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Evacuation Safety and Local Crowd Density in Arenas

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Master thesis submitted in the Erasmus+ Study Program

International Master of Science in Fire Safety Engineering

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Abstract

Arenas and large entertainment venues host significant crowds during events, presenting challenges in evacuation safety management, particularly during emergencies such as fires or terrorist threats. In this study, critical aspects of arena evacuation are investigated, with a focus on methodology to identify local densities in key three-dimensional arena spaces where merging flows occur during emergency evacuations. Through a literature review, existing research and theories related to evacuation safety in arenas are analyzed, emphasizing the importance of considering local densities in evacuation planning. Additionally, a simplified method for measuring local density in 3D is developed, mainly for the key areas where merging flows occur at different levels, improving the overall safety of the evacuation process. Furthermore, evacuation simulations may present issues in representing flow and density at highly congested merging points such as stairs and gates. Consequently, a simple control volume method for crowd density measurement is proposed, providing an easy approach to quantifying local density in critical areas of the arena. This method was applied to a small-scale experiment using real-world data. The resulting crowd density measurements obtained through the control volume method were then compared with those obtained from modeling the same experiment using an appropriate evacuation model that is suitable for high local density scenarios. Moreover, a case study has been conducted (the Pala Alpitour Arena) to offer insights into crowd movement and evacuation dynamics in a real-world setting with high local density at merging points. Through simulating evacuation scenarios at full capacity, the study highlights critical factors influencing evacuation dynamics, particularly in areas with high local densities.

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Abstract in mother tongue (Arabic)

نبذة مختصرة

تستضيف الملاعب والأماكن الترفيهية الكبيرة جماهير هائلة أثناء الفعاليات، مما يثير تحديات في إدارة السلامة والإخلاء، خاصة خلال حالات الطوارئ مثل الحرائق أو التهديدات الإرهابية. في هذه الدراسة، تم فحص الجوانب الحرجة لإخلاء الملاعب، مع التركيز على منهجية تحديد الكثافات المحلية في الأجزاء الثلاثية الأبعاد الرئيسية في الملاعب حيث يحدث دمج لتدفقات الجماهير من الاجزاء المختلفة كالدرج أثناء عمليات الإخلاء في حالات الطوارئ. من خلال استعراض الأدبيات، تم تحليل الأبحاث والنظريات الحالية المتعلقة بسلامة الإخلاء في الملاعب، مع التركيز على أهمية مراعاة الكثافات المحلية في تخطيط الإخلاء و ليس فقط الكثافة الكلية. بالإضافة إلى ذلك، تم تطوير طريقة مبسطة لقياس الكثافة المحلية في الأجزاء الثلاثية الأبعاد، بشكل رئيسي للمناطق الرئيسية حيث يحدث دمج للتدفقات على مستويات مختلفة، مما يحسن السلامة العامة لعملية الإخلاء. وعلاوة على ذلك، قد تواجه المحاكاة لعمليات الإخلاء مشكلات في تمثيل التدفق والكثافة في نقاط التداخل المزدحمة مثل السلالم والبوابات. وبناءً على ذلك، تم اقتراح طريقة بسيطة لقياس كثافة الحشد باستخدام طريقة الحجم التحكمي، مما يوفر نهجًا سهلاً لقياس الكثافة المحلية في المناطق الحرجة في الملعب. ثم تطبيق هذه الطريقة على تجربة بسيطة باستخدام بيانات من تجربة واقعية. ثم تمت مقارنة قياسات كثافة الحشد الناتجة من طريقة الحجم التحكمي مع تلك الحاصلة من محاكاة نفس التجربة باستخدام نموذج إخلاء مناسب ينطبق على سيناريوهات الكثافة المحلية العالية. وعلاوة على ذلك، تم إجراء دراسة حالة (ملعب بالا ألبيتور) لتقديم رؤى حول حركة الجماهير وديناميات الإخلاء في إعداد العالم الحقيقي مع كثافة محلية عالية في نقاط الاندماج. من خلال محاكاة سيناريوهات الإخلاء بسعة كاملة، تسلط الدراسة الضوء على العوامل الحرجة التي تؤثر في ديناميات الإخلاء، لاسيما في المناطق ذات الكثافة المحلية العالية.

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1. Introduction

1.1 Background

Arenas and large entertainment venues host thousands of people during events, presenting significant challenges in terms of evacuation safety management, particularly during emergencies such as fires. The potential risks associated with these settings can be worsened by the large number of people and the need for immediate and effective evacuation. The strategic design and planning of the arena space is critical to ensuring people's safety, considering factors such as size, layout, the presence of stands, and the availability of evacuation routes. Moreover, in emergency situations, the ability to effectively evacuate people depends on a multitude of factors, including the number and location of exits (Haghani, 2020), and the flow of pedestrian movement (Sari & Bomo, 2023). Unlike other types of buildings, arenas often feature stand steps, presenting additional challenges for evacuation planning (Graat et al., 1999). These elevated seating areas introduce complexities in evacuation routes and crowd management, demanding dedicated solutions to guarantee people leave safely and on time.

In high-density crowd situations, issues such as crowd crushing, bottlenecks, and turbulence can arise (Helbing & Johansson, 2009). Crowd crushing involves individuals being compressed within tightly packed crowds, potentially leading to injuries or fatalities. Bottlenecks occur when narrow exits or congested pathways hinder the smooth flow of evacuees, increasing the risk of crush incidents. Turbulence emerges when congestion intensifies, causing chaotic movement, particularly if doors or paths are blocked (Helbing et al., 2007). Effective management of these challenges requires clear evacuation protocols and crowd control strategies to ensure the safety of individuals in densely populated areas. The identification of local densities within the arena, accounting for factors such as population distribution and travel paths, plays a key role in optimizing evacuation procedures. While existing safety regulations typically focus on global density metrics, there is a growing recognition of the importance of assessing local densities in evacuation planning (Klüpfel et al., 2010). This is particularly challenging in arenas where many of the egress components are natively 3D (e.g. arena stands), while most of the engineering tools and calculations in use adopt 2D simplifications. Understanding the dynamics of crowd behavior and the interaction between individuals and their environment is essential for developing targeted and efficient evacuation strategies.

For these large gatherings where the configuration of the space may include large areas where possible movement paths are not as clearly representable through simpler models (e.g. a hydraulic model) (Gwynne & Rosenbaum, 2016), understanding how to improve evacuation safety is therefore crucial for protecting the lives of individuals attending or gatherings in these venues.

Threats that can lead to an evacuation from an arena include fire, bomb threats, or terror incidents (Minegishi, 2023). The need for evacuation can be relieved to some extent if flames and smoke can be controlled, but in certain situations, such as a bomb threat, immediate evacuation is required (H. Xie et al., 2017). Risks associated with these threats, including personal injury, crowd crushing, bottlenecks, and crowd turbulence, highlight the need for continuous improvement in evacuation operations to minimize harm and ensure the safety of all individuals in arenas (Giachini et al., 2010). Mass exits during events in arenas can pose potential hazards. Factors such as crowd accumulation at exits, dispersal of crowds, and poor exit construction can contribute to dangerous situations (Tin et al., 2023).

Historically, numerous accidents have occurred in arenas and stadiums, highlighting the consequences of inadequate evacuation planning. Table 1 documents some of the past tragedies, emphasizing the urgent need for robust safety and crowd management strategies. It is notable that the majority of fatalities in the 1960s were associated with soccer matches, with incidents in Peru, Turkey, and Argentina accounting for most of the victims. Similarly, accidents in the 1970s were largely related to sporting events, but with fewer fatalities despite an increase in frequency (Feliciani et al., 2023).

Table 1 Crowd crushing disasters in sport grounds throughout history.

Date	Place	Event	Incident	Casualties
May 1964 (Helbing et al., 2002)	The National Stadium, Lima, Peru.	Olympic qualifying match	Overcrowding during egress resulted in a crowd crush	318 fatalities and 500 injuries
September 1967 (Akin, 2004)	Kayseri Atatürk Stadium, Kayseri, Turkey	Turkish league match	Crowd crush among the fans of the two teams.	40 fatalities and 600 injuries
June 1968 (Darby et al., 2004)	Buenos Aires, Argentina	First-division league match	Crowds pushing towards a blocked exit resulted in a human crush.	74 fatalities and 150 injuries
January 1971 (Walker, 2004)	Ibrox Stadium, Glasgow, UK.	Football match	Crowd crush at stadium entry/exit points	66 fatalities and 140 injuries
May 1985 (Broeze et al., 2010)	Valley Parade stadium, Bradford, UK.	Football match	Fire in the Valley Parade stadium	56 fatalities and 240 injuries
May 1985 (Logan & Gosseye, 2019)	Heysel Stadium, Brussels, Belgium.	European Champions Cup Final match	Human crush among Italian fans escaping English fans against a collapsing wall	39 fatalities and 600 injuries
April 1989 (Scraton, 2004)	Hillsborough Stadium, Sheffield, UK.	The FA Cup semi-final match	A crowd crush resulting from excessive crowding as fans entered the stadium	96 fatalities and 766 injuries

1.2 Purpose and Aim

Disasters in arenas and other sport grounds involve mostly crowd crushes at stairs and gates due to limited space and their complex three-dimensional geometry (Table 1). Identifying local densities in those key three-dimensional arena spaces where merging flows occur is crucial, especially when merging flows occur at different levels (not just on a flat plane). While evacuation modeling remains a valuable tool, its effectiveness might be limited when it is used for complex 3D arena spaces.

The hydraulic calculations (Gwynne & Rosenbaum, 2016) are often used as simpler alternative to evacuation modelling, those are generally not suitable for the simulation of large gathering where the configuration of the space may include large areas where possible movement paths are not as clearly representable through a hydraulic model. In these cases, a simple method to estimate crowd density would be a more useful tool.

- The aim of the thesis is to define simple methodology to identify local densities in key three-dimensional arena spaces where merging flows occur during emergency evacuations.

- and verifies the applicability of adopting evacuation modeling for high local density scenarios in arenas.

1.3 Limitations

It is important to acknowledge the limitations of this thesis. The scope of the research may be limited to a specific type of arena or may be influenced by the availability of data for analysis. Additionally, the research may be subject to constraints such as time and resource limitations as well as the assumptions that will be made during the simulations. However, despite these limitations, this thesis seeks to contribute to the existing body of knowledge on evacuation safety in arenas and provide practical recommendations for enhancing safety measures.

1.4 Method

This section outlines the methodologies employed to investigate evacuation safety in arenas comprehensively. The methods discussed include a literature review, modeling, and data analysis. The literature review serves as the initial step, aiming to understand existing research and theories related to evacuation safety in arenas. Then, a simplified method for measuring local density in 3D has been developed. Following this, evacuation scenarios are developed during the modeling stage. Finally, the modelling results are analyzed to draw meaningful insights and conclusions.

1.4.1 Literature Review

In this review, a comprehensive literature search in terms of ‘title/abstract/keyword’ has been conducted via both two scientific databases, Scopus and Web of Science as well as the search engine Google scholar. The keywords that were used include ‘Arena OR Stadium’, ‘evacuat OR escap OR egress’ ‘simulat OR model*’, ‘Local density OR high density’. This review aims to gain a thorough understanding of the existing research and theories related to evacuation safety in arenas, with a particular focus on those that investigate global or local densities. In addition, the review will investigate merging flows (given their relevance to the context of study) and the various modeling approaches that have been used in this context. This process will involve the identification of key concepts, theories, available data, and methodologies that have been employed in previous studies. A critical evaluation of the strengths and weaknesses of current evacuation safety measures in arenas will also be conducted. This evaluation is particularly pertinent as the code requirements typically refer to global density, whereas our interest lies predominantly in local density. This discrepancy necessitates a careful and detailed analysis to ensure the most effective and appropriate measures are implemented.

1.4.2 Data Collection

In a small-scale experiment, data is collected through video recordings from various cameras placed throughout the arena. These recordings are then used to assess the effectiveness of a simple method for measuring local density in key three-dimensional arena spaces.

1.4.3 Modeling

An appropriate evacuation model has been selected. It is crucial that this model can be used for simulating large populations with high densities, particularly local density. A small-scale test is modeled with measurement regions positioned at the stairs and gates to calculate the local density. The results are then compared to the real-world results. Then acase study's model is constructed within the software, with measurement regions positioned at critical elements like the stairs, and density calculations conducted accordingly. This process is executed for a full-capacity scenario to capture the worst-case scenario.

2. Literature review

This literature review follows a four-part structure:

1) Exploring relevant experimental research on arenas,
2) Reviewing existing codes and standards,
3) Reviewing methods for density estimation, and
4) Analyzing evacuation modeling in arenas.

By examining current research and methodologies in the field of evacuation safety, this literature review seeks to shed light on the critical aspects of arena evacuation and explore strategies to enhance safety and efficiency in these complex environments. The review will include sport arenas as well as similar sport grounds i.e. stadiums as they have similar characteristics.

2.1 Experimental Research Relevant to Arenas

This section explores studies that focus on optimizing safety and efficiency during evacuations from arenas and sports facilities. During events, careful observation is necessary in areas where people tend to gather. Accurate estimation of crowd density is vital to assess the situation correctly.

In large events, precise pedestrian crowd management is vital to prevent accidents. It is notable that the majority of fatalities in the 1960s were associated with soccer matches, with incidents in Peru, Turkey, and Argentina accounting for most of the victims. Similarly, accidents in the 1970s were largely related to sporting events, but with fewer fatalities despite an increase in frequency (Feliciani et al., 2023). This trend could be attributed to the implementation of stricter regulations for stadium design and crowd management. For example, the first edition of the 'Green Guide', addressing safety in sport venues in the UK, was published in 1973 (Thompson et al., 2002), indicating a growing awareness of crowd safety during that period.

The Health and Safety Executive (HSE) conducted an investigation into the technical aspects of the Hillsborough disaster that occurred on 15 April 1989. This investigation focused on determining approximate crowd densities and assessing factors such as turnstile operation, spectator numbers, and the functionality of the public address system (Nicholson & Roebuck, 1995). It was found that the crowd density in pen 3, where the majority of fatalities occurred, exceeded the allowable maximum of 5.4 persons per square meter, estimated to be over 8 persons per square meter. Additionally, the investigation examined total admissions, crowd pressures, and the strength of barriers. It was concluded that the collapse of barriers was due to crowd pressure, despite the public address system being audible(Nicholson & Roebuck, 1995).

Rinne et al. gathered and analyzed data from two ice hockey stadiums, one with a capacity of 3000 persons and the other accommodating 10000 individuals. Their analysis revealed congestion during normal movement within these venues. The study investigated crowd density and walking speed, finding that walking speed decreased to approximately 0.3 m/s when the crowd density reached about 2.5 persons per square meter. Additionally, regular stadium attendees exiting ice hockey games were observed to utilize multiple doors, indicating their familiarity with the stadium's layout (Rinne et al., 2010).

Zhao investigates safe personnel evacuation strategies in stadiums during emergencies, analyzing causes of casualties from major safety accidents in large Chinese stadiums. The study examines factors affecting evacuation efficiency, including disorder, short times, and slow speeds, emphasizing the importance of staff training. Calculation results determine factor importance and consistency, advocating for preventive measures and ongoing professional training to prevent large accidents (H. Zhao, 2014).

Wagoum et al. investigated pedestrians' route choices in the ESPRIT arena, Düsseldorf, Germany, focusing on spectators' exit behavior during football games. Utilizing data from an automatic person counting system with cameras, they conducted an empirical analysis. The study revealed that pedestrians generally preferred the shortest path for exiting the facility. However, observed and simulated exit choices showed discrepancies. The research underscored the importance of considering route choice behavior outside the facility in evacuation scenarios (Wagoum et al., 2014).

Another study by Larsson et al., conducted at a UK stadium across various events, suggests the need to consider crowd composition in stadium egress planning to optimize safety and performance. Using video analysis, the researchers categorized crowd flows and observed relationships between density, flow, and velocity. Their findings highlighted the influence of crowd composition on egress velocities, flows, and densities, with flow rates consistently below recommended safety levels. These insights underscore the importance of integrating crowd composition considerations into stadium egress planning to ensure the safety and efficiency of crowd movement (Larsson et al., 2021).

Catur Supriyanto's case study examines crowd management strategies at Jakarta's Gelora Bung Karno International Stadium during football matches. The research covers tactics before, during, and after the events, with data collected from various stakeholders including managers, technical personnel, support workers, and police officers. Seven crowd management measures were identified before the event, three during, and three after. The study highlights the importance of security systems and entry gate arrangements for successful strategies, providing insights into the comprehensive approach required to ensure safety and order at such events (Supriyanto, 2022).

Rahmat et al. explored crowd management strategies and safety performance in sports event organization, surveying 40 safety or operation managers from Kuala Lumpur and Selangor. Their study revealed a significant correlation between crowd management strategies and safety performance, emphasizing the importance of effective crowd control in ensuring attendee safety. These findings offer actionable insights for event organizers, suggesting that improved crowd management strategies can enhance safety practices, particularly in the context of sports tourism (Rahmat et al., 2011).

Hoskin & Spearpoint explored stadium evacuations under high-density conditions, prioritizing crowd characteristics for enhancing evacuation procedures. Drawing from research in New Zealand on fire protection and evacuation, their study emphasizes effective crowd management to improve evacuation protocols within stadiums. Investigating occupant characteristics' impact on emergency egress, the study advocates for tailored evacuation planning, backed by speed density data. Overall, the research highlights the challenges of evacuating densely populated stadiums and underscores the necessity of efficient crowd management for successful evacuations (Hoskin & Spearpoint, 2004).

2.1.1 Crowd Evacuation for High Densities in Arenas

The Green Guide suggested that the optimum local density for sport grounds is 2 persons per square meter. However, the maximum density for standing spectators is 4.7 persons per meter square, this will lead to excessive pressure between the spectators which can lead to injuries (Sports Grounds Safety Authority, 2008).

Friberg and Hjelm highlight the potential dangers of extremely high crowd density, which can lead to individuals being unintentionally tumbled around without reason. Forces propagate in all directions within the crowd, increasing the likelihood of people falling. Research indicates that a density exceeding 7 persons per square meter can induce turbulence. The discovery that turbulence serves as a strong indicator of impending catastrophic disasters has prompted efforts to identify critical situations before they escalate(Friberg & Hjelm, 2014).

Kim et al. discuss the influence of crowd density on individual walking speed. They note that when few people are nearby and crowd density is low, individuals can move freely at their regular walking speed without interaction. However, in crowded conditions with higher crowd density, walking speed significantly decreases due to interaction with others in the vicinity (Kim et al., 2019)

2.1.2 Route Choice

Route choice is a fundamental aspect of the evacuation process. Haghani's research explores route choice, focusing on how individuals select paths to reach safe zones. Various models, such as random utility, logit, and prospect theory, aid in understanding decision-making in transportation networks. Route choices are influenced by factors like traffic congestion and road conditions. Advanced technologies like GPS and mobile apps facilitate informed decisions on which route to choose (Haghani, 2020).

Research suggests reliance on familiar routes and past experiences. Sime introduced the affiliation theory in a study examining people's escape direction during a fire evacuation in a large room with an entrance and emergency exit in opposite corners. The research found that individuals' choice of location and exit was influenced by both personal and place affiliations, highlighting the impact of social connections and familiarity on evacuation decisions (Sime, 1985). Understanding route choice behavior can optimize transportation systems and improve travel efficiency by reducing congestion.

Sari et al. conducted a study on route choice using signage in Jakarta International Stadium, with the goal of guiding spectators to exit quickly, precisely, and safely during emergencies. They utilized Environment Graphics Design (EGD) to evaluate the effectiveness of evacuation maps, exit signs, and assembly point signs, ensuring compliance with building amenity regulations. The study emphasized the importance of various signage categories and color-coded zones to prevent navigation errors (Sari & Bomo, 2023). Using the Post Occupancy Evaluation method, the research assessed the interconnectedness of evacuation systems, with signage placement based on circulation routes for clear movement directions (Sari & Bomo, 2023). Overall, the study emphasized the crucial role of well-designed signage, including evacuation maps, exit signs, and assembly point signs, in guiding spectators during evacuations.

2.2 A Review of Standards/Guidelines Regarding Safety in Arenas and Sport Grounds

Current safety standards for evacuation in arenas vary depending on the specific arena design and where they are designed. Each country has its own standards i.e. the Green Guide in the UK (Guide to Safety at Sports Grounds, 2018). This will be discussed in the next section. However, there is a need for ongoing research and analysis to ensure that arenas meet safety standards for evacuation. However, several studies have analyzed the flow of people during evacuation and compared it to existing standards. For example, a study comparing the Roman Colosseum and the Gazprom Arena stadium found that the Colosseum complied with current standards used in Italy (UNI EN 13200-7:2014) for on-time evacuation, while the Gazprom Arena did not comply with the current standers used in Russa (Gravit et al., 2022). Another study analyzed the safety of large arena audiences in a fire emergency evacuation plan and emphasized the importance of analyzing the whole building evacuation time for ensuring spectator safety (Liu et al., 2011). Additionally, a project funded by the

German Government aimed to improve safety in large multifunctional buildings and events through the use of a real-time evacuation simulation (Holl et al., 2014). When it comes to the sport arenas, the safety of spectators and participants is important. This section provides a comprehensive review of various codes, standards, and guidelines that are employed globally to ensure safety in arenas.

These documents, which vary from country to country, serve as a blueprint for designing, constructing, and managing sports arenas and similar facilities. They encompass a wide range of safety aspects, including emergency evacuation planning, structural design, fire safety, crowd management, and more. They provide a framework for planning, designing, constructing, and managing these facilities in a way that prioritizes the safety of spectators and participants.

The differences between countries often arise due to variations in local laws, cultural practices, environmental conditions, and technological capabilities. Each country has its own set of regulations and standards that reflect its unique circumstances. For example, the Green Guide is used in the UK, NFPA 101 in the USA, AS 3745 in Australia, and DIN 18035-1 in Germany.

2.2.1 The Green Guide – The United Kingdom

The Green Guide, primarily used in the UK, is a comprehensive handbook offering guidelines for ensuring safety at sports grounds. It serves as a resource for engineers, architects, and others involved in the design, construction, and management of sports arenas. Focusing on the safety of spectators, it covers various topics such as the design and layout of sports grounds, entry and exit routes, seating arrangements, and emergency procedures. Regularly updated to incorporate the latest research and best practices, the Green Guide plays a crucial role in maintaining high safety standards across sports grounds in the UK (Sports Grounds Safety Authority, 2008).

With a detailed focus on evacuation safety within sports arenas, the Green Guide aims to ensure the efficient evacuation of spectators during emergencies. It provides guidance on creating clear exit routes throughout the venue, calculating the acceptable capacity of an arena, and determining flow rates for different scenarios. Emphasizing the importance of having an adequate number of exits proportional to the venue's capacity to prevent congestion and facilitate quick evacuation, the guide also highlights the necessity of effective communication systems within sports arenas. These systems are essential for providing critical information during evacuations and coordinating responses with emergency services. Essentially serving as a manual for achieving stadium security, the Green Guide offers guidance rather than strict rules, suggesting necessary actions and assigning responsibilities to relevant individuals involved in maintaining safety standards (Sports Grounds Safety Authority, 2008).

The first edition of the Green Guide was largely influenced by a report authored by Lord Wheatley, which focused on the tragic events at Ibrox in 1971. This report highlighted the importance of enhancing safety measures at sports stadiums (Hillsborough Independent Panel, 2012).

2.2.2 NFPA 101 Life Safety - United States

In the USA, NFPA 101, commonly known as the Life Safety Code, plays a role in ensuring evacuation safety in sports arenas. This comprehensive code, developed by the National Fire Protection Association (NFPA), establishes rigorous requirements for the design, construction, and operation of buildings to safeguard occupants during emergencies, including fires and evacuations. While not directed specifically to sports arenas, Chapter 12 of NFPA 101 addresses assembly occupancies, which encompass sports venues, providing essential guidelines for evacuation safety. These provisions cover various aspects crucial to evacuation, such as means of egress, exit capacities, exit arrangements, and fire protection systems. NFPA 101 offers comprehensive guidance on factors like exit design, capacity, and accessibility, which are vital for ensuring the safe and efficient evacuation of spectators and participants during events. Venue operators and designers rely on NFPA 101, along with other relevant codes and standards, to develop robust evacuation plans tailored to the unique characteristics of sports arenas, ultimately enhancing safety and protecting lives (National Fire Protection Association, 2021).

2.2.3 MSB Guidelines for Event - Sweden

In Sweden, the MSB (Swedish Civil Contingencies Agency) Guidelines for Events serve as a crucial framework for ensuring safety and security during various gatherings and events, including sports events held in arenas and stadiums. These comprehensive guidelines provide detailed recommendations and requirements for event organizers, venue operators, and other stakeholders involved in planning, managing, and executing events. Specifically tailored to the Swedish context, the MSB Guidelines cover a wide range of safety and security aspects, including crowd management, emergency preparedness, evacuation procedures, fire safety, medical services, and risk assessment. By following the MSB Guidelines for Events, organizers and venue operators can enhance safety standards, mitigate risks, and ensure the well-being of participants, spectators, and staff during sports events and other gatherings across Sweden (Swedish Civil Contingencies Agency, 2021).

2.2.4 AS 3745:2010 Planning for Emergencies in Facilities – Australia

In Australia, AS 3745:2010 "Planning for Emergencies in Facilities" serves as a key standard for addressing evacuation safety in various facilities, including sports arenas. This standard provides guidance on developing and implementing emergency plans tailored to the specific needs and characteristics of different types of facilities, including sports venues. While AS 3745:2010 does not specifically focus solely on sports arenas, its provisions cover essential aspects of emergency preparedness and evacuation procedures applicable to these venues. By adhering to the guidelines outlined in AS 3745:2010, sports arena operators can enhance evacuation preparedness, minimize risks, and ensure the safety of occupants during emergencies (Standards Australia, 2010).

Table 2 shows the standers and the guidelines used in other different countries for safety in arenas and other sport grounds. It’s important to note that while these standards may vary from country to country, their primary goal is the same: to ensure the safety and well-being of all individuals in these facilities. They all aim to provide a safe and enjoyable experience for spectators and participants alike.

Table 2 Safety standers for different countries.

Country	Standard/Guide	Explanation	Key Differences
Germany	DIN 18035-1:2018-09 Sports grounds	DIN 18035 provides guidelines for the planning and design of sports venues with a focus on safety aspects, including crowd management and evacuation procedures. It addresses aspects like layout, signage, and emergency exits (DIN 18035-1:2018-09).	Tailored specifically for safety in sports venues. Incorporates German building regulations and standards.
France	ERP Regulations	ERP Regulations in France provide guidelines for establishments open to the public, including sports venues, regarding safety measures, crowd management, and evacuation procedures (French Building Code, 2021).	Focuses on safety measures and evacuation procedures for establishments open to the public, including sports venues. Compliance is mandatory for all public facilities.
Canada	National Building Code of Canada	The National Building Code of Canada includes provisions for assembly occupancies, which can encompass sports venues. Additionally, provincial regulations and codes may provide specific guidelines for crowd management and evacuation (National Building Code of Canada, 2015).	Focuses on building regulations and safety standards applicable to assembly occupancies, with adaptations at the provincial level for specific requirements.
Brazil	ABNT NBR 15.465:2019 - Sports facilities	ABNT NBR 15.465 provides guidelines for the planning and design of sports facilities, including safety aspects such as crowd management and evacuation procedures. It addresses factors like accessibility, layout, and emergency exits (ABNT NBR 15.465:2019).	Specific guidelines for the planning and design of sports facilities in Brazil, covering safety aspects and compliance with Brazilian building regulations.
South Africa	SANS 10400-T:2011 - Part T: Fire Protection	SANS 10400-T provides requirements for fire protection, including evacuation procedures, in various buildings, which can include sports venues. It outlines measures to ensure occupant safety in the event of a fire or emergency (SANS 10400-T:2011).	Focuses on fire protection measures, including evacuation procedures, as part of South Africa's National Building Regulations. Adaptations may be made for specific building types.
Netherlands	NEN 8112: Safety in Stadiums	NEN 8112 provides guidelines for the safety of spectators in stadiums, covering aspects like crowd management, emergency evacuation procedures, and facility design to ensure compliance with Dutch building regulations and safety standards (NEN 8112:2004).	Focuses on safety guidelines specific to stadiums in the Netherlands, including crowd management and evacuation procedures compliant with Dutch building standards.
New Zealand	NZS 9201:2008:	NZS 9201:2008 provides guidelines for safety in sports grounds, including crowd management and evacuation procedures. It covers aspects like venue design,	Tailored specifically for sports grounds in New Zealand, focusing on safety measures and

	Safety in Sports Grounds	emergency exits, and safety measures to ensure the well-being of spectators (NZS 9201:2008).	evacuation procedures compliant with New Zealand building regulations.
Saudi Arabia	Saudi Building Code	The Saudi Building Code provides regulations for building construction and safety in Saudi Arabia, which may include provisions for assembly occupancies such as sports venues. It may outline guidelines for crowd management and evacuation procedures (Saudi Building Code, 2022).	Sets out building regulations and safety standards in Saudi Arabia, including requirements for assembly occupancies like sports venues, with provisions for crowd management and evacuation procedures.
Norway	Norwegian Standard NS 3473: Safety at Events	Norwegian Standard NS 3473 provides guidelines for safety at events, including sports events, covering aspects such as crowd management, emergency evacuation procedures, and venue design to ensure the safety of participants and spectators (NS 3473:2012).	Focuses on safety measures specific to events, including sports events, in Norway, with emphasis on crowd management and evacuation procedures compliant with Norwegian regulations.
UAE	UAE Fire and Life Safety Code	The UAE Fire and Life Safety Code outlines regulations for fire safety and life protection in the UAE, including requirements for assembly occupancies like sports venues. It may encompass guidelines for crowd management and evacuation (UAE Fire and Life Safety Code, 2021).	Regulates fire safety and life protection standards in the UAE, including requirements for assembly occupancies like sports venues, with provisions for crowd management and evacuation procedures.
Malaysia	Malaysian Standard MS 2676: Code of Practice for Safety in Sports Grounds	Malaysian Standard MS 2676 provides a code of practice for safety in sports grounds, including crowd management and evacuation procedures. It covers aspects like venue design, emergency exits, and safety measures for spectator well-being (Malaysian Standard MS 2676:2015).	Specifies safety guidelines for sports grounds in Malaysia, focusing on crowd management and evacuation procedures compliant with Malaysian building regulations.

2.3 Density estimations

Estimating crowd density in an arena or any sport venue is crucial because it provides essential information for effectively managing the crowd (García et al., 2024). The common approach used to estimate the density (ρ) is by calculating the average number of pedestrians (N) per unit area within a walkway or queuing area (A).

$$\rho = \frac{N}{A}\; person/m^2$$

Understanding both local and global densities is crucial for effective crowd management and evacuation planning. Global density refers to the overall density of the entire arena. It considers the total number of people present in the arena relative to its total seating capacity or available space. Global density provides an overview of how crowded the arena is, regardless of specific areas within it. On the other hand, local density refers to the density of people within particular areas or sections of the arena during the evacuation process. It focuses on how crowded or congested particular routes or exits become as people move towards the exit.

Local density helps assess the potential for bottlenecks, obstacles, or hazards within specific areas of the arena during evacuation. It is possible to observe two configurations with the same global density under very different local density (Kerner, 2004). In essence, this means that within a given space, certain areas could be experiencing high congestion and slow movement (Stop-and-go waives and turbulent crowd flow), while others remain relatively open and fluid (laminar crowd flow). This is because the global density is static, whereas the characteristics of pedestrians that are moving are neglected. Therefore, to measure the congestion of a certain pedestrian that is moving, the local density has to be calculated (Duives et al., 2015).

To gain a comprehensive understanding of pedestrian dynamics, it is essential to calculate the local densities as this impacts the efficiency, comfort, and safety of pedestrians. Figure 1 illustrates the difference between the two concepts, A and B have the same global density as the area and the amount of people are the same in both cases. However, the local density varies between A and B. This shows the critical importance of local density in evacuation planning, emphasizing the necessity to consider more than just global density measurements.

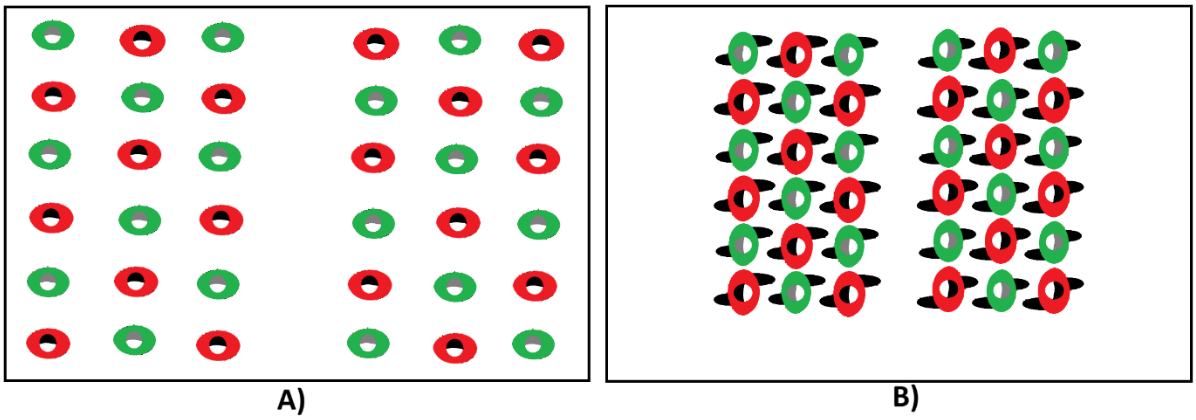

Figure 1 The difference between global density and local density.

2.3.1 Level of Service

The Pedestrian level of service (LOS) is a concept used for assessing the comfort and safety of pedestrians. The most commonly applied document in this regard is Fruin’s LOS (Fruin, 1970). This document classifies the service level into six categories. Table 3 shows Fruin's level of service classifications for varying crowd densities, using letters A through F. Where category A represents the best conditions, with high comfort, while category F represents the poorest conditions, indicating overcrowding and potential safety risks. These categories are based on pedestrian flow characteristics, which include aspects such as density, velocity, and flow rate.

The establishment of the LOS is premised on the pedestrian fundamental diagrams (Seyfried et al., 2005) and (Vanumu et al., 2017). These diagrams depict the mutual relations between the three traffic parameters, namely velocity, density, and flow rate. When applying the LOS to measure a specific region, density is predominantly used as opposed to the flow rate or velocity. This approach ensures a more accurate and relevant assessment of the pedestrian comfort level in the region under consideration.

Table 3 Fruin’s level of service (Fruin, 1970)

Fruin’s level of service	Average area module	
	Walkway (ped/m2)	Stairs (ped/m2)
A	< 0.31	< 0.54
B	0.31–0.43	0.54–0.72
C	0.43–0.72	0.72–1.08
D	0.72–1.08	1.08–1.54
E	1.08–2.17	1.54–2.70
F	> 2.17	> 2.70

Safe crowd density limits vary depending on factors such as event type, venue layout, and available infrastructure. Event organizers face challenges in preventing crowd disasters, including the task of maintaining crowd density within safe limits. According to Wirz et al., a suggested safe limit for a moving crowd is 5.55 persons per square meter, derived from their study methodology utilizing smartphone data and walking speed analysis (Wirz et al., 2013).

Table 4 presents typical crowd density ranges for both static and moving crowds, along with associated behaviors and risks. For sport grounds, the Green Guide defined the maximum density for standing spectators to be 4.7 persons per meter square (Sports Grounds Safety Authority, 2008).

Table 4 Chart of crowd density (Wirz et al., 2013)

Dynamics	Density (P/m2)	Behavior and risk
Standing	7.10	Critical crowd density for static crowd
Walking	0.43	Pedestrian Stream can maintain aver- age walking speed and avoid one another
	2.00	Reduced walking speed
	3.57	People experience Involuntary contact
	5.55	Crowd forces develop potential danger

Most methods to measure the local density are based on the concept of peri-personal space (PPS) (Duives et al., 2015; Steffen & Seyfried, 2010), where the PPS is the region of space surrounding the body immediately (Cléry & Hamed, 2018). One method to study local density is based on Voronoi diagrams (Steffen & Seyfried, 2010). The kernel approach can also be used to estimate local density (Vacková & Bukáček, 2022).

2.3.2 Voronoi Diagram Approach

The Voronoi diagram is a geometric concept used in various fields, including video tracking, pedestrian modeling, and density estimation. It assigns cells to each point in a given set of trajectories, where each cell represents the area closer to that point than any other point (Voronoi, 1908).

Steffen & Seyfried utilize Voronoi diagrams to minimize density scatter in pedestrian measurements. Their study focuses on measuring pedestrian characteristics through Voronoi diagrams and trajectory analysis, enabling the assessment of pedestrian density, flow, speed, and direction with minimal scatter. By assigning personal space to pedestrians using Voronoi diagrams, the researchers offer a solution for analyzing pedestrian behavior at an individual level (Steffen & Seyfried, 2010).

This approach not only reduces density scatter but also enhances measurements of speed and direction. The concept proposed by Steffen & Seyfried facilitates the measurement of microscopic characteristics based on pedestrian trajectories, utilizing modern video methods for in-depth analysis of pedestrian behavior. Through the Voronoi cell concept, the study enables the resolution of density and velocity at an individual level, providing valuable insights into pedestrian dynamics (Steffen & Seyfried, 2010).

Figure 2 illustrates the full process of estimating crowd density. In evaluating density within a detector using the Voronoi approach, there are several methods available. These include incorporating cells that intersect with the detector, considering only cells of pedestrians with their head positions in the detector (Figure 2, E), or cutting cells to fit precisely within the detector area (Figure 2, F).

2.3.3 Kernel-based Approach

Kernel methods, like the kernel density concept, offer a smooth estimation of pedestrian density by treating each pedestrian as a distribution source. These methods utilize various kernels to achieve desired properties in density estimates and commonly integrate established techniques. The developed kernel concept views each pedestrian as a density distribution source, with parameters including kernel type (e.g., Gauss, cone) and size. A quantitative parametric study on experimental data shows that parametrization enhances desired features. The kernel concept reveals common features across density estimates, with the conic kernel producing smooth values while retaining trend features. Results from the minimum distance method are comparable to those from kernel methods (Vacková & Bukáček, 2022). García et al. utilized discrete kernel-based methods to estimate local density at San Mamés Stadium. They explored three pedestrian settings to assess the impact of agent sizes and initial locations in surrounding streets on maximum local densities. Numerical results indicate that pedestrian flow saturates at around Max(ρmax) ≈ 4.25 people/m2, with densities exceeding this threshold attributed to jamming at the stadium entrance (García et al., 2024).

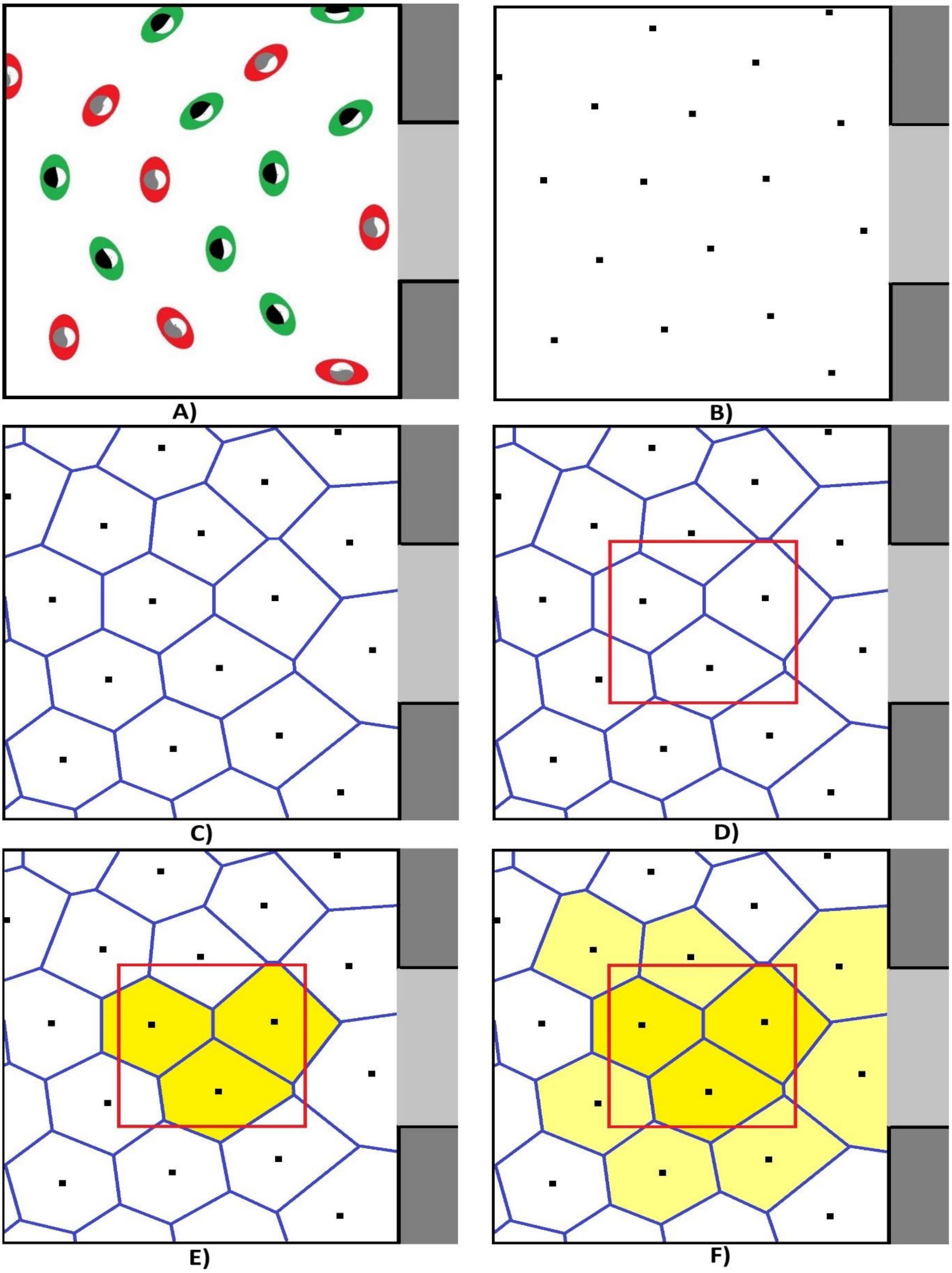

Figure 2 The full process of estimating crowd density using Voronoi diagram approach.

2.4 Evacuation Modeling in Arenas

Evacuation simulations are computer models that simulate the movement of people during an emergency evacuation. They can be used in the arena context to plan and optimize evacuation routes, identify potential bottlenecks, and evaluate the effectiveness of different evacuation strategies. Previously, The Hermes project (Klüpfel et al., 2010) was designed with the objective of enhancing safety in large, multifunctional buildings and during major events. This was achieved by developing an evacuation assistant that utilized real-time simulations to predict evacuation processes reliably. The assistant was specifically designed for large arenas, providing real-time guidance and information to individuals in emergency situations. The project's emphasis on real-time simulation and prediction was aimed at improving the efficiency and effectiveness of evacuation procedures, thereby enhancing individual safety in such environments (Klüpfel et al., 2010). This project serves as good example of the use of evacuation simulations to improve safety of arenas.

Ivanusa et al. present a case study on Arena Lviv, introducing a visual model aimed at enhancing safety during evacuations from sports facilities. Factors such as width, bandwidth, and visitor numbers are identified as critical influences on evacuation strategies. The study focuses on optimizing Total Evacuation Time within the building, proposing physical reductions of seats in rows and sectors as a means to streamline the process. Additionally, the research advocates for an integrated approach to safety at mass presence objects. By offering a visual model for people's movement during evacuations from Arena Lviv, the study contributes valuable insights into optimizing safety measures in sports facilities(Ivanusa et al., 2023).

Lin et al. present a case study on crowd evacuation in Taipei Arena, focusing on optimizing safety strategies. Utilizing Pathfinder software, they model crowd movement, emphasizing guidance for individuals in raised seating areas. The study aims to enhance evacuation efficiency by increasing moving lines and proposing a new stair passage alternative. While Pathfinder's steering movement mode proves effective for diverse crowds and L-shaped movement patterns, the research notes limitations in simulating high-risk evacuations due to manpower constraints. Overall, the study underscores the software's suitability for large venue evacuation simulations, providing insights into safety optimization during mass gatherings (Lin et al., 2015).

When designing an evacuation model in an arena, there are several key factors to consider. First, the capacity and width of the stairs play a crucial role in the flow of people during evacuation (Ivanusa et al., 2023). The specific flow rate, which is the number of people passing through a certain area per unit of time, is also an important factor to consider (Gravit et al., 2022). Additionally, the knowledge and familiarity of the occupants with the space can significantly impact their behavior during evacuation (Chu & Law, 2019). It is also important to consider the design of the venue, including exit locations and signage, to optimize the egress outcome (Mahmudzadeh et al., 2020). By using simulation models, researchers can calculate the time it takes for people to evacuate a stadium and identify areas where improvements can be made (Shirvani & Kesserwani, 2021). These models can take into account factors such as age, gender, and walking speeds to provide more realistic and accurate results (Liang et al., 2020). By analyzing the data generated from these simulations, stadium designers and planners can make informed decisions about space planning, such as the width of stairs and the capacity of evacuation routes, to ensure efficient and safe evacuation (Gravit et al., 2022) . Finally, the use of simulation software can help evaluate and improve the design of safe egress systems and emergency preparedness planning, also it can help in developing emergency evacuation plans and software that can be used to train stadium staff and educate the public on evacuation procedures .

Simulation and multi-agent modeling can be used to study crowd behavior and simulate evacuation scenarios (Minegishi, 2023). By analyzing space-planning decisions and flow of people during evacuation, the capacity of evacuation routes and potential bottlenecks can be identified (Liang et al., 2020). Factors such as age and gender can also be considered in the modeling process to factor in walking speeds and individual risk perception. Furthermore, crowd control measures such as closing certain exits, installing temporary fences, and providing staff guidance can be implemented to relieve congestion and facilitate evacuation. Moreover, to improve the accuracy of evacuation modeling in arenas, several approaches have been proposed in the literature. One approach is the use of hybrid agent reinforcement learning algorithms and multi-objective improved particle swarm optimization techniques have been proposed to simulate dynamic crowds and find optimum evacuation routes (Senthil Kumar Thangavel, 2021). Furthermore, the development of continuous models, such as the continuous floor field cellular automata model, has been suggested to improve accuracy while reducing time complexity (R. Zhao et al., 2021). Finally, the application of deep reinforcement learning and 3D physical environments has been proposed to create more realistic simulations and explore the laws of crowd evacuation (D. Zhang et al., 2023).

Evacuation simulations have limitations and cannot replace other methods for crowd management and evacuation planning. Some of the limitations include the complexity involved in creating simulation models, which requires accurate data and assumptions (Kuligowski et al., 2023). Another challenge is the lack of real-time capabilities in current modeling approaches, limiting their usefulness for informed decision-making during evolving disaster events (Chapuis et al., 2022). Additionally, the effectiveness of evacuation procedures depends not only on technical aspects but also on governance issues, such as evacuation protocols and policies (González-Villa et al., 2022). Furthermore, the capacity of simulation models to reproduce a context of mixed traffic is a major limitation in accurately modeling evacuation scenarios (Abu Bakar et al., 2023). These challenges and limitations highlight the need for improved simulation tools that can address these issues and provide more realistic and effective evacuation strategies for crisis management.

One of the practices for evacuation safety in arenas and sport grounds is presented in research by Chu & Law on evacuation safety emphasizes timely and unobstructed evacuation to safe zones. By considering occupants' behaviors, background, and knowledge, Chu & Law aims to optimize egress performance. The study suggests that evacuation efficiency improves with occupants' knowledge and strategic crowd control. It focuses on simulating evacuation scenarios while highlighting the impact of occupants' behaviors on evacuation walking patterns. Chu's findings that a 40% increase in evacuation efficiency with occupants' floor plan knowledge (Chu & Law, 2019). Nowadays, there are research developments in this area for other practices include the following strategies: 1. Considerations for accessibility and movement of different demographics, taking into account future population and demographic trends (Ivanusa et al., 2023). 2. Utilize AI-based analysis of large datasets to analyze pedestrian movement and behavior (Gales et al., 2023). 3. Modify open-source software for pedestrian analysis to improve evacuation and circulation simulations (Gravit et al., 2022). 4. Analyze space-planning decisions and compare the flow of people during evacuation by simulation to identify advantageous design choices (Chu & Law, 2019).

Klupfel et al. introduced the PedGo Guardian, an evacuation assistant designed for large venues such as arenas. This system predicts occupants' future positions using real-time data on rescue routes, fire protection systems, and crowd distribution. By incorporating this information, the PedGo Guardian enables flexible responses to emergent situations in venues without specialized emergency plans. It employs a traffic-light scheme to categorize crowd densities and risks, facilitating efficient crowd management during evacuations (Klüpfel & Meyer-König, 2014).

2.4.1 Evacuation Modeling for High Densities in Arenas

Evacuation safety in arenas with high local density is a critical concern for ensuring human safety. To effectively evacuate an arena with high local density, several strategies can be employed. One approach is to use a density navigation algorithm that guides crowd movement by calculating density and distance factors (Liang et al., 2020). Another method is to utilize simulation models to identify optimal evacuation and crowd management strategies, even in high density scenarios (Ines Cilenti, 2019). These models can be calibrated using field observations and data collected from real events (Mahmudzadeh et al., 2020). Additionally, timed schedules for evacuating each sector based on priority can help avoid the simultaneous presence of all people at a single location (Peterson & Jonsson, 2018). It is also important to consider the design of the arena, ensuring that access routes and exits have enough space to accommodate the population (Ji et al., 2018).

This strategy involves the use of optimal models for vehicle parking, channel design, and evacuation of subways and buses. It consider factors such as density, flow, and evacuation time to guide the design and optimization of evacuation routes and facilities (Huang et al., 2013). These findings highlight the importance of understanding crowd dynamics and implementing effective strategies to ensure evacuation safety in arenas with high local density.

Some of the methods adopted for ensuring safety during evacuation of an arena with high local density involve understanding crowd dynamics, using modeling tools, and considering factors such as bottleneck areas and pressure increase among pedestrians. Modelling tools can help identify optimal evacuation and crowd management strategies, but their use for high density scenarios needs to be evaluated (Ines Cilenti, 2019). It is important to collect data on speed, density, and flow through field observation to calibrate simulation models for high density scenarios (Peterson & Jonsson, 2018). In addition, a simple model can be used to forecast the force among pedestrians, which is a major factor leading to fatalities in crush events (Zhang, 2013). Moreover, Smith and Lim investigated crowd pressure against crush barriers, identifying discomfort thresholds exceeded by current spacing recommendations by the Green Guide (*Guide to Safety at Sports Grounds*, 2018) . Their research suggests flat barriers are more comfortable, and exploring alternative designs with reduced spacing could significantly improve spectator experience, especially during moments of heightened excitement (Smith & Lim, 1995). The evacuation time and response rate can be improved by increasing the percentage of agents with greater knowledge of the arena and by increasing the crowd density, although the average evacuation time may be slower with higher density (Abu-Bakar et al., 2017).

Evacuating an arena with high local density poses several challenges. The design of outdoor spaces, which were not originally intended for safe evacuation, can make the process complex. The interaction among pedestrians and the space design can create high density conditions, especially at bottleneck points, despite controlled densities in other areas (Peterson & Jonsson, 2018). Modelling tools designed for low to middle density scenarios may not be suitable for high and extreme density scenarios, requiring evaluation (Abu-Bakar et al., 2017). Understanding crowd dynamics in high density conditions is crucial for safe crowd management (Ali & Shah, 2008). Additionally, the pressure increase among pedestrians in high density scenarios can lead to fatalities in crush events. These challenges highlight the need for reliable simulation models, data collection, and understanding of crowd behavior to optimize evacuation strategies and ensure safety.

2.4.2 Current Challenges with Evacuation Modeling in Arena

Evacuating arenas presents several challenges. One challenge is the need for sufficient space outside the arena for crowd accumulation during emergencies such as fires or terrorist threats (Minegishi, 2023). Another challenge is the potential for overcrowding, which can result in casualties and issues with comfort along with safety (Liang et al., 2020). The complexity of the scenario is another challenge, the diversity of individuals and the environment, and the lack of direct evidence. Different outcomes can be analyzed using evacuation modeling and simulation, however, it can be difficult to include various aspect categories in a single modeling space (Zia & Ferscha, 2020).

To overcome these challenges, it is important to consider factors such as stadium exit layout, circulation planning, and the deployment of guiding staff (Wang, 2017) . Simulation models and software can be used to predict population behaviors and optimize evacuation plans. By analyzing evacuation characteristics, identifying problems, and making modifications, designers can better evaluate the safety and reliability of stadium fire protection designs. Overall, a combination of proper planning and crowd control measures can help ensure efficient and safe evacuations in arenas.

2.4.3 Evacuation Management Through Evacuation Modeling

Evacuation simulations can be used to inform evacuation management by providing insights into the effectiveness of evacuation procedures and the impact of various factors on evacuation outcomes. These simulations can incorporate governance strategies, agent-based models, and social force theory to model human behavior during disasters (Abu Bakar et al., 2023). By conducting simulations, emergency management plans can be developed and tested, allowing for the identification of the best evacuation routes and strategies to minimize evacuation time (Üreden et al., 2023). Additionally, the integration of intelligent models, such as the Conscious Movement Model (CMM), into simulation frameworks can produce realistic outcomes and improve the accuracy of evacuation simulations (Bin Othman & Tan, 2022). Furthermore, simulations can consider traffic conditions and help in the planning of evacuation paths, optimizing traffic control measures, and identifying bottlenecks in the road network (Xu et al., 2022). Evacuation simulations are crucial for effective evacuation management. They help authorities prepare for emergencies and mitigate disastrous outcomes. Simulations can be used to study events, create emergency management plans, and evaluate the effectiveness of evacuation plans. By incorporating intelligence in Multi-Agent Systems (MAS) and using data-driven machine learning models, simulations can produce realistic outcomes and perform better than traditional methods (Abu Bakar et al., 2023). The integration of trained models, such as the Conscious Movement Model (CMM), into simulation frameworks can further enhance the realism of evacuation simulations (Bin Othman & Tan, 2022). Additionally, the automated generation of simulation models, like EURASIM, enables the evaluation of evacuation plans in urban areas and serves as a testbed for the development of better solutions (Xu et al., 2022). These practices in using evacuation simulations contribute to effective emergency preparedness and disaster management. Overall, evacuation simulations provide valuable information for policymakers and practitioners to enhance the effectiveness of evacuation procedures and improve disaster management and emergency response.

2.5 Summary of Literature Review

Evacuation safety in arenas is a crucial concern due to the large number of people they host during events, posing significant challenges during emergencies like fires. Experimental research underscores the significance of crowd management, evacuation strategies, and safety measures in arenas and stadiums, emphasizing factors such as crowd density, walking speed, route choices, and crowd composition. Safety standards and guidelines vary across countries, reflecting unique regulatory frameworks and cultural practices, necessitating ongoing research to ensure compliance and improve evacuation procedures. Accurate estimation of crowd density is crucial for effective crowd management and evacuation planning. While existing safety regulations typically focus on global density metrics, there is a growing recognition of the importance of assessing local densities in evacuation planning.

Current research and methodologies in evacuation safety emphasize the importance of optimizing space planning decisions, utilizing simulation models, considering crowd dynamics, and implementing safety measures to ensure efficient and safe evacuations. Strategies such as density navigation algorithms, simulation models, timed schedules, and architectural layouts are employed to address evacuation challenges, particularly in high-density arenas. To improve evacuation safety, implementing strategies like AI- based analysis, real-time occupancy tracking, and digital twin modeling can be useful. Evacuation data from various studies provide valuable insights into evacuation safety in arenas and can inform evacuation planning and design.

Evacuation simulations offer valuable insights into optimizing evacuation routes, identifying bottlenecks, and evaluating the effectiveness of evacuation strategies, demonstrating the importance of considering factors such as stadium design, and crowd behavior. Still their applicability to be used to calculate the local density for three-dimensional arena spaces where merging flows occur is not verified yet. But still it is effective for two-dimensional problems related to evacuation from arenas.

Overall, this review highlights the critical need for ongoing research and analysis to enhance evacuation safety in arenas and sports facilities. By integrating insights from experimental studies, standards, density estimations, and evacuation modeling, stakeholders can develop more robust safety protocols and emergency response plans tailored to the unique characteristics of each venue. This approach is essential for ensuring the safety and well-being of spectators and participants during events, contributing to a safer and more secure environment for all.

3. Density Estimation Method and Application

3.1 Simple Method to Estimate Local Density

This section is about the methodology developed in determining the local density of the critical parts of arenas like the merging flow at stands and the gates as shown in Figure 3. It is expected that these areas will have high densities (when used at full capacity) which will limit the flow of people and possibly lead to congestions. Moreover, the limited space available to spectators, combined with the possible inability to overtake others, significantly affects queuing time and overall evacuation efficiency. This will reflect on the overall evacuation time.

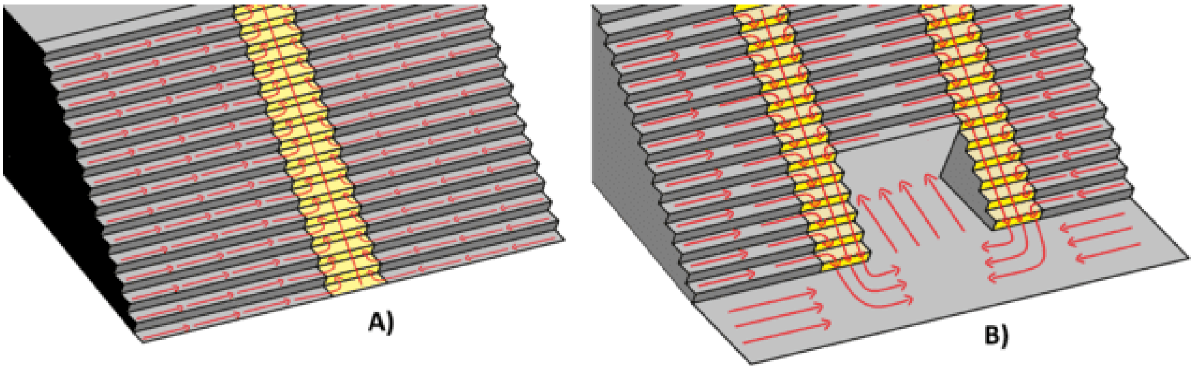

Figure 3 Merging point at the stands B) Merging point at the gates.

3.2 Manual Estimation of Crowd Density

Most of the current tools for evacuation simulation have been created and implemented using 2D calculations which can then be visualized in 3D. However, many of the egress components (and people) in arenas are natively occupying a 3D space (e.g. arena stands). In 2D, pedestrian movement on stairs is often calculated based on 2.5D sloped surface, allowing each location on the surface to have a single elevation or z-value per x, y coordinate. This approach has been adopted in various simulation software packages (R. Xie et al., 2022). However, this approach fails to capture the complexities of the motion of people and behaviors such as stepping on stairs on any 3D elements in the space, which significantly impact crowd movements and behaviors.

The 2D representation may not be entirely accurate, as pedestrians in reality tend to stand perpendicular to the horizontal plane of the stairs' steps, not on the sloped surface which will have an impact on calculating the local density. Therefore, a stair, including its flights and landings, is better represented as a 3D surface that can store multiple z-values per x, y coordinate.

To be able to capture the motions in 3D spaces, and hence the crowd density, a 3D view approach can be used. A proposed method for measuring crowd density in 3D spaces is by counting the number of people in a certain control volume where the area is known. In the present example, real world data (e.g. from video cameras) are used to demonstrate the approach. The method involves using control volumes for sections of interest, such as an entire stair or a row of seats. As the dimensions of the arena is known, if the amount of people on that area can be obtained (e.g. from camera recordings), the local density can be calculated.

This simple method can be shown in Figure 4 where hypothetical people locations were assumed. The camera should then be set at a point able to give a clear view, the camera can be perpendicular to the inclinations of the stands to be able to capture the 3D movement especially at high local density. The amount of people on the stands and the stairs will be counted and divided over the area to get the local density for the stands and the stairs at different time steps.

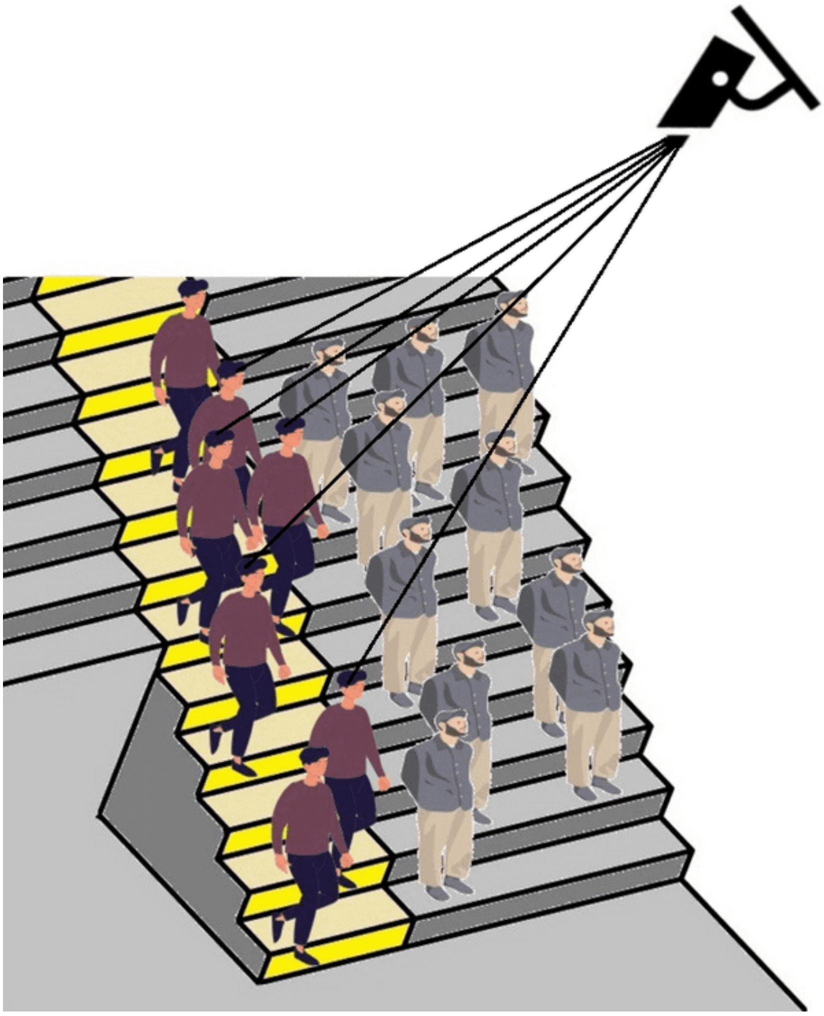

Figure 4 Illustration of the method.

The local density can be calculated by tracking the flows in and out the control volume at any time step (Figure 5), this can be done by tracking through the video recording or by using other types of sensors. The following equation can be used to calculate the local density at any time step.

$$\boldsymbol{Local\ Density} = \frac{\sum \boldsymbol{Flow\ in} - \sum \boldsymbol{Flow\ out}}{\boldsymbol{Total\ area\ of\ the\ control\ volume}}$$

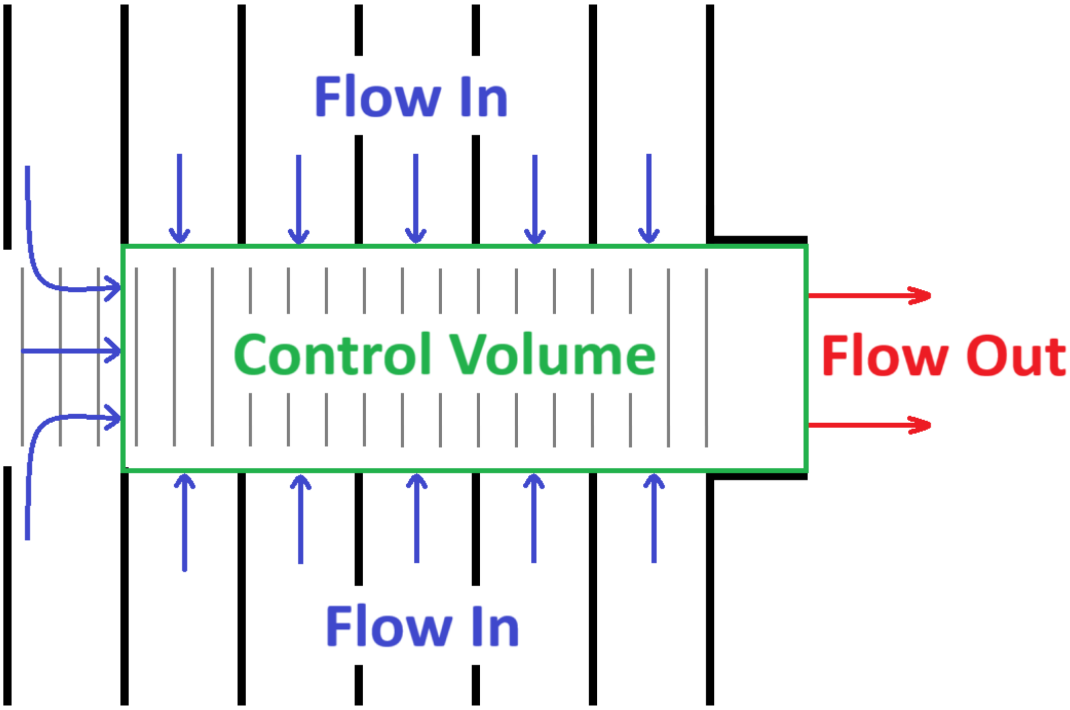

Figure 5 Example of the control volume method.

The proposed method is here exemplified with real-world data from the pedestrian dynamic data archive by The Research center in Julich (Forschungszentrum Jülich et al., 2005). This data was collected at the ESPRIT arena in Düsseldorf, Germany, with a capacity of 60,000 individuals. Figure 6 shows screenshots from the evacuation experiment in the arena before and after moving.

Data was collected at the gate of the arena, where all escape routes of the stand (including stairs) leading to the 2.4 m wide mouth hole are 1.2 m wide. The passage width in the rows of seats is 0.6 m. All the dimensions are illustrated in Figure 6.

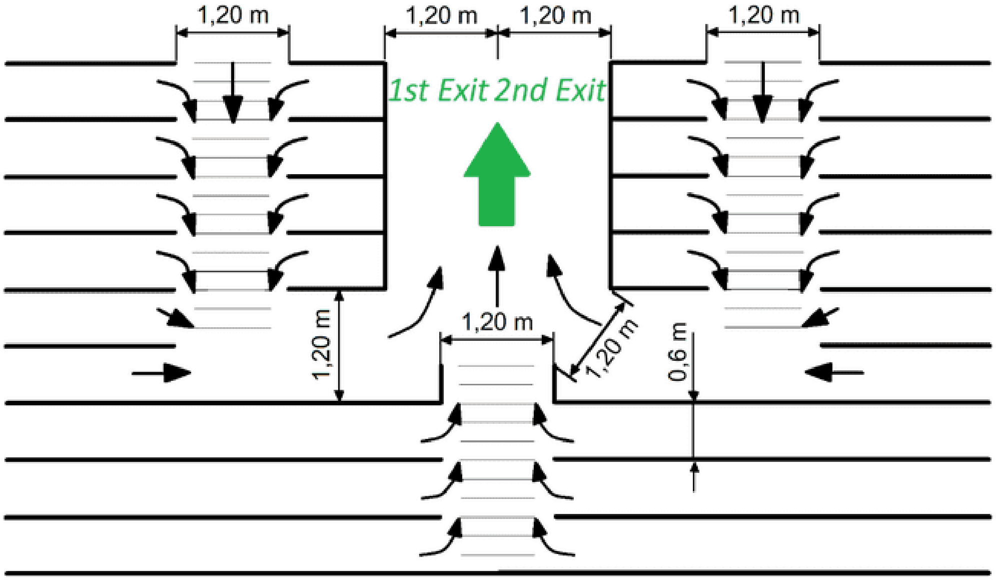

Figure 6 The dimensions of the arena. Redrawn from (Burghardt, 2013).

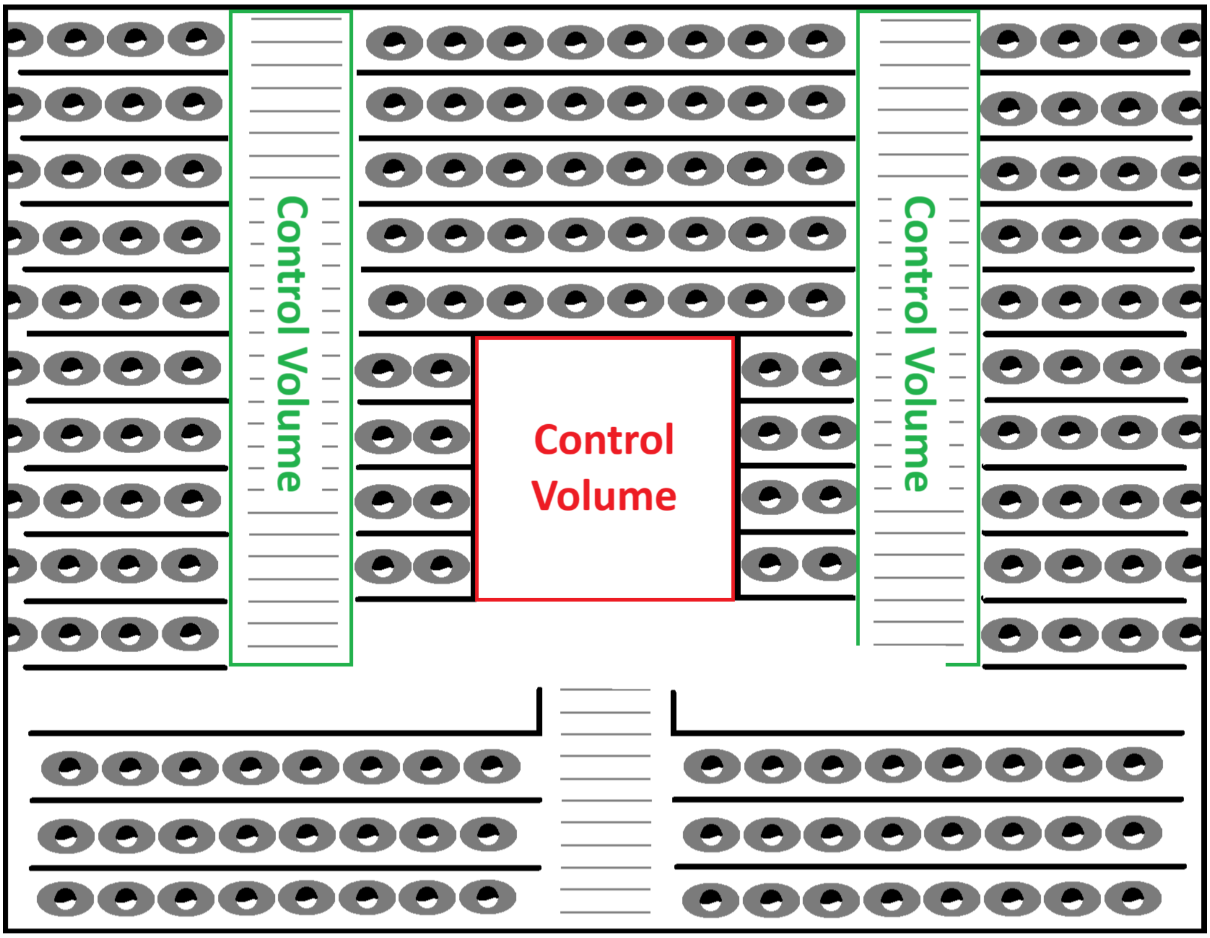

Figure 7 The setup of the experiment.

3.2.1 Local Density for Stairs and Gates

The video footage for different evacuations is used to calculate the local density at the stands and stairs for different number of people (i.e. 100 or 300 persons) and different area of interest (i.e. at the stands, stairs, and the gate). The density is measured by counting the number of people in a certain control volume manually from the video every 5 seconds. The width of the stairs and the stands is 1.2 m and 0.6 m respectively. The control volumes are shown in Figure 7. The local density and the flow are measured for the following scenarios. Figure 7 shows simple drawings for the part of the arena during the evacuation.

A) 50 persons merging at the stairs.

B) 100 persons merging at the stairs.

C) 300 persons merging at the stairs.

D) 300 persons merging at the gate with 2 doors open.

E) 300 persons merging at the gate with 1 door open.

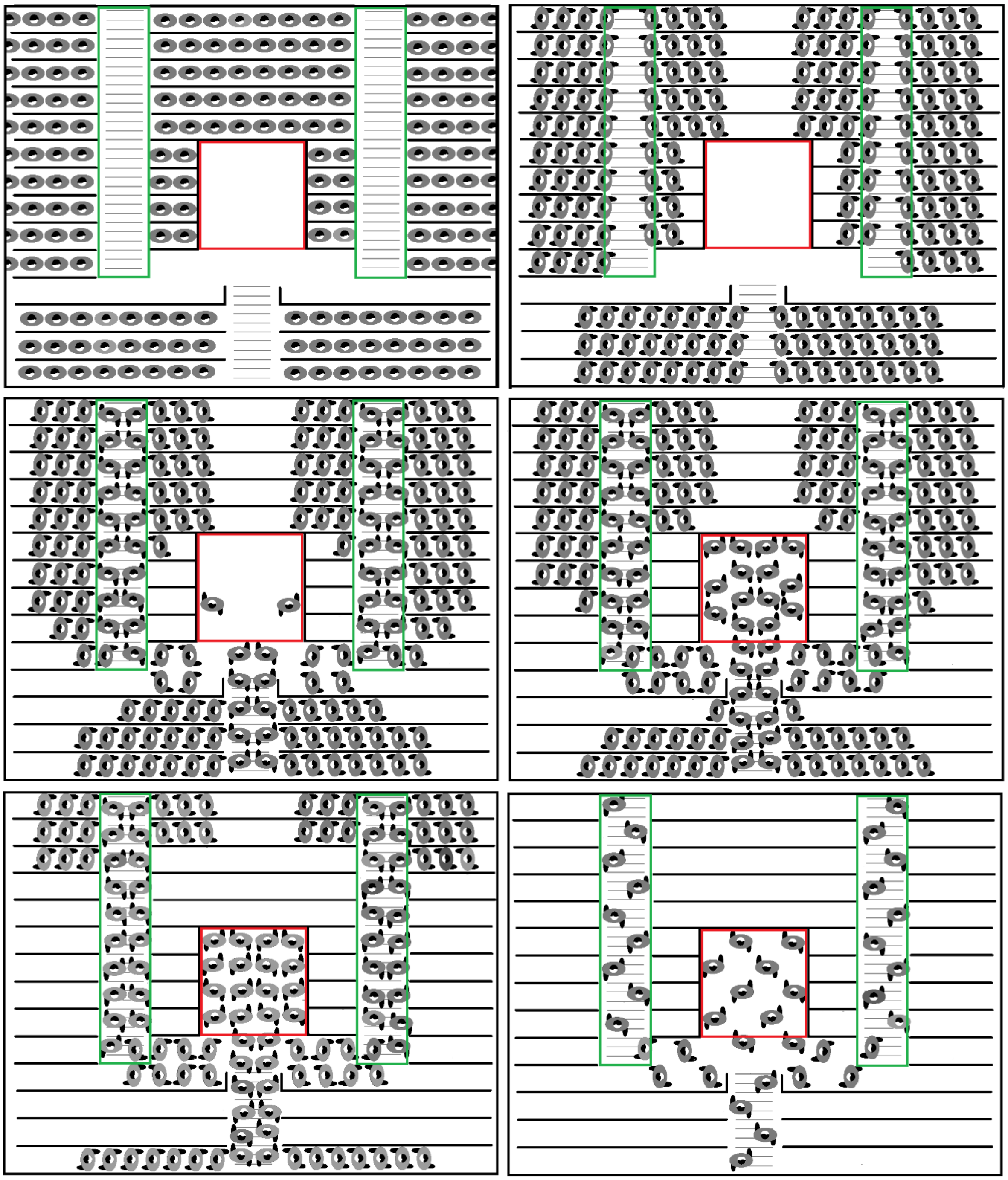

Figure 8 Schematic representation of the evacuation process.

3.3 Evacuation Modeling

For simulating large populations with high density, selecting the appropriate evacuation model is crucial. Some of the existing crowd models may prioritize low computational cost, such as coarse network models (Bellomo & Dogbé, 2008) and cellular automata model (Bandini et al., 2011). However, for high local density scenarios, continuous models seem more suitable, as they would allow local density predictions without being affected by the network assumptions (Ronchi & Nilsson, 2016). This study involves conducting a series of simulations using Pathfinder (Thunderhead Engineering., 2014), chosen because it is a widely used agent-based continuous model (Lovreglio et al., 2020). Pathfinder has been chosen as a viable option for the simulation, since it has the feature that the agent body size can gets reduced to move through narrow geometry. The evacuation modelling market includes several other continuous models which could have been used as well (Lovreglio et al., 2020).

3.3.1 Pathfinder

Pathfinder, developed by Thunderhead Engineering, is an agent-based egress simulator used for modeling pedestrian movement, evacuation scenarios, and crowd management. It simulates individual occupants' behavior within a given space and it models human behavior (Thunderhead Engineering, 2023).

Pathfinder software serves in this case as an agent-based egress simulator focusing on evacuation behavior. Operating as a continuous model, it accommodates individuals of varying size and facilitates their movement within a coordinate system instead of a grid (Ronchi & Nilsson, 2016). It employs steering behaviors which account for crowd movement and physical constraints (Reynolds, 1999). It provides two primary options for occupant motion, SFPE mode and Steering mode. The simulator has here been used adopting its default steering mode.

In steering mode, Pathfinder uses a combination of steering mechanisms and collision handling to control how the occupant follows their seek curve. These mechanisms allow the occupant to deviate from the path while still heading in the correct direction toward their goal (Thunderhead Engineering, 2023). The speed on stairs may either be left at the SFPE default or may be user-defined in the occupant profile as piece-wise linear functions.

Pathfinder estimates the density by using the spacing of the near occupants and the average longitudinal and lateral spacing density relationship demonstrated in Chapter 3 of Pedestrian planning and design book (Fruin, J.J. & G.R. Strakosch., 1987) as shown in Figure 9. The density lines in the figure are treated as contours, each being estimated as an ellipse (Thunderhead Engineering, 2023).

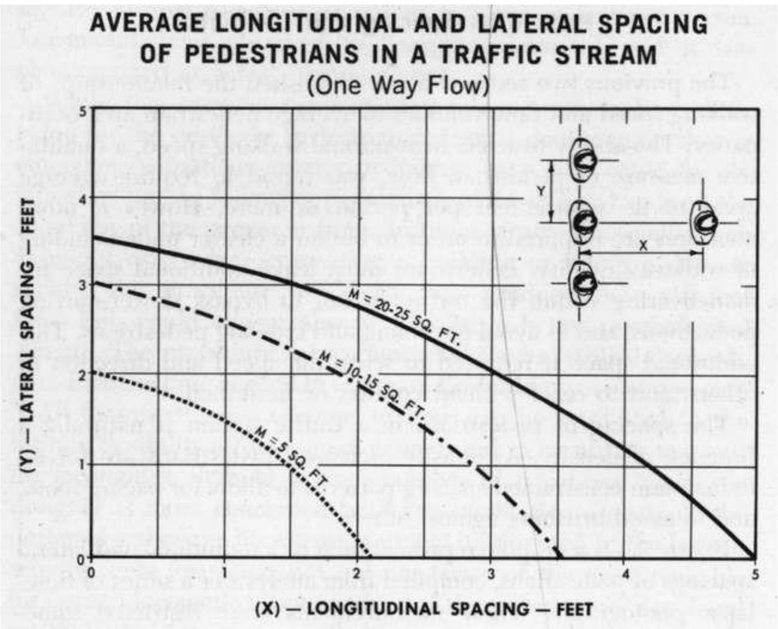

Figure 9 Average Longitudinal and Lateral Spacing of Pedestrians in a Traffic System (Figure 3.4 of Fruin's book on pedestrian planning and design)

When the "Measurement Region" function is used in Pathfinder, the calculation of density and velocity in those regions uses an implementation of Steffen and Seyfried's Voronoi diagram-based method (Steffen & Seyfried, 2010). This method was explained earlier in section 2.2.

3.3.2 Agent Characteristics

When simulating pedestrian movement, considering the characteristics of the people (agents) is crucial, especially when studying crowd density. Factors like body size and walking speed significantly impact the results. Different populations, like children, adults, and elderly people, have varying body sizes and walking speeds. Adjusting these parameters in simulations allows for more realistic scenarios. Real-world data collected from a stadium in Canada, detailed in Table 5, presents the percentage distribution of each demographic profile and their walking speeds, modeled as a normal distribution(Chin et al., 2022).

Table 5 Walking speed and body size for different profiles.

		Walking Speed (m/s) (Chin et al., 2022)					Body size (m) (Korhonen & Hostikka, 2021)	
Profile	%	Max	Min	Mean	Median	Std Dev	Max	Min
Adult	77%	1.86	0.59	1.05	1	0.23	0.58	0.44
Elderly	12%	1.3	0.41	0.92	0.91	0.3	0.54	0.46
Child	11%	1.63	0.62	1.15	1	0.23	0.45	0.39

3.4 Modeling the Juelich Experiment

Pathfinder was used to model the experiment conducted by the research center in Julich (Forschungszentrum Jülich et al., 2005) involving 300 persons (assumed to be adults). The agent characteristics in Table 5 were used. To minimize fluctuations in the data, measurements were recorded every 5-second interval. The model geometry replicated a section of the ESPRIT arena in Düsseldorf (Figure 10).

Figure 10 Part of the ESPRIT arena.

3.5 Case Study

A case study of an arena has been identified. This is the Pala Alpitour Arena (see Figure 11), and it is a multi-purpose indoor arena located within the Olympic Park in the Santa Rita district of Turin, Italy. This arena has been chosen as it is a large indoor arena (the largest in Italy) with a capacity of around 12,500 persons, and it is expected to have high local densities.

Pathfinder was used to model a series of evacuation. The arena consists of 8 stand sections. Sections are divided into four upper and four lower, and the capacities of the stands are illustrated in Table 6. Those capacities are hypothetical assumed and other capacities may be used according to the event and number or seats available. The arena has also various amount of vomitories, which number of 3 to 6 for different stands.

Figure 11 The Pala Alpitour Arena (Wikipedia contributors, 2024)

Table 6 The assumed capacity of the arena for its sections.

Stand	Capacity
Upper West	1800
Lower West	1965
Upper East	1800
Lower East	1965
Upper North	1300
Lower North	1185
Upper South	1300
Lower South	1185
Total	12500

4. Results

This section presents the findings from the experiments as follows:

- Results for the small-scale experiment using the control volume method.
- Results for the small-scale experiment using an evacuation modeling tool.

The results from both small-scale experiments will be compared to verify the applicability of using evacuation modeling tools for high local density scenarios in arenas. Finally,

- Results for the full-scale case study using an evacuation modeling tool.

4.1 Results for the small-scale experiment using the control volume method.

The local density at the stairs and gates was calculated using the control volume method on the area of interest. By analyzing video footage, the number of people within the control volume, as well as the inflow and outflow, was determined manually.

Figure 12 presents the local densities observed at various locations within the venue as the number of individuals increases. Initially, with 50 persons present, the local density at the stands was approximately 3.25 persons per square meter. As individuals began to move towards the stairs, the density at the stairs increased to around 3 persons per square meter, while the density at the stands gradually decreased to zero due to the movement. This transition occurred smoothly due to the low number of people and continuous movement.

As the crowd size increased to 100 persons, the local density at the stands initially rose to 4.2 persons per square meter before decreasing as more individuals moved towards the stairs, resulting in a density of around 3.5 persons per square meter at the stairs. Although the movement speed was slightly affected, it remained relatively steady. However, with 300 persons present, the local density at the stairs significantly increased to around 4 persons per square meter, causing movement to slow down and eventually stop at certain points due to overcrowding.

Notably, the number of available doors at the gate also influenced local density, with a lower density of 3.5 persons per square meter observed when two doors were available, compared to 4.5 persons per square meter when only one door was accessible. Gate density can be higher than the stairs density because individuals stand closer together and require less space to move through a flat opening compared to stairs, where navigating steps requires more space around each person for leg movement and balance. These findings highlight the critical impact of crowd size and configuration on local densities and movement dynamics within crowded 3D environments.

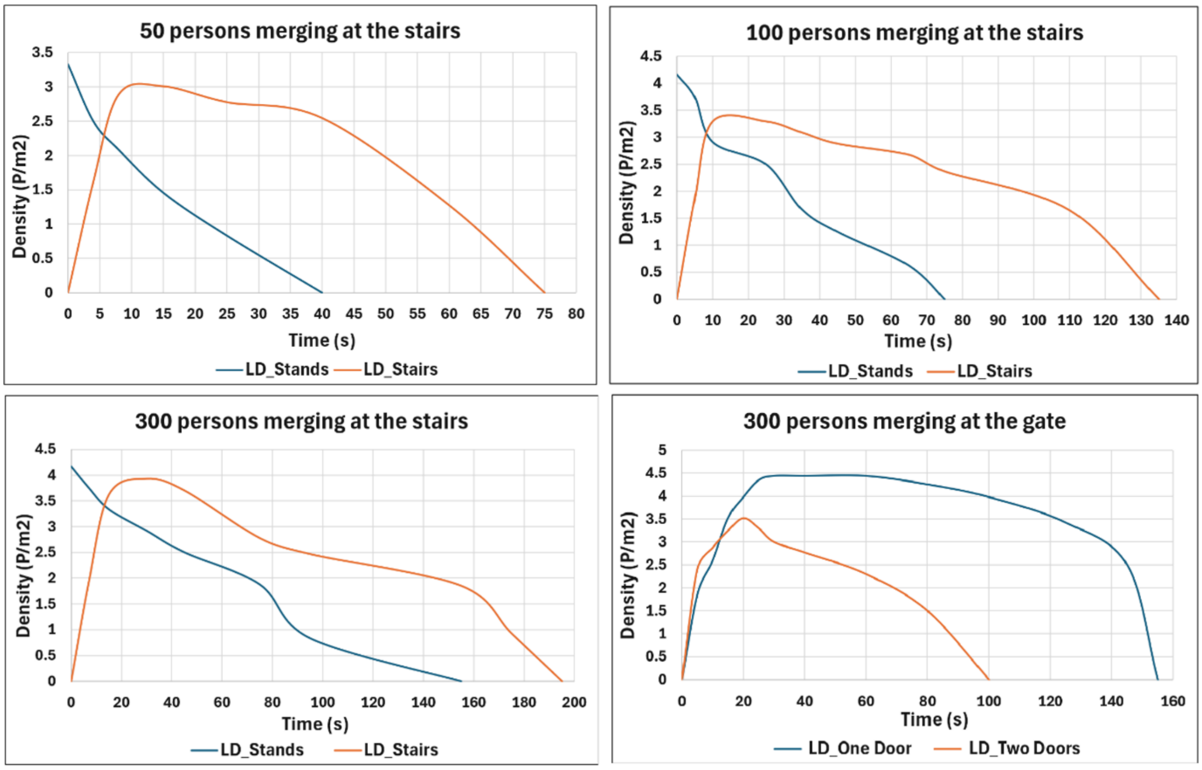

Figure 12 Local density for different parts of the arena with different amount of people.

Figure 13 illustrates the flow into the stairs from the stands (inflow) and the flow out from the stairs to the lower level (outflow). Initially, the stairs are empty, and people in the seats directly adjacent to the stairs have immediate access. This leads to a high initial inflow rate. However, as people progress along the stairs, the outflow is constrained by the limited width of the stairs. Consequently, there is an accumulation of density at the stairs, resulting from the inflow exceeding the outflow, leading to a significant reduction in the inflow to the stairs. Meanwhile, the outflow remains relatively constant due to the structural constraints imposed by the narrow width of the stairs.

The highest flow rate into the stairs is observed when 300 persons are present, and as many people have direct access to the stairs, the initial inflow reaches up to 20 people per second. However, the outflow is restricted to as low as 2 persons per second. Similar patterns are observed for scenarios involving 100 and 50 persons, but with proportionally lower initial inflow rates. The outflow rate remains relatively constant in all scenarios.

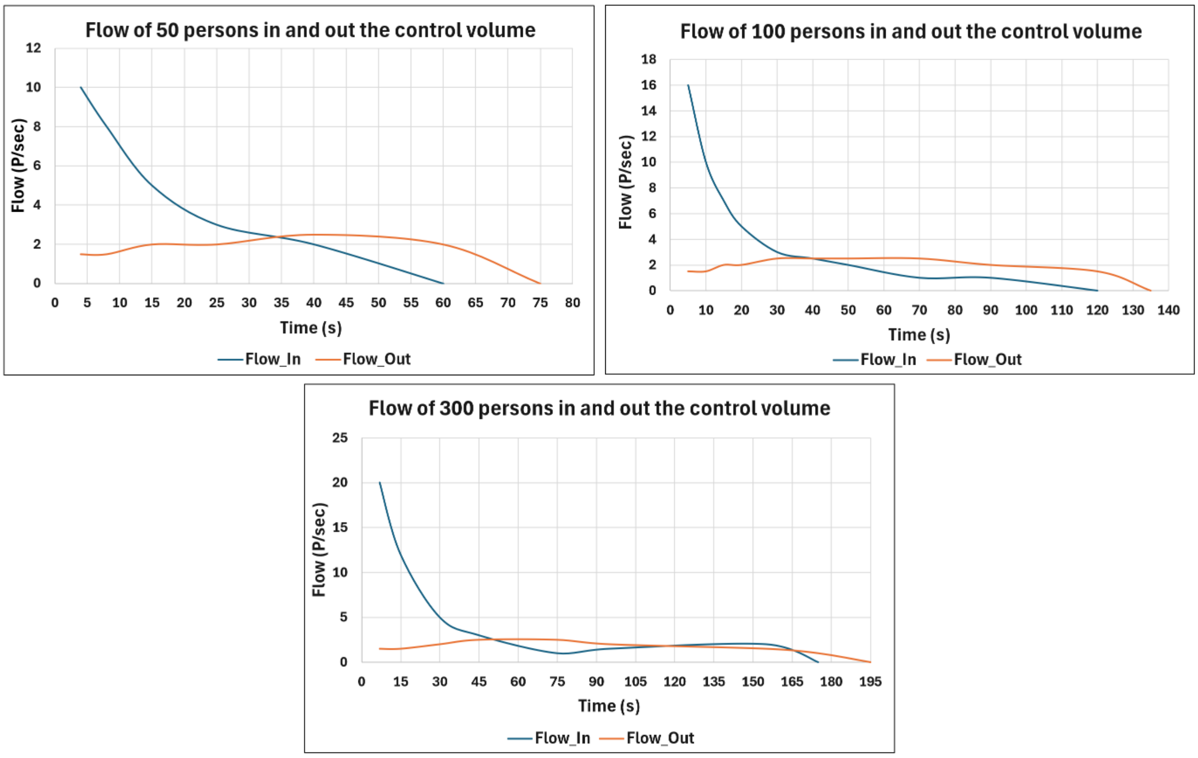

Figure 13 Inflow to the stairs and outflow for the stairs.

4.2 Results for the small-scale experiment using an evacuation modeling tool

The local density was obtained using Pathfinder for the same layout as the small-scale experiment. These outcomes were then compared to the results from the control volume method, as shown in Section 4.1, to evaluate the effectiveness of evacuation modeling tools in representing high local density scenarios in arenas.

Figure 14 shows the outflow rate from the stairs towards the exit gate, with a maximum value of approximately 1 person per second. However, Figure 13 showed that the actual outflow from the stairs was around 2 persons per second, while the inflow rates were almost similar in both scenarios. The maximum density at the stairs is around 3.2 persons per meter square, however, in the real-world scenario it is around 4 persons per meter square. The density in the real-world experiment dropped faster than the modeled results. The total evacuation time for the modeled results and the real-world data is 300 and 185 seconds respectively. This is mainly due to the lower flow out from the stairs in the modeled results.

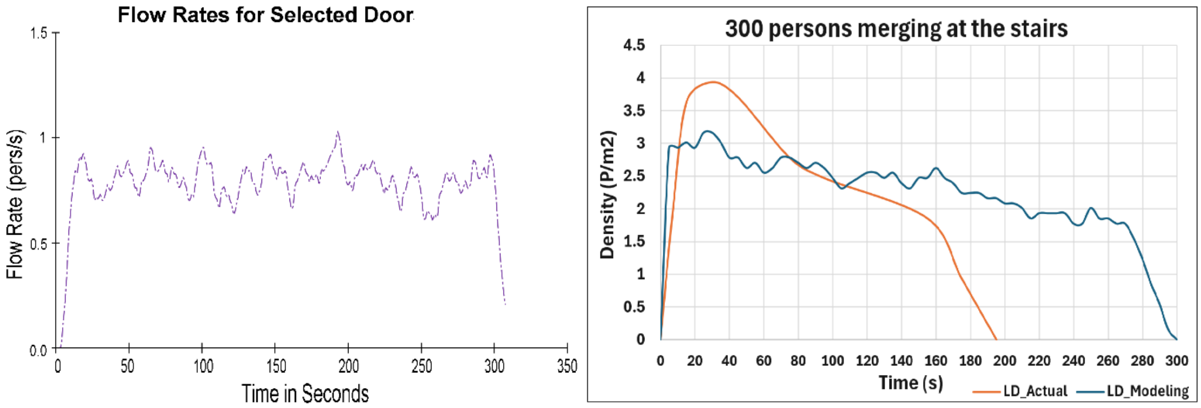

Figure 14 The out flow from the stairs to the exit gate (at the left) and the local density at the stairs for the actual and the modeling results (at the right).

While Pathfinder can reduce occupant diameter to account for navigating narrow spaces, the software would benefit from incorporating non-rigid body mechanics instead of relying on simplified circles to represent people. This is a common issue for all continuous models thus having non-rigid body in those models would enhance the model accuracy in reflecting real-world crowd behavior, especially in high-local density scenarios.

The flow of people merging at the exit was simulated for scenarios with one and two doors available (Figure 15). A measurement region was established at this location, and the density of people within this area was calculated and plotted in Figure 16. When the modeling result is compared with the real-world results in Figure 12, it is clear that the local density is higher in the real-world results than the modeling one. In the modeling the highest density was around 2.9 and 1.8 persons per meter square for one door and two doors available respectively. On the other hand, for the real-world data, the highest density was around 4.5 and 3.5 persons per meter square for one door and two doors available respectively. This is mainly due to the lower outflow from the stairs (which is the inflow to the gate) in the modeling case compared to the real-world data.

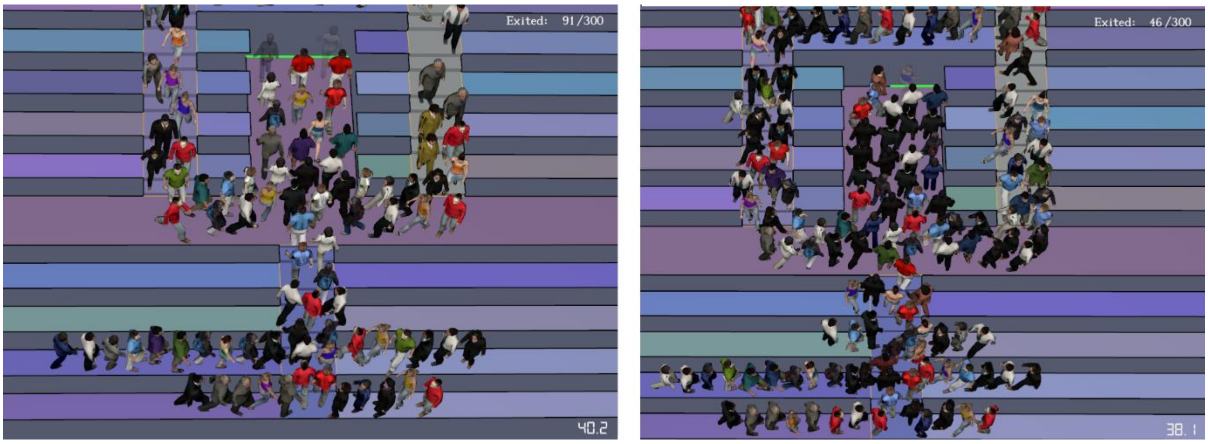

Figure 15 The flow of people merging at the exit with 2 doors available (on the left) and only one door available (on the right)

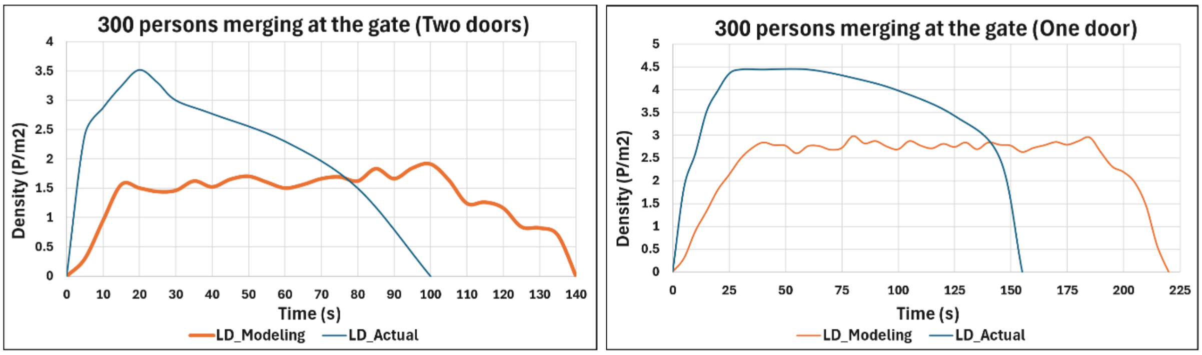

Figure 16 Local density at the gate for one and two doors available for the actual and the modeling results.

4.3 Results for the full-scale case study using an evacuation modeling tool

The case study was modeled at full capacity to assess the impact of maximum occupancy compared to the previous case with only 300 persons. The full-capacity scenario was simulated using the agent characteristics detailed in Table 5 and the steering model. To minimize data fluctuations, measurements were recorded at 5-second intervals. Given the arena's symmetry, the simulation was run for both the North and East sides. Measurement regions were selected at various stair locations, as shown in Figure 17. All stairs had a width of 1.2 meters, which is expected to limit flow, while gate widths were approximately 7 meters for the lower part of the arena and 4 meters for the upper part, allowing free flow.

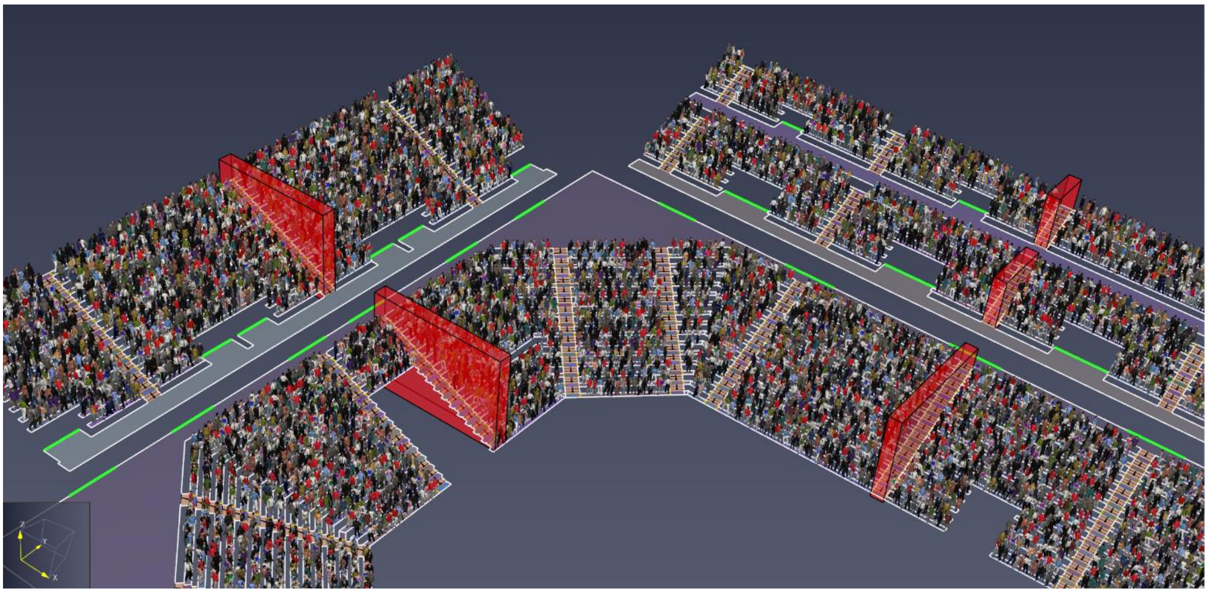

Figure 17 The full capacity of the North and East sides of the arena with measurement regions in red.

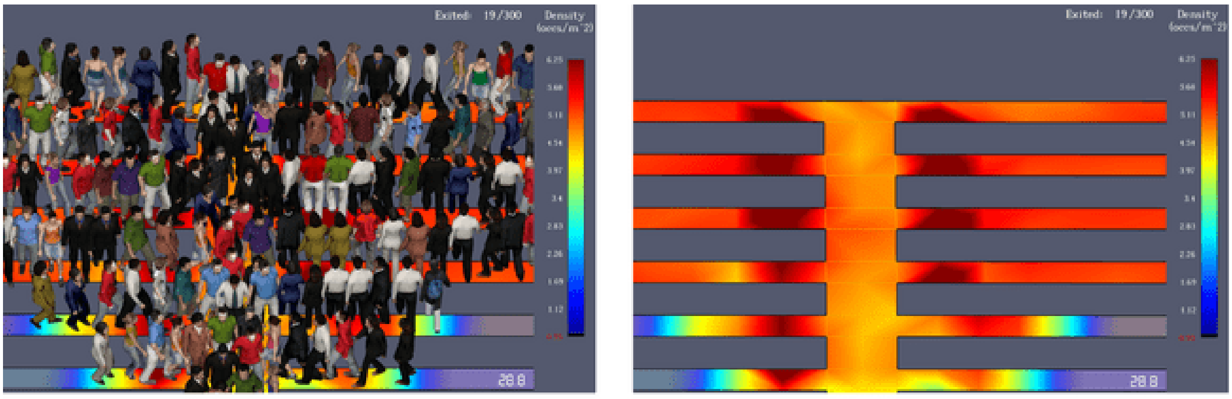

Figure 18 The local density at the stairs calculated by Pathfinder.

As mentioned in the previous section, evacuation simulators generally perform calculations assuming human bodies in 2D, while pedestrian movement on stairs is often calculated based on 2.5D sloped surface, allowing each location on the surface to have a single elevation or z-value per x, y coordinate. This representation has some limitations, as pedestrians in reality tend to stand perpendicular to the horizontal plane of the stairs' steps, not on the sloped surface which could possibly have an impact on calculating the local density.

The density of the stairs using the measurement regions is illustrated in Figure 19 calculated by the Voronoi diagram-based method. According to the Pathfinder's technical guide, occupants whose location is up to 1.41 meters outside the measurement region will contribute to the measurement, but more distant agents will be ignored (Thunderhead Engineering, 2023). This means that people in the stands just close to the stairs were involved in calculations. Higher densities (around 4 people/m²) are observed in the lower East and upper North due to the presence of more stands and people merging from two sides. In contrast, the lower North has a lower density (3.7 people/m²) as people enter from one side only. The upper East has the lowest density (3.4 people/m²) due to fewer stands. When 300 persons were simulated in the previous section the maximum density was around 4 persons per square meter. However, when a full scale is run with 12500 persons, it was expected to get a density of more than 4 persons per square meter. But the density didn't exceed that value which is mainly because of body representation in Pathfinder (i.e. 2D representation and using rigid bodies).

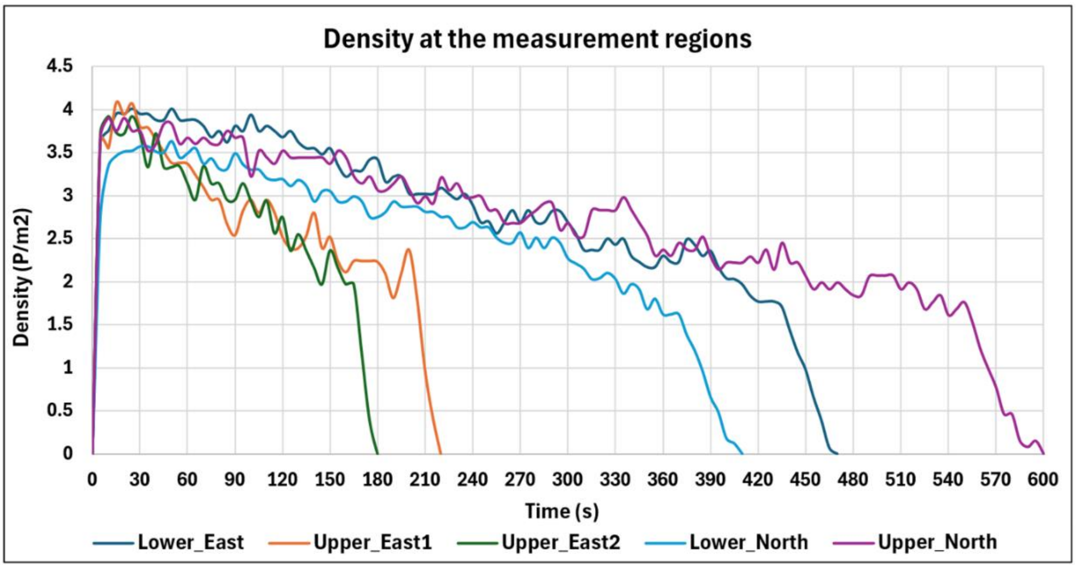

Figure 19 Local density at the stairs.

To check the consistency of the results, the simulation is run 10 times and the results for the Lower East and Lower North are plotted in Figure 20 and Figure 21 respectively. The results are overall consistent since this is a flow-dominated scenario. The approach in use is very simple, while a quantitative approach to quantify convergence associated with behavioral uncertainty is generally needed (Ronchi et al., 2014) .

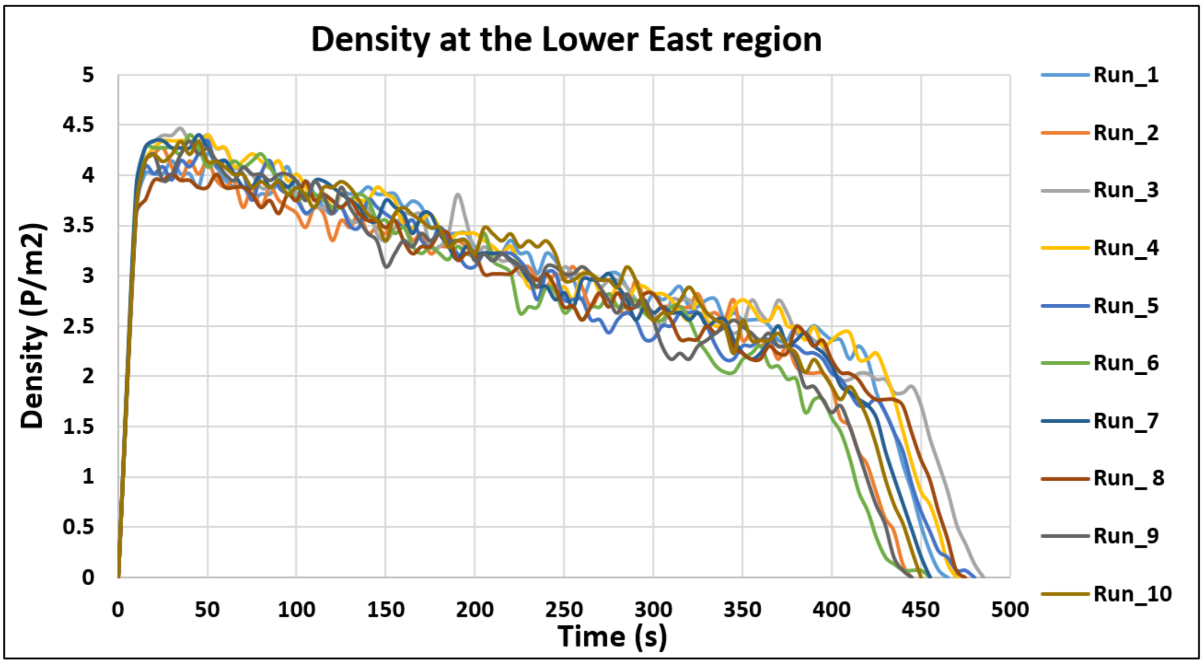

Figure 20 Densities at the Lower East region using Monte Carlo method.

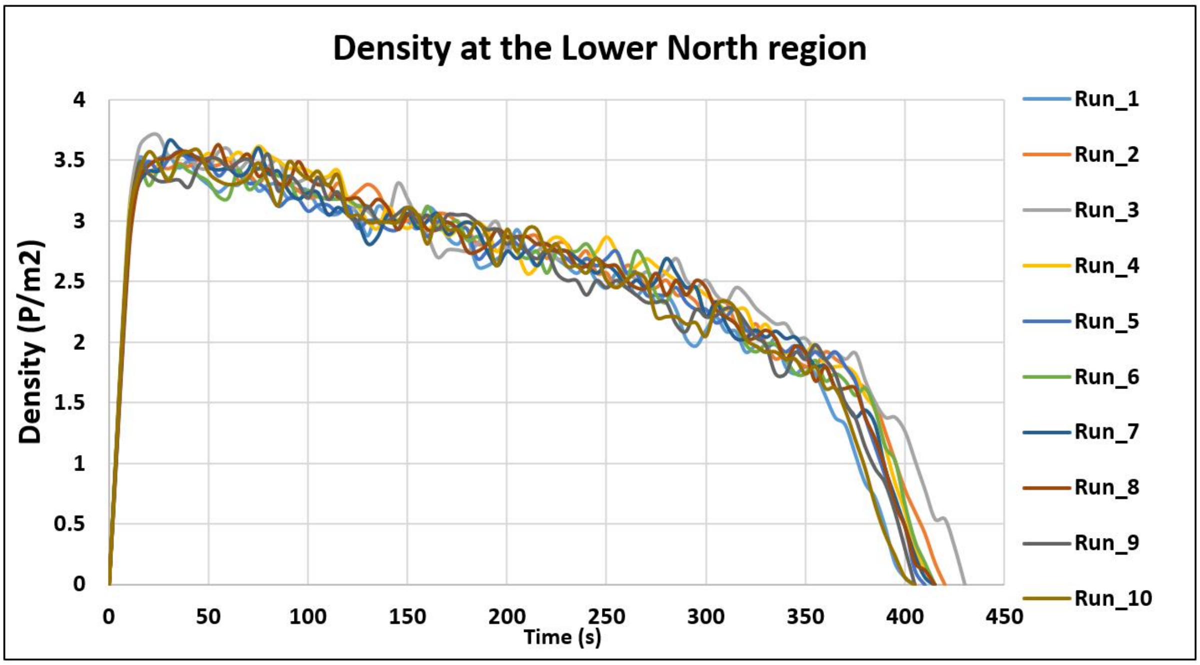

Figure 21 Densities at the Lower North region using Monte Carlo method.

5.Discussion

Controlling crowd congestion on sports grounds is essential to ensure the safety and comfort of spectators. Overcrowding can lead to accidents, such as crowd crushes, resulting in injuries or fatalities, as evidenced by historical incidents like those in the 1960s and 1970s (Feliciani et al., 2023). To address this, various guidelines, such as the 'Green Guide,' have been implemented to enhance safety measures on sports grounds (Guide to Safety at Sports Grounds, 2018). Evacuating arenas and sports grounds present several challenges due to the limited space available to spectators, combined with the possible inability to overtake others, significantly affecting queuing time and overall evacuation efficiency. This, in turn, is expected to result in high densities along evacuation routes and exits when used at full capacity, potentially leading to congestion and restricting the flow of people.

Effective crowd management requires consideration not only of the global density but also of the local density. Local density focuses on how crowded or congested routes or exits become as people move toward the exit. This is important for key three-dimensional arena spaces where merging flows occur during emergency evacuations. The hydraulic model (Gwynne & Rosenbaum, 2016) may not be suitable for representing high-local density scenarios. As this model assumes a design curve where crowd movement stops at a specific density level. In reality, people may still be able to move even at high densities (Lohner et al., 2018). However, studying local crowd density in arenas can be done by estimating it through simple control volume methods and simulating them using an appropriate evacuation model.

The simple control volume method is applied on a small-scale test. The local densities and the flows are obtained. Those results from the real-world data are compared to the modeling results for the same layout of the test. The modeling results showed relatively lower values compared to the real-world result particularly in terms of flow and density at the merging points of stairs and gates. The modeled outflow from the stairs was lower than observed in reality, affecting both stair density and evacuation time. Additionally, the reduced outflow from the stairs resulted in lower inflow at the gates, decreasing gate density compared to real-world data. This might be due to how occupant is represented in the model and the use of default settings adopted by the model. Increasing the width of the vomitory and reducing the slope of the stairs can improve evacuation efficiency (Liu et al., 2014).

Evacuation modeling relies heavily on calibrated data, such as body size and walking speed, to accurately represent crowd behavior. Developers typically aim for a balance between model simplicity and realistic evacuee characteristics. To ensure the credibility of simulations under various conditions, they often use conservative default values (Gwynne et al., 2015). While these defaults guarantee credible scenarios, they might underestimate evacuation efficiency. Ideally, incorporating accurate and up-to-date data would lead to more realistic simulations. However, obtaining such data can be challenging. Factors like variations in body size across different populations (Pheasant, 2002), age, gender, and physical condition (Spearpoint & MacLennan, 2012) also influence evacuation due to changes in walking speed. These variations necessitate ongoing data collection and model updates to ensure accurate crowd management strategies.

Pathfinder is an agent-based egress simulator widely used for modeling pedestrian movement and evacuation scenarios. High density scenarios with complex 3D spaces, such as arenas may present challenges when relying solely on 2D simplifications of body size and rigid body representation. Calculating the density on sloped surfaces might not accurately reflect real-world conditions, as individuals primarily navigate the horizontal sections of stairs. There are several ongoing discussions into the best way of calculating densities (García et al., 2024), especially in stairs as some assumptions (e.g., using the sloped area of the stairs considering the same number of people), would lead to lower density estimations (R. Xie et al., 2022).

When applying the Voronoi diagram-based method to 3D elements such as stairs, adaptations are needed as this method is generally used for 2D surfaces (Voronoi, 1908). Adjustments must be made like modifying the shape of Voronoi cells to reflect the footprint of the space occupied on the stairs, considering both horizontal and vertical dimensions. Additionally, density calculations using the Voronoi method need to be adjusted to integrate the volume of the space occupied by each cell on the stairs. These adaptations ensure a more precise analysis of density and velocity distributions in environments with 3D elements like stairs.

Evacuation models like Pathfinder may reduce the occupant diameter to account for navigating narrow spaces. This is an artificial solution which is used to avoid occupants getting stuck, and currently represents one of the best available ways to solve this issue in existing crowd evacuation models. However, incorporating non-rigid body mechanics instead of simplistic circle representations could enhance the model's accuracy in simulating real-world crowd behavior, especially in high-local-density 3D scenarios(Cilenti et al., 2019).

The limitations of traditional approaches to evacuation modelling through 2D representations (e.g., representing the stairs as sloped surface) can be overcome with a simple control volume method for crowd density measurement. By counting individuals within defined control volumes or measuring flows in and out of the control volume, this method provides a simple approach to quantifying local density in critical arena areas. In real life monitoring the local density might be difficult. However, the control volume method provides a simple way to determine the local density in real life. As counting people and measuring the flows entering and leaving the control volume is straightforward. This method offers valuable insights into 3D movement, facilitating the development of effective crowd-management strategies in complex environments.

The findings from the case study conducted at the Pala Alpitour Arena showed a similar behavior like that in the real-world experiment. However, the estimation of local density is highly reliant on the assumptions adopted by the user (e.g. body size) and the model (rigid bodies for body representation) which is the reason why the highest local density was around 4p/m2.

The case study's representation of agents as individuals overlooks the reality that a significant portion of the attendees might arrive in groups. Group behavior significantly impacts crowd dynamics due to factors like social communication and spatial organization (Moussaïd et al., 2010). Social interactions within these groups influence crowd flow and behavior, with group walking patterns adapting to varying density levels.

Evacuation safety in arenas can be improved by providing safety stewards who can guide crowds to reduce congestion and counterflows, particularly at stairs. Additionally, increasing the width of stairs can improve crowd flow and reduce local density. The Stop-and-Go system can improve evacuation efficiency in arenas by adjusting crowd flow based on real-time density monitoring. When local density reaches critical levels at key points like stairs and exit gates (high-density merging points), stewards start to stop people. This allows the density to decrease before allowing further movement, preventing congestion and potential crowd-crush. Furthermore, during a fire scenario in an indoor arena, the Stop-and-Go system can be beneficial. By prioritizing the evacuation of people from higher levels before the smoke starts acclimating at the ceiling of the arena.

6.Conclusion

The evacuation of arenas and other sports grounds during emergencies presents a significant challenge due to the complex configurations and high local density at some elements. This thesis has explored various aspects of arena evacuation safety, focusing on methodology to identify local densities in 3D spaces during evacuations.

Through a literature review, this study has reviewed existing research and theories, highlighting the importance of considering local densities in evacuation planning. Traditional approaches often rely on global density, overlooking the intricacies of crowd behavior in critical areas of arenas. By developing a simple method for measuring local density in 3D, the overall safety of the evacuation process is improved.

The analysis of evacuation simulations revealed that knowledge of the population is critical for accurately representing flow and density at merging points such as stairs and gates. Evacuation models require information on population body size and initial speeds which may affect results and that may not be easily available to the model users. The implementation of a control volume method for 3D crowd density measurement offers a solution to overcome the challenge of traditional tools. Regardless of the technology in use for measuring the density in control volumes (from manual counting to automation), this method provides a simple approach to quantifying local density in critical areas in the arena, which in turn can allow for more effective crowd management strategies.

The findings from modeling the small-scale experiment and the case study conducted at the Pala Alpitour Arena provide valuable insights into the dynamics of crowd movement and evacuation in a real-world arena setting. By simulating evacuation scenarios at full capacity, this study focuses on the critical factors influencing evacuation dynamics, particularly in areas with high local densities.

In conclusion, this thesis investigated local crowd density in arenas, exploring two key approaches: estimating it through simple control volume method and simulating it with evacuation models. While the control volume method offers a practical assessment, current evacuation models have limitations with accurate density estimation due to limitations in representing human movement and body size and operating mostly through calculations performed in 2D. To address these limitations, the need for models that fully capture these complexities through 3D simulations is important as well as allowing for non-rigid bodies in high densities scenarios. This will help in realistically simulating high-density scenarios and ultimately leading to the development of more reliable evacuation models that improve evacuation safety in arenas.

7. Acknowledgement

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