exit-2) on the total evacuation time of the occupants were investigated and evaluated. (Figure 1).

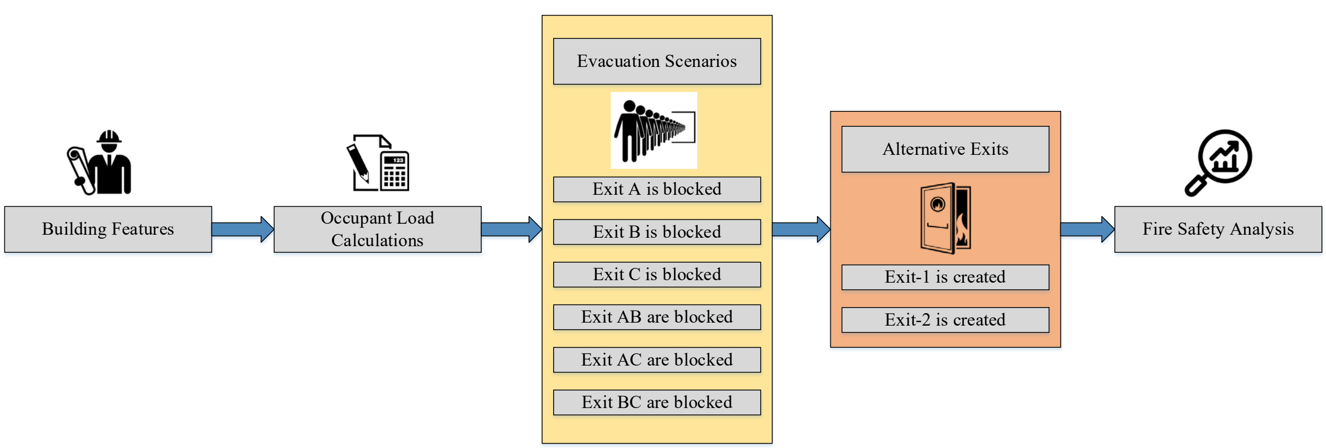

Figure 1. Method of the fire evacuation scenarios

3. Fire Evacuation and Crowd Management Simulations

3.1. Cross-sectional Study

A cross-sectional study was conducted to represent multi-functional sports halls. The sports halls used as a case study represent typical sports halls of colleges. The examined hall consists of a ground floor and first floor with a total construction area of 1460 m^2. The ground floor has locker rooms, storage rooms, administrative units, and the main hall at the entrance of the facility. The first floor has a plan layout with spectator areas. In the main hall, the floor is finished with laminate flooring, the walls with PVC and plastic paint, and the ceiling with plastic paint. The multi-functional sports hall has a main exit door (A) and two emergency exit doors from main hall (B-C). The occupant load of the sports hall used as a cross-sectional study was determined according to national standards, TRFP. First, the occupant load was calculated for each space and then a floor-based occupant load was calculated. The total occupant load for the ground and first floor was determined as 564 people. Additionally, floor finishing materials were transferred into the spaces (Table 1). It was determined that the floors in the space were selected from non-combustible materials ($A1_{fl}$) with high ignition temperatures and would not cause any negative effects during evacuation.

Table 1. Occupant load calculations and floor materials

Ground Floor	**Area (m^2)**	**Floor Materials**	**Occupant Load Coefficient (m^2/pers)**		**Occupant Load (pers)**
Main Hall	413	Laminate Flooring	3		137
Storage 1	15	Ceramic	30		1
Storage 2	15	Ceramic	30		1
Storage 2	15	Ceramic	30		1
Storage 4	15	Ceramic	30		1
Locker Room-Women	24	Ceramic	5		5
Locker Room-Men	24	Ceramic	5		5
Referee Room	12	Ceramic	10		1
Administrative Unit	12	Granite-Ceramic	10		1
Corridor	-	Granite-Ceramic	-		-
Total	-	-	-		153
First Floor	**Area (m^2)**	**Floor Materials**	**Occupant Load Coefficient (m^2/pers)**		**Occupant Load (pers)**
Seating Area	285	Ceramic	TRFP	1	285
			Number of Seats*	411	411
Total	-	-	-	-	411
Total (Building)	-	-	-	-	564

* The number of seats is accepted for the calculation of the occupant load of the space.

3.2. Simulation Analysis

The characteristics of the occupants were defined for the crowd evacuation of the occupants in the multi-functional sports halls. A scenario with a homogeneous sex distribution for the occupants (282 females - 282 males) was used. The occupants' speed in the crowd evacuation situation was taken as 1,41 and 1,42 m/s (Bohannon and Andrews, 2011; Fitzpatrick et al., 2006; Young 1999). Occupants choose the minimum justified direction based on an optimization of various values, including the recommended direction of movement compared to the shortest path angle and the chance of colliding with other occupants. The activities that occupants are engaged in the building, such as their distribution within the building, also influence their response and how long it will take them to leave the activity before taking protective action. Since sports halls are usually used in a common space, simultaneous warning systems and communication are taken into consideration and a simultaneous evacuation strategy is adopted. Occupants were modeled as fully occupied according to their position in the main hall and spectator area while watching any performance. Modeling was done by considering the most crowded principles (the most significant risk) in terms of reality and fire safety. Existing and alternative exits are presented on ground and first floor in the cross-sectional study (Figure 2).

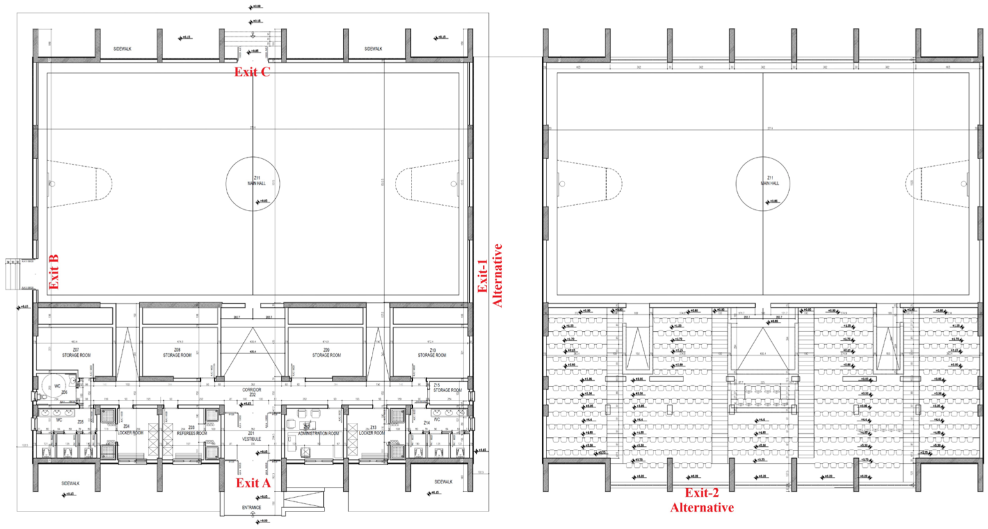

Figure 2. Exits on ground and first floor in the cross-sectional study for simulation analysis

4. Results and Discussion

As a result of the analysis, the total evacuation time was 186,3 s in the scenario where the fire in the building did not affect any escape (free scenario). The total evacuation time was 205,3 s in the case of blocked Exit A, 223,5 s in the case of blocked Exit B, and 187,5 s in the case of blocked Exit C. The fire evacuation time in case of blockage of each single exit was analyzed. In case of blockage of Exit B, which can provide common service to the main hall and spectator area, the total evacuation time is considerably increased. In this case, the location of Exit B was found to be important for a high-impact exit scenario. The fact that Exit A is also preferred by the occupants as the closest direct distance shows that its location is appropriate in architectural planning. The blockage of Exit C did not affect the total evacuation time of the building (Table 2). Additionally, it is seen that congestion (density of more than 3 people/m^2) occurred in the spectator area in all scenarios (Figure 3).

Table 2. Single exit blocking and evacuation process*

	Free Scenario	Exit A Blocking	Exit B Blocking	Exit C Blocking
30 s	168	127	103	103
60 s	284	263	193	240
90 s	363	358	258	353
120 s	432	429	327	436
180 s	560	542	470	554
Total Evac. Time, s	186,3	205,3	223,5	187,5

* p: Exited people number

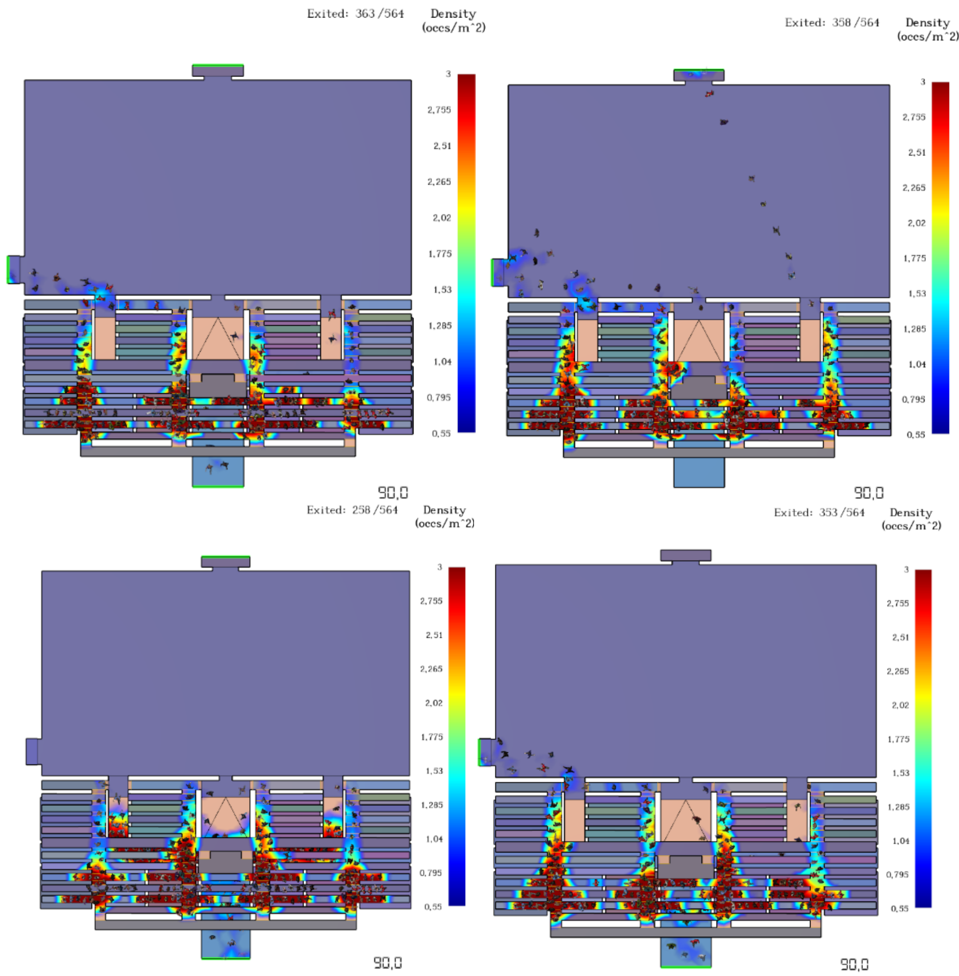

Figure 3. 90th s in free evacuation, Exit A blocking, Exit B blocking, Exit C blocking

In the single analysis of the exits, it was determined that Exit B provided the most effective fire evacuation. With the blockage of Exit B, the total evacuation time reached the highest levels. This is evidenced by the fact that Exit B is close to the high-density spectator area. Additionally, the fact that the total evacuation time was very close to the free evacuation as a result of the blockage of Exit C can be explained by the increase in the flow rate of the doors (Exits A-B) during the evacuation time (until 100th s) (Figure 4). Increased flow rates at the exits decreased the total evacuation time of the occupants.

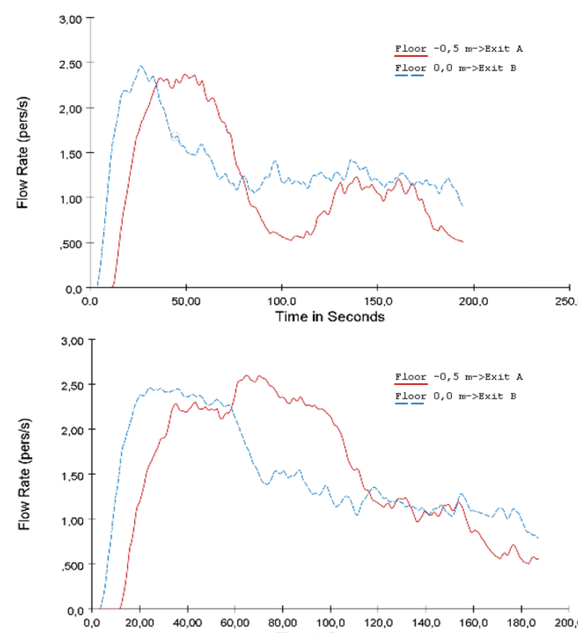

Figure 4. Flow rates at Exits A-B evacuation, Exit C blocking

As a result of the analyses, in cases where the exit alternatives are double blocked, the total evacuation time is 259,8 s if only Exit A is available; the total evacuation time is 243,3 s if only Exit B is available; and the total evacuation time is 236,5 s if only exit C is available. In this type of scenario, the fact that there is only one escape opportunity directs the occupants to only one escape. As a result of this situation, the width of the exit played a critical role. Only for Exit B route, the total evacuation time was increased because it was less wide than Exit C route, although it was close to the spectator area (Table 3). Moreover, in all scenarios, congestion (density of more than 3 people/m^2) occurred in the spectator area and exits (Figure 5).

Table 3. Double exit blocking and evacuation process

	Exit AB Blocking	Exit AC Blocking	Exit BC Blocking
30 s	65	61	41
60 s	138	137	107
90 s	210	209	177
120 s	284	279	246
180 s	432	418	386
Total Evac. Time, s	236,5	243,3	259,8

* p: Exited people number

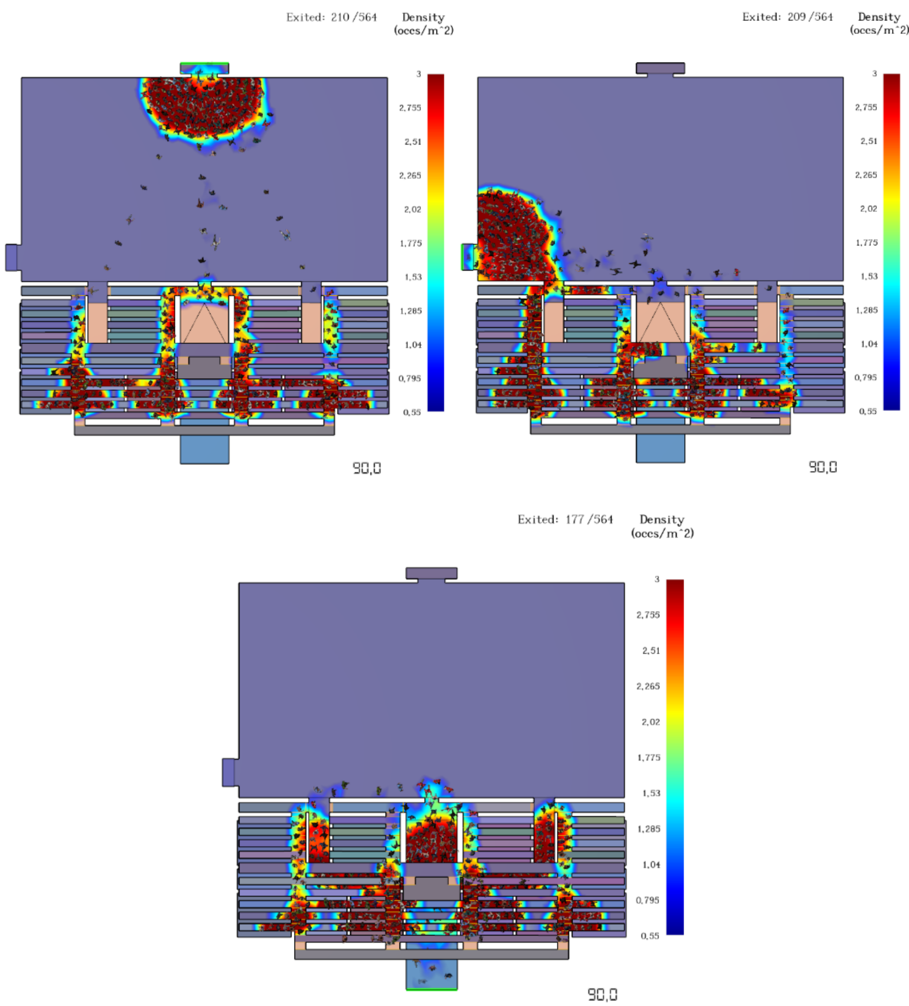

Figure 5. 90th s in Exit AB blocking, Exit AC blocking, Exit BC blocking

In the fire evacuation scenarios examined, a total evacuation time of more than 3-4 minutes (180-240 s) may cause problems in fire evacuation and crowd management. Based on previous fire incidents, the duration of a fire significantly increases the risks associated with evacuation, especially if the fire or smoke begins to spread and intensify (Yaman, 2021). In evacuation scenarios where the only exit is blocked, the congestions detected in the spectator area make it necessary to increase the escape routes of those areas. This is in line with the findings in the literature on the evacuation of assembly buildings (Brunnberg, 2021; Mattsson and Umeh, 2022; Minegishi and Takeichi, 2018). The fact that the congestion detected in evacuation scenarios where double exits are blocked is mostly at the exits makes it necessary to expand the exits. For this purpose, it is necessary to increase the width of the effective exit doors. In case of insufficient exits (when occupant's needs are not met), the congestion at the exits is in line with the findings in the literature (Cotfas et al., 2022; Mattsson and Umeh, 2022; Rinne et al., 2010). As a result of the evacuation analysis, it was determined that the most effective escape route was at Exit B located at the intersection of the spectator area and the main hall. According to Exit B, designing an alternative exit to the other opposite facade on the symmetry axis of the building or designing an exit on the upper part of the spectator area (1st floor) can be presented as a suggestion. With these suggestions, occupants in the spectator area follow a more controlled escape scenario by determining a second evacuation route. Exit-1 and Exit-2 alternatives provided a more efficient evacuation and were effective in fire evacuation and crowd management (Table 4). The congestion (density of more than 3 people/m^2) in the spectator area was less visible (Figure 6). This was achieved by designing exits and creating alternatives in the most densely occupied area of the building.

Table 4. Alternative exits and evacuation process*

	Exit-1 Alternative	Exit-2 Alternative
30 s	214 p.	217 p.
60 s	301 p.	348 p.
90 s	375 p.	448 p.
120 s	445 p.	519 p.
180 s	-	-
Total Evac. Time, s	174,8	152,3

* p: Exited people number

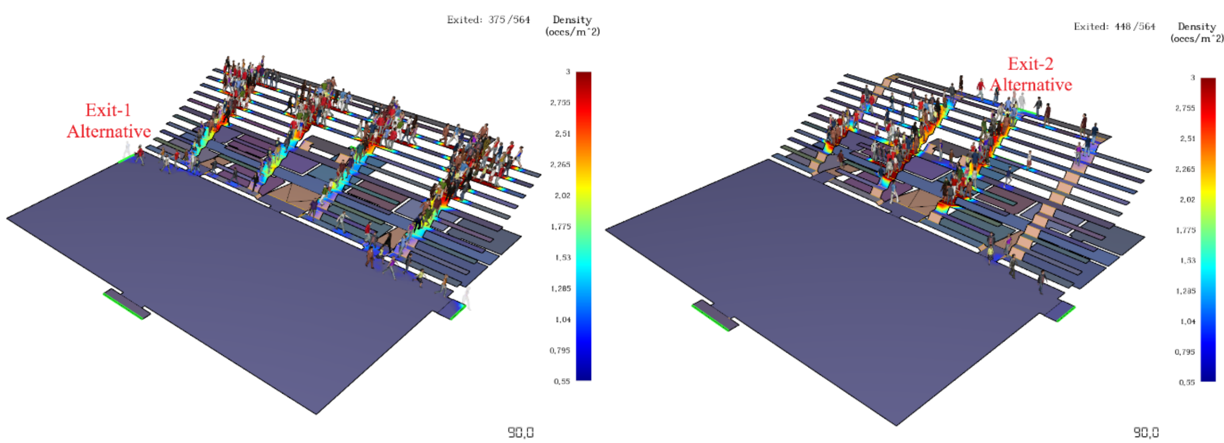

Figure 6. 90th s in evacuation scenarios in Exit-1 and Exit-2 alternative exits

In sports halls used for different purposes, the risk of knowing the building for the first occupants arises with the use of students who know and recognize the building. First-time occupants have difficulty identifying exits and taking action for evacuation routes during a fire. This leads to an increase in the total evacuation time (Kobes et al., 2008). During a fire, emergency lights and warning systems provide an effective pre-evacuation time to prevent this situation. It is necessary to raise awareness of the occupants within the framework of evacuation conditions before the event and to show the exits to raise awareness.

Fire evacuation simulations form the basis of performance-based research. The fires that have occurred in the past periods reveal the necessity and importance of the topic. However, the limited nature of prescriptive-based approaches, the need for continuous revision with the development of technology, and the lack of unique alternatives for different architectural designs and planning make performance-based approaches necessary. Performance-based approaches date back to the 1970s, when the United States developed goal-oriented approaches to building fire safety. Later, the National Fire Protection Association (NFPA) and the Society of Fire Protection Engineers (SFPE) modelled guidelines for comprehensive analysis processes. In 1985, the British Regulations published a performance-based document. Over the next 10 years, the Britain was followed by New Zealand, Australia, Japan, and the Nordic region, which also published their performance-based design documents (Alvarez et al., 2013; Murray, 2023). Unfortunately, Turkey (TRFP) has not made sufficient progress on performance-based fire safety regulation. Additionally, there is a need for Turkey to develop performance-based regulation and make progress in line with the various approaches of other countries. Various initiatives, analyses, and processes are being undertaken in this regard, with government support, by non-governmental organizations and various universities.

5. Conclusion

Sports halls used for functions other than assembly buildings pose risks for fire evacuation and crowd management. To prevent smoke poisoning during a possible fire and to prevent reduced evacuation visibility due to smoke, the spectator should be evacuated as early as possible. Simultaneous evacuation of the crowd (spectators) unfamiliar with the building in a short time is a major design input. As a result of the study, the importance of the location and number of exits was revealed. In multi-functional sports halls, the most intense congestion occurred in the spectator areas. It has been determined that a remote exit alternative does not offer an effective scenario for spectator evacuation in preventing these congestions. However, it has been determined that there will be more effective exit alternatives in the architectural planning of the hall, unlike a distant exit. In multi-functional sports halls, designing exits at the intersection of the main hall and the spectator area or designing exits at the upper part of the spectator' area gave more effective results in reducing the total evacuation time. Additionally, increasing the width of the exits close to the spectator area and keeping the other exits at acceptable levels were found to be appropriate for fire safety performance. The study emphasizes the need for rational and performance-based analysis of the number of exits and exit locations in multi-functional sports halls.

The research presents fire evacuation analysis for multi-functional sports halls, which is limited in the literature. In particular, it investigates the effectiveness of differently located exits during fire evacuation. Evacuation analyses are performed using simulation-based crowd management techniques to realize the dynamic movement of occupants and their routing to exits. The analysis emphasizes the importance of strategic positioning of exit points in the architectural design of multi-functional sports halls. Furthermore, how the total evacuation times change under different scenarios and the effects of these changes on crowd management are analyzed in detail. For future studies, topics of fire and smoke analysis, crowd management, and fire evacuation in the spectator area are recommended. The results of the study provide a guide for architects and engineers working on performance-based fire safety precautions. It also provides an alternative evacuation analysis approach for researchers, ministries, professional bodies, and authorities as stakeholders in the fire safety engineering.

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