Exit Configuration Effect on Evacuations at Outdoor Mass Gatherings

A Simulation-Based Study on Exit Clustering and Width at Danish Festivals

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Abstract:

The present master's thesis investigates the effect of exit configurations on evacuation performance in outdoor mass gatherings, using advanced agent-based simulation techniques. The study is inspired by safety and emergency preparedness in Danish festivals, which often attract large crowds in open-air environments. To this end, simulations are conducted using Pathfinder software to evaluate how exit width, placement, and clustering impact egress times and congestion levels. The response surface method is applied in order to formulate the egress time as a function of statistically significant exit confirmation parameters. The results indicate that while wider exits significantly reduce evacuation time, the optimal arrangement involves a balanced trade-off between exit width and the number of available exits. Exit clustering emerges as a critical factor, influencing crowd flow dynamics and the formation of bottlenecks. Practical recommendations for event organizers include optimizing exit placement and width to enhance evacuation efficiency while maintaining compliance with safety regulations. The findings underscore the importance of simulation-based analysis in improving the safety and operational planning of mass gatherings, with implications for policymakers and festival organizers in Denmark and beyond.

Contents

Preface

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Abbreviations and Terminology

Abbreviation	Meaning
ASET	Available Safe Egress Time
DEMA	Danish Emergency Management Agency
DOE	Design of Experiments
ECDC	European Centre for Disease Prevention and Control
EMS	Emergency Management Services
ET	Egress Time
EU	European Union
GUI	Graphical User Interface
IMO	International Maritime Guideline
LoS	Level of Service
NFPA 101	NFPA Life Safety Code
NIST	National Institute of Standards and Technology
PBL	Problem Based Learning
RSET	Required Safe Egress Time
RSM	Response Surface Method
SFPE	Society of Fire Protection Engineering
V&V	Verification and Validation

Terminology	Meaning
Beredskabsloven	Emergency Preparedness Act
Bottleneck	A (narrow) junction that hinders traffic flow
Bygningsreglementet	Danish Building Regulations
Congestion	A place too blocked or crowded, making movement difficult
Egress	Exit used for leaving the building
Hotspot	A place of significant activity or high density area
Occupants	People residing within the fenced event area
Politiloven	Police Act

Chapter 1

Introduction

Mass gatherings have become increasingly frequent and significantly larger in scale in today's globalized and urbanized world. From music festivals and sporting events to national celebrations, these events draw massive crowds and are often held in confined or fenced environments. This can create significant challenges even in regular scenarios, as safe and efficient egress from fenced areas can be difficult and slow, a situation the author has personally observed many times while participating in such events. This issue becomes even more critical during emergencies, where inadequate exit strategies can lead to tragic outcomes. As a Hungarian author, the 2006 Budapest fireworks disaster, where a sudden storm resulted in fatalities due to poor crowd management, stands out as a somber reminder of these risks [1]. Motivated by these personal observations and the broader relevance of this issue, this thesis focuses on evacuation scenarios in mass gatherings, with a determination to utilize advanced egress simulation tools. The selected tool was Pathfinder, and after a detailed review of available research in the domain, the research gap was identified as the effects of exit clustering on evacuation time. The study was therefore conducted with the aim of contributing to the existing literature. Specifically, it explores how different exit configurations, particularly exit clustering and width, affect evacuation performance in outdoor festival environments. The ultimate aim is to provide practical insight for event organizers, ensuring that mass gatherings, such as Danish festivals, can be safer and better prepared for emergencies.

Chapter 2

State of the Art

2.1 Evacuation of Mass Gatherings

The topic of mass gatherings has gained more and more attention in recent years due to the complex challenges they pose to safety, security, and emergency preparedness. Mass gatherings are often organized for various reasons, including cultural events like concerts and religious pilgrimages, as well as unplanned events triggered by natural disasters. Understanding the dynamics of these gatherings is important to ensure the safety of participants and optimize evacuation strategies in the event of emergencies [2][3]. The different types of mass gatherings have different characteristics, which necessitate tailored emergency management strategies that account for the specifics of the event and the crowd dynamics involved [4].

The impact of emergencies on mass gatherings can´t be underestimated, as they can lead to serious health risks, physical injuries, and deaths. After the pandemic, one of the common issues talked about in relation to mass gatherings is the rapid transmission of infectious diseases, especially in situations where large crowds are assembled in fenced, limited spaces. This has been particularly highlighted during pandemics, wherein the risk of transmission escalates during mass gatherings due to close contact among individuals [5]. Consequently, adequate public health measures, including vaccination and health monitoring, must be prioritized to mitigate the risk posed by these events [3].

The planning and logistical aspects of handling mass gatherings are also significant, particularly in relation to the provision of emergency medical services (EMS) and evacuation protocols. Effective communication and crowd management practices are essential to guiding attendees to safety during emergencies [6][7].

The physical layout of venues or fenced areas where mass gatherings occur plays a significant role in determining the effectiveness of evacuation efforts. Factors like exit locations, crowd density, and spatial design can significantly influence how quickly and efficiently the occupants can exit a venue or leave a fenced area during an emergency. Studies have examined scenarios where the architectural design of spaces affects pedestrian flow and can contribute to risks associated with overcrowding [8][9]. The design of evacuation pathways should thus prioritize safety alongside speed of exit [10]. This is going to be the direction in which this paper addresses mass gatherings.

The application of simulation and modeling has recently become increasingly available and popular in evaluating crowd dynamics and evacuation strategies in mass gatherings. These approaches allow for rigorous testing of different emergency response strategies, helping identify optimal paths for egress and assessing potential bottlenecks that may hinder evacuation efforts [11]. By simulating varied scenarios, such as fire emergencies or terrorist attacks, researchers can obtain critical insights that inform best practices for real-world applications [8].

The psychological aspects of crowd behavior play a big role in evacuation success. Panic and social dynamics can lead to unexpected crowd behaviors during emergencies, complicating evacuation efforts [12]. Addressing these psychological factors through training for emergency responders and clear communication with the public can help stabilize the situation and promote orderly evacuation protocols [13].

There is a need for multi-disciplinary collaboration among emergency services, health agencies, and local governments to effectively manage mass gatherings. Making partnerships and clear communication channels can help with rapid decision-making and resource allocation during emergencies, ensuring that all stakeholders are adequately prepared [14].

As urbanization and global connectivity increase, the probability of mass gatherings occurring near critical infrastructure, such as airports or transit hubs, will also rise. Ensuring the safety and security of these events requires interdisciplinary approaches that unify urban planning, emergency management, and public health efforts to mitigate health and safety risks. The need for comprehensive strategies that encompass mitigation, preparedness, response, and recovery components will ultimately dictate the success or failure of evacuations during these large-scale events [8].

This paper aims to create an overview of a wide variety of contributing factors regarding the evacuation of mass gatherings, due to the relation of human behavior, possible triggers, and legislative background. While offering this broad perspective, the paper later focuses primarily on the physical layout and simulation aspects of evacuation planning. To provide context for the existing research and to place the questions in a well-established field, a general overview is necessary. Recognizing that precise planning, efficient execution, and continuous improvement through simulation and real-world experience are essential, the focus on layout was established later. Contributing to research and innovation in this area is needed to enable communities with the tools and insights they need to manage mass gathering events in an increasingly crowded and complex world.

2.2 Evacuation Triggers

Outdoor mass gatherings, such as music concerts and festivals, by nature involve complex crowd dynamics and variable environmental conditions. Historical case studies have shown that events like fires, severe weather conditions, terrorism, and infrastructure failures can result in the need for rapid evacuations [15] [16]. In Denmark, where weather instabilities like pouring down heavy rain or strong winds and evolving security challenges have been reported in national terror situation reports [17], it is critical to address a broad spectrum of evacuation triggers. These triggers also determine many factors, such as the direction of crowd movement, and therefore the efficiency of evacuation. This chapter identifies the main hazards and discusses their documented impact while also establishing their relevance to the Danish context.

Fire Incidents

Fire represents one of the most commonly considered and investigated hazards during mass gatherings. Fires may occur accidentally (due to electrical faults or cooking equipment) or be intentionally set during terror events [16]. Research has detailed the use of fire as a weapon in mass casualty scenarios, emphasizing that even a small-scale fire can quickly evolve into a mass evacuation crisis if it intersects with high crowd density. In outdoor concerts where temporary structures are employed, the use of pyrotechnic equipment, combustible materials, and flammable temporary installations further increases the risk profile. Danish event safety guidelines have increasingly incorporated lessons from international studies that link fire hazards to prolonged evacuation times, making fire prevention and rapid response a must-include part of evacuation planning [15].

Severe Weather and Environmental Hazards

Rapidly changing weather conditions, including severe storms, heavy rain, and high winds, can lead to infrastructure collapse or hazardous environmental exposures for the occupants. Due to extreme weather, the collapse of temporary structures during tented events can occur [18]. In Denmark, despite a temperate climate, there have been instances of high wind events and localized storms that have threatened the structural integrity of temporary installations at mass gatherings. Furthermore, research indicates that climate change is driving more frequent and severe weather-related hazards in northern Europe, prompting event organizers to invest in robust evacuation protocols [19]. Outdoor mass events led to crowding-induced injuries and fatalities in Hungary, where a crowd crush occurred due to a sudden storm at the banks of the Danube, where people gathered to watch an announced fireworks show [1]. Such weather-induced emergencies require that the events integrate real-time meteorological data into their evacuation planning.

Terrorist Threats and Security Incidents

The risk of terrorism, including planned attacks or coordinated acts of sabotage, remains a critical concern for outdoor mass gatherings [17]. The literature highlights a growing awareness of terrorism as a trigger for mass evacuations, particularly when fire or explosive devices are used as part of the attack strategy [16]. In addition, studies focusing on evacuation planning for public events highlight that the unpredictable nature of terrorist threats makes it necessary to create preplanned and adaptive evacuation strategies [20]. Despite Denmark not experiencing large-scale terror incidents recently, periodic terrorist threat assessments indicate that mass events are potential targets [17]. The incorporation of terrorism-triggered evacuation scenarios ensures that security measures remain robust and adaptive to emerging threats [20].

Hazardous Materials and Chemical Incidents

While less frequent than other hazards, the accidental release of hazardous materials (or deliberate chemical, biological, radiological, and nuclear attacks (CBRN) has the potential to force rapid evacuations. Advances in detection technologies have improved the identification of CBRN agents, but the possibility of exposure remains a risk in scenarios where industrial facilities lie near mass gathering sites or where a terror actor may attempt such an attack [21]. In Denmark, ongoing risk assessments in urban planning and event safety often include modules for chemical hazard management, reinforcing the need for specialized evacuation routes and decontamination protocols.

Structural Failures and Crowd Dynamics

Evacuation triggers are not solely confined to environmental or intentionally caused hazards. Structural failures of temporary installations (e.g., stage collapses or tent failures) and crowd-induced incidents (such as stampedes that may follow a trigger event, further escalating the situation) are also significant factors. Although crowd dynamic failures are typically a consequence of panic induced by another event, planning for these secondary disasters is critical. Studies that integrate crowd behavior provide evidence that inadequate structural resilience or miscommunication among event participants can lead to rapid and uncontrolled evacuations [15]. This is particularly relevant in the Danish context, where the use of temporary structures is common at outdoor venues.

Relevance in the Danish Context

Denmark's safety and security agencies have noted that, although the overall risk of terrorism remains moderate, the country is not immune to the spillover effects of international terror and extreme weather events [20] [17]. National reports have increasingly highlighted severe weather episodes even in temperate climates, emphasizing the need for comprehensive evacuation strategies. The complexity of these threats, coupled with lessons learned from international mass gathering incidents [15], requires Danish event planners to adopt multihazard evacuation protocols that integrate real-time hazard detection with robust simulation-based planning.

The evaluation of potential evacuation triggers at outdoor mass gatherings demonstrates that fires, severe weather, terrorist threats, hazardous material incidents, and structural failures are all important to consider in developing a resilient evacuation plan. The literature provides a robust empirical basis for these risks, while Danish safety practices and threat assessments further prove their relevance. Future research should focus on integrating multidisciplinary simulation tools with real-time monitoring systems to further refine evacuation strategies specific to Danish outdoor events.

2.3 Laws and Regulations

Mass gatherings, such as outdoor concerts, pose significant logistical and safety challenges, especially when it comes to emergency preparedness and crowd evacuation. The safe and orderly evacuation of large crowds is a complex task that requires meticulous planning, adherence to legal frameworks, and the integration of risk-based strategies. In the European Union (EU) and Denmark, specific regulations and standards have been developed to ensure the safety of attendees during such events. This chapter presents an overview of the relevant EU and Danish laws and guidelines concerning event safety, emergency preparedness, and evacuation planning. These frameworks provide a foundation for simulation-based investigations such as the one undertaken in this study.

EU Regulations and Guidelines

While the EU does not provide a single, unified directive specifically tailored to mass gatherings, several legislative instruments and international standards adopted by EU member states are relevant to evacuation planning and emergency preparedness at such events.
One of the foundational pieces of EU legislation is Directive 89/391/EEC on the introduction of measures to encourage improvements in the safety and health of workers at work [22]. Although primarily aimed at occupational settings, at a mass event, there are also employees present to carry out various roles. This directive mandates that employers (including event organizers) assess all potential risks to health and safety, including those related to emergency evacuation procedures and crowd management. This implies a legal duty for event organizers to conduct hazard identification, risk assessment, and implement necessary mitigation strategies. Another important regulation is Directive 2001/95/EC on general product safety, which indirectly influences event safety by ensuring that all equipment used in temporary structures, such as stages, lighting rigs, and crowd barriers, meets safety standards and does not pose a risk to public health [23].
From a planning and procedural perspective, the international standard ISO 22315 : 2014, adopted by several EU nations, offers structured guidance on mass evacuation planning. The standard provides a framework for preparing, coordinating, and implementing evacuation plans, taking into account variables such as human behavior, communication strategies, and logistical constraints. Although not legally binding, ISO 22315 is considered a best-practice guide for emergency planners [24].

In addition, the European Centre for Disease Prevention and Control (ECDC) has issued several technical reports relevant to the planning of mass gatherings. For example, the 2024 ECDC Technical Report emphasizes the importance of conducting health risk assessments, managing communicable disease threats, and ensuring robust surveillance and emergency response capabilities. The ECDC particularly underscores the need for cross-sector coordination among health services, civil protection, and event organizers [25].

Danish National Regulations and Practices

In Denmark, the legislative responsibility for civil protection and emergency management falls under the Emergency Preparedness Act (Beredskabsloven). This act outlines the roles and responsibilities of municipalities, the Danish Emergency Management Agency (DEMA), and private actors in ensuring emergency readiness. Under the act, municipalities are required to prepare contingency plans for emergencies, which include mass gatherings. Event organizers are expected to align their emergency plans with municipal strategies and ensure that all critical scenarios, including evacuations, are addressed [26].

A crucial component of Danish safety regulation is found in the Danish Building Regulations (Bygningsreglementet), which apply to both permanent and temporary structures. The regulations specify requirements for the number and placement of emergency exits, minimum exit widths per person, and acceptable travel distances to the nearest exit. For temporary events, such as outdoor concerts, these provisions are adapted to consider the nature of the venue and the expected crowd size. For example, the regulations may require multiple exits with a minimum width of 0.77 meters each, spaced adequately to prevent bottlenecks and ensure flow continuity. Additional fire safety provisions mandate the presence of firefighting equipment and clear escape signage [27].

Event organizers are also subject to requirements under the Police Act (Politiloven). Large public events must be reported to the local police, who have the authority to require modifications to plans if they deem crowd management or evacuation procedures insufficient. Organizers must submit detailed safety and crowd management plans, including evacuation routes, barrier placements, and communication strategies. The police may consult with DEMA and local fire authorities during the approval process [28].

Practical Application in Event Planning

The combined application of EU directives, Danish national law, and international standards forms the basis for safe event planning. In practice, this involves several critical steps. First, a comprehensive risk assessment must be carried out, taking into account crowd size, venue layout, possible emergencies (e.g., fire, structural failure, crowd surges), and environmental conditions. Second, evacuation routes must be designed with sufficient width, number, and dispersion to accommodate the anticipated flow. Third, the event must be coordinated with relevant authorities—municipal emergency planners, police, fire brigades, and health services—to ensure that a coherent response plan is in place. The base requirements are well regulated in Danish law, but other than some minimum requirements, the details of the plan can be adjusted/planned by professionals and later have to be approved by the authorities. In this process optimization, planning strategies can be freely utilized to achieve the possible lowest safe egress time.

In the context of this research project, these regulatory requirements serve as the baseline conditions under which Pathfinder simulations are run. For example, compliance with the Danish Building Regulations informs the minimum exit widths evaluated in the simulation. Similarly, police requirements influence the spatial constraints and acceptable configurations for exit clusters. Finally, ISO 22315 guides the selection of parameters related to human behavior, such as pre-movement time and crowd density thresholds.

2.4 Evacuation Factors

This section provides a comprehensive overview of the influencing factors in evacuation time at mass gatherings. In formulating evacuation strategies, a multitude of variables can affect both the pre-movement delay and the overall egress time of occupants. The identified factors can be grouped into demographic, physical, behavioral, environmental, and structural categories. Each category is described below, with supporting evidence from the literature.

Demographic Factors

Age is a well-established parameter affecting mobility and reaction time during evacuations. Older occupants often have slower walking speeds and longer pre-movement delays, which can extend overall evacuation time [29].

Gender differences can influence reaction time and physical performance during emergencies, with studies indicating variance in evacuation speed due to differences in gait and decision-making processes [30, 31].

Height and Physical Stature: The occupant's height and leg length can affect stride length and walking speed, thereby influencing evacuation efficiency. Taller individuals may cover distances more quickly, although this advantage may be negated by other mobility constraints [32].

Health Status and Physical Fitness: Pre-existing health conditions or reduced physical fitness, including disabilities, play a crucial role in individual evacuation performance. These factors contribute to slower movement and extended safe evacuation times [29, 30].

Physical and Behavioral Factors

AlcoholConsumption Alcohol impairs judgment, decreases motor skills, and slows reaction times during emergencies. Its influence on decision-making and coordination has been documented as a critical factor in delaying evacuation [30].

Grouping and Social Behavior: The tendency of individuals to form groups, follow emergent leaders, or exhibit herding behavior is known to influence evacuation time. Group dynamics can either facilitate orderly movement or cause congestion, particularly when groups are hesitant or delay their movements to remain together [30, 33].

$Pre-movement$ and Response time: The interval between perceiving the emergency cue and initiating movement is influenced by individual cognitive and psychological factors. Factors such as risk perception, situational awareness, and prior training are essential determinants of the pre-movement delay [34].

$Decision-Making$ and Delay Behaviors: The process of deciding on an evacuation route and reacting to dynamic conditions in an emergency can affect overall performance. Variability in directional-choice parameters has shown that even small calibration errors in decision-making can lead to significant differences in evacuation time [35, 36].

Environmental and Structural Factors

Terrain and Surface Conditions: External factors such as slippery conditions, mud, or uneven surfaces can considerably slow movement. Studies on construction site evacuations have reported that adverse terrain conditions reduce effective evacuation speed and increase the risk of falls or injuries [37].

Layout and Obstructions: The configuration of the environment—including the number, width, and placement of exits, as well as obstacles like stacked equipment or temporary installations—directly influences evacuation time. Limited exit widths, local bottlenecks, or the presence of obstacles adversely affect flow rates and reduce overall efficiency [38, 39].

Visibility and Sensory Cues: Environmental factors such as poor visibility (due to smoke or low lighting) are critical in determining the speed of evacuation. Sensed parameters (e.g., temperature, CO concentrations) can also indirectly contribute to delays as occupants seek to avoid perceived danger zones [37, 40].

Uncertainty and Randomness in Human Behavior

Psychological Stress and Panic: Under emergency conditions, the psychological state of an evacuee is highly variable. Stress, confusion, or panic can exacerbate delays and lead to erratic behavior, while under controlled guidance, individuals may evacuate more efficiently [35, 41].

Uncertain Evacuation Route Selection: The randomness inherent in human behavior under emergency conditions—such as the choice between multiple exits—adds an element of unpredictability to evacuation timing. Simulation studies have demonstrated that even slight variations in exit-choice behavior can result in significant variations in total evacuation time [33, 35].

In summary, safe evacuation planning must integrate a comprehensive assessment of these factors. The combination of individual demographic characteristics, the behavioral responses elicited by stress, and the physical constraints of the environment all interact to determine evacuation efficiency. Understanding each of these contributors through robust simulation and empirical analysis is essential for developing targeted interventions to reduce egress times and enhance overall public safety during emergencies.

2.5 Festival Attendees

Danish music festivals have evolved to attract diverse demographics, significantly impacting planning and management. This also needs to be considered while planning for evacuation scenarios. This section shows data on age and gender distribution among attendees.

Age Distribution

Data indicate that the average age of festival attendees in Denmark has shifted, with younger crowds historically dominating these events. An increasing trend shows that a significant portion of attendees falls into the 20-29 age range (approximately 45%), with 30% in the 30-39 bracket, highlighting the equaling between younger festival participants and older attendees. However, specific data supporting these figures are not available in the cited references. While trends may suggest these patterns, precise attendance figures should be verified [42].

The data indicate a structural demographic change in attendees is available in psychology and marketing research papers. These papers are pressing organizers to adapt programming and marketing strategies to the age groups of attendees. Research suggests that younger attendees gravitate toward high-energy genres, while older attendees often seek genres like rock or classical [43].

Gender Distribution

Gender representation at Danish festivals has improved significantly, becoming more balanced than in earlier years. Current estimates suggest that women constitute approximately 45–50% of festival attendees, a substantial increase from previous decades. However, the cited references do not support the exact proportion of gender representation [44, 45].

Additionally, differences in behavior based on gender have been evidenced; females are more inclined to seek safety and social experiences compared to their male counterparts, who may engage more with substance use. This point has been supported by relevant literature [45].

Nationalities

The examples for age and gender were taken from Roskilde Festival. The festival boasts a notably diverse international attendance, with the majority of its audience coming from across Europe. Among the prominent nationalities represented, Great Britain, France, Finland, Germany, and the Netherlands each account for several hundred festivalgoers, reflecting the festival's broad European appeal[46]. Cultural and linguistic differences significantly impact evacuation procedures during emergencies. When disaster strikes, the effectiveness of communication is paramount, yet varying cultural contexts and languages can hinder timely and efficient evacuation. For instance, disaster management strategies must consider local cultural practices and languages to ensure that critical information is conveyed in ways that resonate with diverse communities [47]. In multicultural settings, disparities in emergency responses can emerge due to variations in risk perception and trust in authorities influenced by cultural backgrounds [48]. Furthermore, language barriers can complicate the dissemination of information regarding evacuation routes, safety protocols, and available resources, ultimately affecting the overall effectiveness of evacuation efforts [49].

This brief showcase of age, gender, and nationality distributions highlights the evolving demographics of Danish festival attendees, with the average age increasing and a more balanced gender representation. The data presented herein require additional sourcing and validation to ensure accuracy, thus providing a foundational understanding that will inform planning and evacuation strategies and enhancing safety.

2.6 Mobile Fencing Solutions

Fencing solutions play a vital role in the organisation of festivals, offering the base for crowd management, defining event boundaries, and enhancing overall safety. The popularity of mobile fencing has surged in recent years, particularly due to its adaptability and ease of deployment across diverse festival environments [50]. Effective crowd management and perimeter security are critical for the successful organization of festivals and mass gatherings. Temporary fencing solutions are central to achieving these objectives, offering both safety and logistical control in dynamic environments. This section presents a brief insight into fencing solutions available for festival organization, product types, market trends, and practical considerations for deployment.

Market overview

The temporary fencing industry has witnessed steady growth over the past decade, driven by heightened awareness of crowd safety and evolving regulatory standards [51]. Festivals and large-scale events increasingly rely on modular fencing solutions to manage access, create controlled zones, and ensure safe evacuation routes [52]. This has resulted in a diverse marketplace offering a range of products tailored to the needs of event organizers.

Product types and features

Fencing solutions for festival environments can be broadly categorized as follows:

StandardTemporaryFencing Modular steel mesh panels, typically 2 meters high, supported by weighted bases. Used for site perimeters and general site security [53]. Temporary fencing systems are among the most widely used in festival organisation. These fences are typically made from lightweight materials such as plastic or metal, allowing for easy installation and removal. They can be configured to create enclosures for restricted areas, directing foot traffic while preventing unauthorized access. Smith notes that these temporary structures can normalise restricted access, thus mitigating opposition to enclosed public spaces during festivals [50].

CrowdControlBarriers Low-height barriers for guiding pedestrian flows and forming secure queues. Portable and modular [54]. These barriers are designed specifically to manage the flow of people during large gatherings. They often feature interlocking systems that allow for flexible configurations depending on the crowd size and movement patterns. Barriers can delineate paths for entry and exit, segregate different audience groups, and provide a buffer between attendees and other activities. This variability ensures that festival organisers can respond effectively to changing crowd dynamics throughout the event [50].

$High - SecurityFencing$ Dense mesh fences that deter climbing and secure VIP or technical areas [55].

AcousticandSoundBarriers Panels with sound-absorbing materials to mitigate noise impact in residential areas [56].

DecorativeandThemedFencing Fencing solutions with branded or themed covers that enhance visual appeal and sponsor visibility [33].

EmergencyandEvacuationPathwayFencing Flexible barriers for emergency routes, facilitating clear and safe egress during evacuations [35].

Market trends and considerations

Several trends shape the market for fencing solutions in festival settings:

- **Regulatory Compliance and Safety Standards**: Rising awareness of crowd safety has driven festival organizers to comply with ISO 22315 standards and national building codes [24, 27].
- **Sustainability and Reusability**: Eco-friendly and reusable fencing materials are increasingly prioritized to reduce environmental impact and lifecycle costs [51].
- **Customization and Branding**: Organizers integrate branded wraps and themed fencing to enhance festival identity and sponsorship visibility [33].
- **Smart and Modular Systems**: Innovations include sensor-equipped fencing for monitoring crowd density and modular panels adaptable to changing crowd flows [52].

Geographical distribution and pricing

European countries, notably Denmark, Germany, and the UK, have robust temporary fencing markets driven by stringent safety and noise regulations. North America and Asia-Pacific also show growing demand, driven by the expansion of festival culture [51].

Approximate rental prices in Denmark in 2024 include:

- Standard temporary fencing panels: €20–€40 per panel per day.
- Pedestrian barriers: €5–€10 per barrier per day.
- Acoustic barriers: €50–€100 per panel per day, depending on acoustic rating.
- Custom branding wraps: €5–€15 per square meter.

The market for fencing solutions in festival organization is diverse and dynamic, shaped by safety imperatives, evolving regulations, and aesthetic considerations. Selecting appropriate fencing solutions ensures compliance, enhances crowd safety, and contributes to a positive festival experience. As sustainability and smart technologies continue to develop, future fencing solutions are poised to become even more adaptable and environmentally conscious [50].

The variability of fencing solutions enables festival organisers to tailor their approach to specific contexts. For example, some festivals may require more substantial, secure fencing to manage high-risk crowds, while others may opt for lighter barriers that are easy to navigate. The ability to adjust the configuration based on the festival's unique needs is crucial for ensuring optimal crowd flow and enhancing the attendee experience.

The modern trend involves integrating fencing solutions with technology, including digital signage, CCTV monitoring, and crowd management software. This integration enables real-time data monitoring, allowing for faster response times to crowd issues and enhancing overall safety. This technological adaptability showcases the contemporary versatility of fencing solutions in festival settings [50].

In conclusion, fencing solutions have become indispensable tools in the effective management of festival environments. Mobile fencing solutions offer flexible, adaptable, and cost-effective solutions for responses to varying crowd dynamics while sustaining accessible public spaces. This flexibility in area design is unique to open-air mass gatherings and festivals. This allows a wide range of different exit configurations to be executed.

2.7 Egress Simulation Literature for Festival Scenarios

The utilization of the Pathfinder simulation model in evacuation scenarios at large-scale music festivals was applied multiple times fitting a concrete location. Use of Pathfinder in Evacuation Modelling In the study by Ronchi et al., Pathfinder is employed as a multi-agent continuous evacuation model to simulate various evacuation scenarios, including a preventive evacuation due to a fire and a total evacuation prompted by a bomb threat. in the paper this model was selected for its capacity to represent large populations and high densities more accurately than previous methodologies. The study aims to create sophisticated representations of crowd behavior under different evacuation triggers and to analyze how variations in layout and delay parameters can impact evacuation efficiency [57].

Okřinová et al. [58] similarly leverages numerical models to optimize crowd evacuation processes, focusing on realistic variables that affect crowds during an emergency. This includes assessing body space, walking speeds of different demographic groups, and the impact of pre-evacuation behavior based on real crisis incidents. The model integrates empirical data to refine the simulation parameters, ensuring that the scenarios closely mimic real-world conditions, which is crucial when developing emergency plans for large public gatherings.

Both papers highlight a historical context of crowd disasters, citing incidents such as the Love Parade in 2010, which resulted in significant casualties due to poor crowd management practices [58]. This historical backdrop emphasizes the necessity for sophisticated modelling tools like Pathfinder. By utilizing such models, festival organizers can preemptively address key failings observed in previous incidents, such as insufficient exit paths and inadequate crowd control measures, by testing different layout scenarios and identifying optimal evacuation paths [57, 58]. Moreover, Ronchi et al.[57] emphasizes the critical aspects of pre-evacuation behavior, taking into account the social dynamics and psychological responses of attendees during an emergency. These dimensions are often overlooked in traditional evacuation planning but can significantly influence the overall effectiveness of the evacuation process. The dynamic modeling of movement speeds—factoring in variations among individuals, including those with mobility impairments—further illustrates the nuanced approach of these studies [57].

Implications for Future Evacuation Models Both studies advocate for a continuous improvement approach to evacuation modeling through detailed simulations. For instance, research by Ronchi et al. indicates the significant role of social media during emergencies, impacting how quickly individuals begin to evacuate [57]. The incorporation of such social behaviors, alongside empirical data on participant demographics and physical capabilities, allows for a more refined understanding of potential bottlenecks and escape routes [57].

Okřinová et al. work stresses legal and safety compliance by highlighting issues like overcrowding and the need for proper authorizations, which can directly affect the safety and efficacy of emergency plans. By presenting quantitative data on evacuation times and operational capacity under various scenarios, these models can inform better regulatory frameworks and organizational practices for large events [58].

In conclusion, the integration of Pathfinder in these research endeavors exemplifies the application of advanced simulation technology in crisis management. It underscores the ethical responsibility of event organizers to leverage such tools to enhance public safety. These two studies serve as typical examples of application possibilities for outdoor mass gathering scenarios. However, it is important to note that while they provide detailed modeling of human behavior and crowd dynamics, they largely take the given layout as fixed and do not explore the broader freedom and flexibility of fencing or exit layout configurations in detail. As the simulation literature is already saturated in terms of human behavioral aspects and refined movement models, this highlights a gap in studies that treat the spatial design itself as an adjustable parameter. Both studies collectively advocate for continued research and innovation in crowd management strategies at large-scale events. Yet, there remains ample scope for future work to systematically investigate how alternative fencing arrangements and layout flexibility could further optimize evacuation performance and public safety.

2.8 Literature on Exit Configuration

Evacuation safety in mass gatherings is heavily influenced by the physical layout and design of exit routes. A substantial body of literature explores various aspects of exit configurations, including exit width, positioning, and clustering, to understand how these factors impact egress performance and crowd safety. These studies draw from diverse fields, from architectural design to behavioral psychology, underscoring the multifaceted nature of emergency evacuations. While general evacuation modeling and simulation applications are well-established, the specific configurations of exits, especially in the dynamic settings of outdoor mass events, require a focused examination. The following subsections synthesize key insights from the literature, providing context for the exit configuration parameters analyzed in this paper.

2.8.1 Effect of exit width

The relationship between exit width and egress time has been extensively studied across various domains, including architectural safety. Understanding how exit width influences the efficiency of crowd evacuation and movement dynamics is critical, especially in emergency situations. A variety of research demonstrates that both the geometry of egress points and the surrounding conditions significantly influence egress time.

A substantial body of work has established that the width of an exit significantly affects flow rate and subsequent evacuation time. For example, Wei et al. found that various exit structures affect evacuation efficiency, highlighting that narrower exits tend to lead to increased congestion and prolonged egress times [59]. This conclusion is also reflected in the study by Wang and Lin (2017), the paper observed that in a controlled experiment involving ants, the mean flow rate did not linearly increase with exit width, showcasing the complexities involved in determining effective egress configurations [60].

The geometry of exit points plays a role in shaping evacuation dynamics. Tavana et al. conducted experiments demonstrating that relocating an exit point from the center to a corner of a walkway decreased evacuation times significantly [61]. This finding highlights the multifaceted factors influencing egress, indicating that exit width alone does not determine egress time; the spatial placement of exits is also a crucial consideration [61].

Moreover, specific configurations, such as bottlenecks, further complicate the effects of exit width on egress time. Bode et al. explored how social interactions and environmental obstacles modify movement dynamics, noting that narrower exits can result in extensively longer evacuation times due to increased interactions among individuals attempting to escape [62].

These observations also align with findings by Kodur et al., who indicated that various parameters, including geometric characteristics of exits, govern evacuation efficiency in hospital environments, reiterating the importance of exit width in emergency design [63].

In conclusion, the literature strongly supports the assertion that exit width is a critical determinant of egress time and efficiency. They have a non-linear relation. It also indicates that exit width is not the sole structural factor in egress time.

2.8.2 Effect of exit positioning

Architectural studies have demonstrated that strategically positioning exits can alleviate some negative effects associated with narrow exit designs, effectively reducing egress times [64]. In this paper, Tavares (2009) investigates how the positioning of exits influences evacuation times in a square room occupied by 200 individuals. By examining various exit configurations for single and dual exits of equal width, the study reveals that placing exits in corners leads to slightly faster evacuations due to reduced congestion around exit points. Notably, the study demonstrates that congestion plays a significant role in determining evacuation times, and the influence of exit positioning can outweigh the impact of exit width in certain scenarios. Furthermore, the literature is saturated with analyses of exit positioning in relation to walls and corridors, underscoring the relevance of spatial layout beyond just the width of exits. While the research is limited to idealized behavior, such as zero response time and straightforward exit choice, it highlights the importance of optimizing exit placement to enhance overall safety and reduce egress times in enclosed spaces [64].

2.8.3 Effect of exit clustering

The design and clustering of exits in buildings, particularly with reference to regulations in Denmark and the EU, are subject to various guidelines and studies in evacuation planning. Such regulations prioritize safety and effectiveness to facilitate egress during emergencies, generally emphasizing the need to avoid clustering exits too closely together.

In Denmark, the Building Regulations [27] stipulate requirements for exit placements in buildings, focusing on providing adequate egress routes to enhance safety.

The Danish regulations adhere closely to the principles outlined in the EU directives on construction, which focus on ensuring that exits are adequately spaced to minimize congestion during emergencies. The EU Directive 2014/24/EU sets standards for public safety in building designs, including the necessity of having multiple exits located in such a manner as to avoid over-reliance on a single exit route [65]. This directive aligns with recommendations emphasizing that exits should be positioned near pathways that can handle high densities of occupants without leading to delays due to congestion.

Moreover, the NFPA Life Safety Code [66], which often inform regulations across EU member states, advocate for a formal approach to clustering exits. They indicate that exits should not be clustered too closely together to provide redundancy in case of blockages or obstructions. The recommended distance between clustered exits or the number of exits in relation to the maximum occupant load helps ensure that during an emergency, individuals can navigate toward the exits without being funneled into singular points of failure [64].

Research has extensively analyzed the dynamics and implications of exit clustering on crowds during evacuations. Studies examining pedestrian flow emphasize that while clustering exits can reduce the time to reach an exit, it can simultaneously lead to dangerous bottlenecks if not designed properly. For instance, a simulation study by Asadi et al. demonstrated that improper placement of exits could lead to increased egress times, especially in scenarios with high traffic density [67, 68].

Research shows that emergency situations often see individuals making quick decisions, which can result in clustering behavior at certain exits if individuals see others heading in that direction. This observation aligns with findings from major studies which utilized agent-based modeling to simulate evacuations[67]. Such studies indicate that the effects of social influence can lead to uneven distributions of crowd pressures at exits, influencing how effectively they are utilized during an emergency.

Additionally, studies exploring architectural adjustments have highlighted how certain modifications can alleviate congestion at exits, thereby promoting a more effective evacuation process. For instance, Al-Khalidi et al. noted that altering the architectural design of exit zones tends to relieve bottlenecks and facilitate smoother egress flows during emergencies [69].

The concept of the Level of Service (LoS) is often applied in evacuation studies, providing a quantitative measure of exit performance based on crowd density estimates and flow rates. This framework helps understand how clustered exits might operate under different occupant load scenarios, delineating minimum distances required between exits to maintain a high level of safety [70].

Research into Danish evacuation protocols, combined with broader EU norms, indicates a pressing need for policies that integrate behavioral psychology with architectural design to inform exit strategies. A detailed study by M. F. H. Zaman et al., focusing specifically on Danish evacuation routes, found that behavioral patterns of occupants during an emergency could move certain exits to be under- or over-utilized relative to their design capacity [71].

As the balancing act of exit clustering continues to evolve, it is clear that regulations in Denmark and the EU, and research emphasize the necessity of careful consideration in exit placement beyond simply adhering to spatial dimensions. The general consensus is pointing towards the need to avoid exit clustering as much as possible.

2.9 State of the Art Conclusion

Mass gathering evacuations are a relevant and pressing topic due to the increasing scale and frequency of such events worldwide. The literature covers a broad range of factors influencing evacuation, including behavioral, demographic, and environmental triggers, with significant research already available. Simulation techniques are also well-established and widely utilized for modeling crowd dynamics in specific scenarios.

While the spatial layout and exit configurations have been extensively studied, exit clustering is generally discouraged due to its tendency to create bottlenecks and congestion. However, for outdoor mass gatherings—where mobile fencing and flexible setups are necessary for security and controlling incoming crowds—exit clustering is often unavoidable. This practical reality highlights a gap in the current literature, as optimal exit clustering configurations have not been thoroughly investigated in simulations. To address this, the present work focuses on simulating different exit clustering setups using Pathfinder to identify optimal strategies for safe and efficient evacuation in festival environments.

Chapter 3

Problem Formulation

3.1 Research Question

How do different exit width and exit clustering configurations influence evacuation efficiency, congestion patterns, and optimal egress times in large-scale outdoor mass gatherings in Denmark, and what practical insights can be derived to improve crowd safety and event planning through simulation-based analysis?

3.2 Objectives

The primary objective of this study is to systematically investigate the influence of exit clustering on egress times and crowd dynamics during emergency evacuations at outdoor mass gatherings. Specifically, the research aims to:

- Quantify the impact of exit clustering on overall evacuation time for different crowd densities typical of Danish outdoor events.
- Identify critical clustering configurations that either mitigate or worsen bottlenecks during evacuation.
- Evaluate crowd flow patterns and density distributions associated with various exit configurations, using agent-based simulations in Pathfinder.
- Provide practical recommendations for event organizers and planners in Denmark on how to optimize exit placement to improve crowd safety during emergencies.

This focus reflects the need for data-driven insights to guide evacuation planning in outdoor venues, a topic of particular relevance in the context of large-scale festivals and public events in Denmark.

3.3 Delimitations

- **Single Simulation Software**: The analysis exclusively utilizes Pathfinder 2024.2, an agent-based egress simulator. While other software solutions exist (e.g., MassMotion, Simulex), the choice of Pathfinder is justified by its robust validation and established use in evacuation modeling.
- **Focus on Exit Clustering**: The study narrows its scope to the examination of exit clustering (number, placement, and proximity of exits). Other exit parameters such as shape, signage, and environmental factors (e.g., lighting, weather) are not considered in this study.
- **Fixed Crowd Profile**: Simulations are based on a representative crowd profile reflecting typical festival attendees in Denmark. Variations in demographic factors (e.g., mobility impairments, age distribution) are not explicitly explored.
- **Geographical and Cultural Context**: The analysis is constrained to scenarios relevant to Danish festival events and does not extend to international contexts or venues with significantly different regulatory frameworks or cultural crowd behaviors.

3.4 Limitations

- **Validation Scope**: The study's validation of simulation results relies on comparisons with published peer-reviewed studies and Pathfinder's internal verification and validation documentation. No large-scale real-world evacuation exercises or field experiments were conducted to directly calibrate or verify the simulation results.
- **Time and Resource Constraints**: Conducted within the scope of a single semester, the study's duration limited the number of scenarios and variations tested. Further refinements (e.g., testing additional crowd profiles or exit geometries) were beyond the available timeframe.
- **Generalizability**: The use of a single crowd profile and static environmental conditions means that the findings may not fully capture the variability of real-world crowd behavior under different circumstances (e.g., extreme weather, panic).
- **Simplified Assumptions**: Although Pathfinder can simulate complex occupant behaviors, some aspects of human decision-making and environmental variability (e.g., group behavior under stress, real-time weather changes) are not fully represented in the current simulation scope.

Chapter 4

Methodology

The methodology of this thesis follows the Problem-Based Learning (PBL) approach, a cornerstone of academic inquiry at Aalborg University. This approach guided the research process as a funnel-shaped progression: beginning with a broad and explorative literature search, which led to the identification of a research gap, resulting in the problem formulation. After this point, the topic to address the research question, the focus remains narrow through detailed simulations and analyses, then expanding outward again as various applications are discussed.

4.1 Methodology Overview

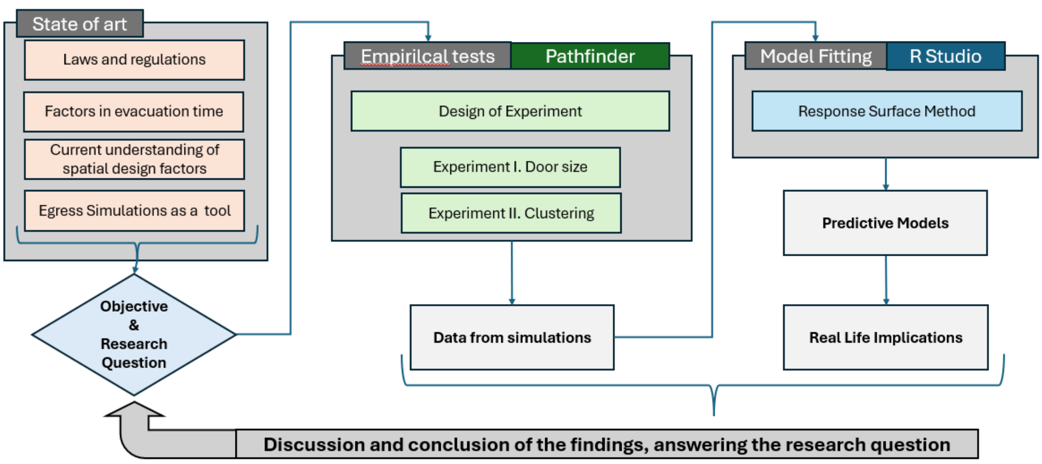


Figure 4.1: Methodology Flowchart [Own Creation]

The Overview can be seen in Figure 4.1. Initially, a comprehensive literature search and scientific theoretical perspective review were conducted to establish a solid foundation for understanding evacuation modeling and simulation techniques. This initial phase incorporated insights from both Danish and international guidelines, studies on pedestrian evacuation dynamics, and the broader context of simulation-based emergency planning. The insights gathered were distilled into a focused problem formulation that explicitly addressed the role of exit clustering in evacuation performance—an area not thoroughly explored in previous literature.

Building on this foundation, the simulation framework was developed using Pathfinder, a robust agent-based modeling tool validated for crowd movement and egress scenarios. Pathfinder's flexibility and detailed representation of both occupant behaviors and geometries made it ideal for systematically testing how exit number, placement, and width influence egress times in large-scale outdoor events.

To interpret the simulation data and quantify relationships between key variables, R was employed as the primary tool for statistical analysis and visualization. Using advanced function fitting, regression techniques, and heatmap generation, the analysis captured both the global and localized effects of exit clustering on crowd dynamics. To ensure systematic exploration and robust parameter tuning, a structured Design of Experiments (DOE) approach was implemented. This structured framework allowed for controlled variation of exit parameters—such as gap lengths and door counts—across different scenarios. Building on DOE, the Response Surface Methodology (RSM) was then used to refine the identification of local optima, including the observed optimal gap length of approximately 1 m. The RSM approach confirmed how small variations in exit design can have significant impacts on evacuation performance.

The conceptual framework of ASET-RSET (Available Safe Egress Time vs. Required Safe Egress Time) was integrated throughout the study, providing a safety-focused interpretation of the simulation outputs. This helps placing the findings from a technical number to a practical view aligned with safety engineering principles.

In line with the PBL philosophy, the entire methodological process—starting from broad exploration, narrowing to the problem formulation, and then expanding into detailed simulation-based investigation—was iterative and reflective. This ensured that the research question was addressed comprehensively, while still being responsive to new insights and challenges encountered during the project. The following sections will elaborate on each of these methodological components in greater detail.

4.2 Literature Search

The data collection for this thesis began with an exploratory search using references suggested by professors and the supervisor. This initial exploration was complemented by a chain search method to identify foundational documents related to emergency evacuations in outdoor mass gathering scenarios. Key studies emerged, providing a baseline for the problem formulation and highlighting research on pedestrian movement, exit design, and the use of simulation software for evacuation analysis.

Building on this foundation, a systematic literature search was conducted to expand the understanding of exit clustering effects and to identify relevant studies within the context of outdoor events and crowd management. The PICo model was adapted to guide the controlled block search [**HÃÿrmann_2015**]:

- P (population): Attendees at outdoor mass gatherings.
- I (interest): Human behavior, exit clustering, evacuation simulation.
- Co (context): Emergency evacuation scenarios in outdoor environments.

These categories informed precise search terms, including phrases such as "exit clustering," "crowd movement," and "evacuation modeling." The block search was structured into three thematic blocks with synonyms and related terms for each keyword, broadening the scope using phrase searching and the Boolean operator "OR." The blocks were then combined using the Boolean operator "AND" to narrow the focus to studies addressing all relevant aspects.

Inclusion and Exclusion Criteria were applied to ensure relevance and applicability to the study objectives:

- Publication year: 2000–2024.
- Geography: Industrialized countries with comparable event safety protocols and evacuation guidelines.
- Language: English, Danish.

Titles and abstracts were screened to assess relevance to the themes of outdoor evacuation dynamics and exit clustering.

The systematic search uncovered a range of theoretical frameworks and empirical studies addressing evacuation modeling, exit clustering, and simulation-based analyses in crowd safety. These included agent-based simulation studies, empirical evacuation data, and guidance documents from safety organizations. Key data sources included academic databases such as ScienceDirect, Scopus, IEEE, and official reports on crowd safety at outdoor events.

The findings from these sources were systematically cataloged and analyzed, forming the basis for the theoretical framework and informing the simulation models built in Pathfinder. This comprehensive literature search ensured that the research questions were grounded in the current state of knowledge and that the study's methodology aligned with best practices in evacuation analysis and safety engineering.

4.3 ASET and RSET

In emergency evacuation scenarios at mass gatherings, two core concepts are often employed to evaluate safety: Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET). ASET denotes the maximum allowable time for attendees to safely evacuate before hazardous conditions render exits ineffective. This depends on various factors, including environmental conditions, crowd density, and the temporary nature of structures at festivals.

On the other hand, RSET represents the time actually required for people to reach safety and comprises several distinct phases, also seen in Figure 4.2:

$DetectionTime:$ The interval needed for occupants to recognize that an emergency has occurred.

$AlarmTime:$ The period in which the alarm is activated and attendees become aware of the need to evacuate.

$Pre-movementTime:$ The time spent by individuals deciding whether to evacuate, gathering belongings, or communicating with companions.

$TravelTime:$ The actual walking time to reach safety, which involves walking speeds and flow dynamics in the crowd.

Among these, the pre-movement phase is particularly unpredictable and influenced by individual decision-making, perceived urgency, and social interactions within the crowd.

The relation between the two is important, because for a safe evacuation, ASET needs to be bigger than RSET. See Figure4.2 [72]. The margin of safety is as follows in Equation 4.1:

$$T_{\text{SAFETY}} = T_{\text{ASET}} - T_{\text{RSET}} \tag{4.1}$$

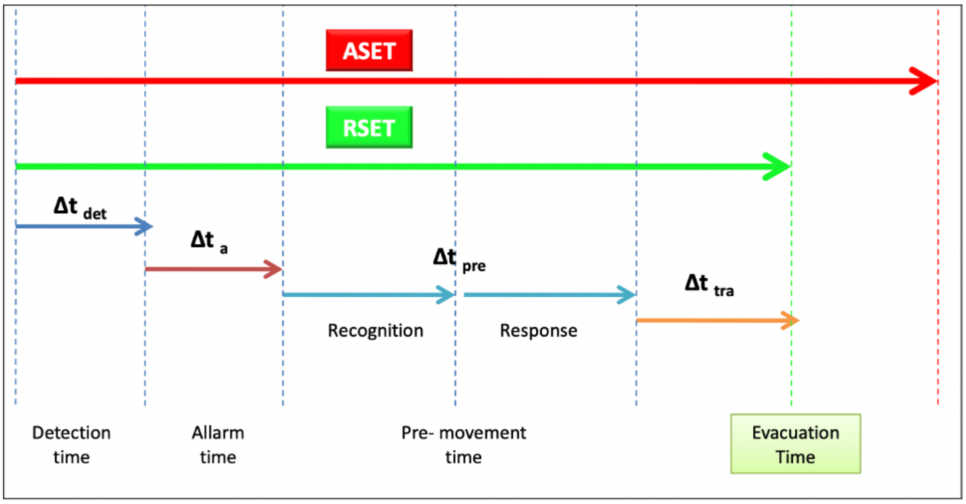


Figure 4.2: ASET and RSET Timeline (Evacuation Time) [72]

This structured framework is widely used in evacuation analysis and is recognized for its comprehensiveness in considering both human behavior and physical egress dynamics [72]. However, to maintain a parametric focus on the influence of exit clustering and configuration in the context of outdoor festival evacuations, this thesis will exclusively consider the travel time phase, consisting of walking time and flow time. This approach ensures that the impact of spatial layout and exit arrangements can be isolated and systematically analyzed without the added variability introduced by behavioral responses and detection delays.

4.4 Pathfinder Software

In this study, Pathfinder was selected as the primary simulation tool. Developed by Thunderhead Engineering, Pathfinder is an agent-based egress and human movement simulator that was utilized to model and analyze evacuation scenarios for the Exit width and exit cluster scenarios. Its use is natural as part of the educational framework, given its robust features and established track record. Pathfinder offers a comprehensive platform for designing, simulating, and visualizing occupant movement during emergency evacuations, making it well-suited for detailed assessments of evacuation procedures and the identification of potential bottlenecks and congestion as areas for improvement [73].

Pathfinder comprises three primary components [73]:

- **Graphical User Interface (GUI):** This interface facilitates the creation and editing of building models, occupant profiles, and evacuation scenarios. Users can import existing building geometries from various formats, including DXF, DWG, and IFC, or construct models directly within the software.
- **Simulator:** The core engine that executes the evacuation simulations based on the defined parameters and scenarios. It employs agent-based modeling techniques, allowing each occupant to make individual decisions and interact dynamically with the environment and other occupants.
- **3D Results Viewer:** A visualization tool that provides both 2D and 3D representations of simulation outcomes. It enables users to observe occupant movements, identify congestion points, and assess the overall effectiveness of evacuation strategies.

While Pathfinder has been widely used in research and practice, these prior studies typically focus on detailed modeling of human behavior and refined crowd dynamics within a given layout. They serve as typical examples of Pathfinder's application potential in outdoor mass gathering scenarios. However, these works do not delve into the broader flexibility of fencing and exit clustering effects, and the simulation literature in general is already saturated with these behavioral aspects. This thesis, in contrast, highlights the potential of using Pathfinder to explore alternative spatial configurations, namely exit clustering in a parametric way, extending beyond the fixed layout assumptions seen in earlier works (Section 2.7.

4.5 Pathfinder Verification and Validation

As the scope of this paper doesn´t allow for conducting large-scale human tests to verify the Pathfinder software, an overview of established literature is reviewed for validation and verification purposes. The Pathfinder 2024.2 Verification and Validation (V&V) documentation provides a comprehensive framework for assessing the accuracy and reliability of Pathfinder, Thunderhead Engineering's agent-based egress and human movement simulator. This V&V process ensures that the software's simulations align with real-world human behavior and established engineering standards [74].

Overview of the V&V Framework

The V&V methodology encompasses a series of structured tests and scenarios designed to evaluate various aspects of pedestrian movement and behavior within simulated environments. These tests are categorized into several key areas [74]:

FundamentalDiagramTests : Assess the relationship between pedestrian speed and density in different flow scenarios, including unidirectional, bidirectional, and merging flows.

FlowRateTests : Evaluate the rate at which occupants pass through doors, stairs, and corridors, ensuring consistency with empirical data.

BehaviorTests : Examine complex behaviors such as group dynamics, merging in corridors and stairways, overtaking slower occupants, elevator usage, and navigation through corners.

SpecialProgramFeatures : Test advanced functionalities like assisted evacuation, source flow rates, Fractional Effective Dose calculations, walking speed reductions due to smoke, and social distancing measures.

IMOTests : Based on the International Maritime Organization's guidelines, these tests simulate various scenarios to ensure compliance with maritime safety standards.

NISTEvacuationTests : Derived from the National Institute of Standards and Technology's benchmarks, these tests validate aspects like pre-evacuation time distributions, movement speeds in different environments, and behaviors under reduced visibility.

Integration with Automated Testing

Pathfinder incorporates an automated build, verification, validation, and regression testing process using a continuous integration system. This system performs nightly tests to detect errors, collect performance statistics, and ensure consistency across software revisions. The process includes:

- Stage 1: Retrieval of the latest source code from the repository.
- Stage 2: Compilation of the source code, logging any compiler warnings.
- Stage 3: Execution of a comprehensive unit test suite, with results compiled into reports for review.

This rigorous testing framework ensures that Pathfinder maintains high standards of reliability and accuracy in its simulations.

Referenced Studies and Standards

The V&V documentation references several authoritative sources to benchmark and validate Pathfinder's performance:

$InternationalMaritimeOrganization(IMO)Guidelines:$ Provide standards for evacuation analysis on ships, ensuring Pathfinder's simulations align with maritime safety requirements.

$NationalInstituteofStandardsandTechnology(NIST)Reports:$ Offer empirical data and methodologies for evacuation modeling, serving as a basis for several validation tests within Pathfinder.

$SocietyofFireProtectionEngineers(SFPE)Handbook:$ Supplies foundational knowledge on fire protection engineering, informing the development of Pathfinder's simulation models.

These references ensure that Pathfinder's simulations are grounded in established research and best practices within the field of evacuation modeling.

For a detailed exploration of the Verification and Validation processes, including specific test scenarios and results, you can access the full documentation. This resource is invaluable for engineers, safety professionals, and researchers seeking to understand or utilize Pathfinder for accurate and reliable evacuation simulations.

4.6 Statistics Tool

In this thesis, R was utilized as the primary statistical analysis tool, executed within the RStudio integrated development environment (IDE). This decision was not only encouraged by Aalborg University's curriculum but also driven by R's capabilities for robust data manipulation, non-linear regression modeling, and advanced visualization.

R's ecosystem of libraries and its intuitive syntax provided a versatile framework for analyzing the simulation data generated by Pathfinder. In particular, R was used for:

Reading simulation data from CSV files using the `read.csv()` function.

Visualizing raw and processed data with `plot()`, `points()`, and `lines()` to explore relationships between exit width, exit clustering, and egress time.

Fitting hyperbolic and polynomial regression models with `nls()` and `lm()` to quantify the impact of exit configurations on evacuation times.

Conducting response surface analysis with the `rsm` package, using the `rsm()` function to build second-order polynomial models of the evacuation response surfaces.

Generating contour and 3D surface plots with `contour()`, `persp()`, and `plotly` for interactive and intuitive exploration of complex relationships between exit clustering variables and evacuation performance.

Additionally, `ggplot2` was employed for creating clear and informative plots that depict trends, outliers, and cluster-specific evacuation patterns. This included bar charts and scatter plots showing the variation in average egress time with gap length and number of exits.

By integrating these R functions and visualization tools, the statistical analysis not only provided key insights into the simulation data but also ensured reproducibility—each analysis step was captured in scripts that can be rerun or adapted for future research. The adaptability of R and its broad suite of libraries made it a vital component in quantifying evacuation performance and optimizing exit design strategies [75].

4.7 Design of Experiments

The Design of Experiments is a systematic framework used to plan and conduct experiments in a structured and statistically sound manner. In this thesis, DOE was employed to ensure that the exploration of exit width, exit clustering, and other evacuation parameters was carried out in a methodical and efficient way.

The DOE approach involves defining a set of input factors (or parameters) and systematically varying them to observe their effects on one or more response variables. This structured framework provides insights into:

- The main effects of each parameter (e.g., exit width, number of doors, gap length).
- The interactions between parameters, which can reveal synergistic or antagonistic effects on evacuation performance.
- The presence of non-linearities in the response that may not be captured through simple linear modeling.

The DOE methodology typically involves creating an experimental matrix that specifies the different combinations of parameter levels to be tested. These combinations are chosen to maximize information gain while minimizing the number of simulations required. Key benefits of using DOE include:

- Efficient exploration of a multi-dimensional design space.

- Reduction of experimental bias through randomized and balanced test designs.
- The ability to detect interactions and higher-order effects.

By integrating DOE principles into the simulation framework, the study ensures that results are statistically valid and that conclusions drawn are robust and generalizable.

4.8 Response Surface Methodology

Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques used for modeling and analyzing problems in which a response variable is influenced by several input factors. In the context of this thesis, RSM was utilized to further refine the insights generated by the DOE phase.

RSM involves fitting a polynomial regression model (typically second-order) to the data obtained from the DOE experiments. This approach allows for the creation of a smooth surface, or "response surface," that approximates the relationship between input parameters and the response variable. The general goals of RSM include:

- Identifying local or global optima in the response variable (e.g., minimizing egress time).
- Characterizing the curvature of the response surface to detect non-linear effects.
- Providing a predictive model that can estimate responses at untested parameter combinations.

The methodology for RSM typically involves:

1. Conducting a DOE to gather data across the parameter space.
2. Fitting a second-order polynomial model (or higher order if needed) using regression analysis.
3. Validating the model through residual analysis and goodness-of-fit statistics.
4. Visualizing the response surface using contour and 3D plots to interpret interactions and optimal conditions.

RSM Overview

- **Input factors**: Number of doors (treated as a continuous numeric factor for modeling), length of gaps (continuous).
- **Response**: Egress time.

A second-order polynomial model was fitted:

$$\text{Egress Time} = \beta_0 + \beta_1 N + \beta_2 L_G + \beta_{12}(N \cdot L_G) + \beta_{11} N^2 + \beta_{22} L_G^2 + \varepsilon$$

4.8.1 Outcome Variables and Interpretation of RSM

Key Outcome Variables The primary response variable captured through RSM in this thesis is the egress time (*ET*), representing the total evacuation time for attendees at a mass gathering event. The RSM model provides insights into:

- **Linear Effects:** Quantify the direct, proportional changes in egress time as a single factor (e.g., number of exits or gap length) changes.
- **Quadratic (Curvature) Effects:** Indicate non-linear behaviors, revealing potential points of diminishing returns or optimal performance ranges.
- **Interaction Effects:** Show how the combination of two factors (e.g., exit number and gap length) can produce synergistic or antagonistic impacts beyond their independent effects.

ModelValidation The robustness of the RSM model is assessed through residual analysis and goodness-of-fit statistics. This involves examining residual plots to ensure there is no systematic pattern (indicating model adequacy) and calculating adjusted R^2 to quantify the proportion of variance in egress time explained by the model. Significant p-values for each term further validate the model's reliability.

Visualization To aid interpretation and identify optimal configurations, the response surface is visualized using:

- **Contour Plots:** Provide a top-down view of the response surface, clearly highlighting the regions of minimum or maximum egress time and the interactions between factors.
- **3D Surface Plots:** Offer a three-dimensional perspective, illustrating how egress time varies across different levels of exits and gap lengths, facilitating intuitive understanding of the response surface shape and optimal points.

PracticalInterpretation In the evacuation context, these RSM outcomes highlight that:

- **Main Effects:** Increasing exit numbers or gap lengths generally reduces egress time, but only up to a certain limit.
- **Quadratic Terms:** Both variables show diminishing returns, indicating the presence of an optimal gap length and exit count.
- **Interaction Effects:** The influence of one factor depends on the level of the other—joint optimization is crucial.

StationaryPointandEigenanalysis The local minimum (stationary point) of the response surface is computed, pinpointing the configuration that minimizes egress time within the tested parameter space. Eigenanalysis of the second derivative matrix is performed to confirm the existence of a true minimum (positive eigenvalues) and to compare the sensitivity of the response to changes in gap length versus exit number. Findings here typically show that gap length exerts a greater influence on egress time than the number of exits.

Note: Although RSM is a comprehensive framework, for this thesis's parametric exit clustering analysis, only the travel time components (walking and flow) are considered as the main factors of interest. Pre-movement times, while relevant in emergency evacuations, are not included in the modeling scope here to maintain the study's focus on exit configuration performance.

Chapter 5

Pathfinder

5.1 SFPE and Steering Mode

In evacuation modeling, particularly within the context of the Pathfinder simulation software, two primary modes are utilized: the Society of Fire Protection Engineers (SFPE) mode and the Steering mode. These modes serve distinct purposes and employ different methodologies to analyze pedestrian behavior during emergency evacuations. A comprehensive examination of both modes provides insight into their respective strengths and weaknesses and the mathematical principles that underlie their functionalities.

SFPE Mode

The SFPE mode is grounded in a flow-based methodology, which simplifies the representation of pedestrian movement in evacuations. This approach focuses on aggregated behaviors and typically assumes that individuals do not attempt to avoid each other, which makes it easier to calculate optimal evacuation routes based on crowd density and flow rates. In *SFPE Mode*, occupant movement is modeled using flow-based calculations from the SFPE Handbook of Fire Protection Engineering [76]. The base occupant speed v_{base} is computed as:

$$v_{\text{base}} = v_{\text{max}} \cdot f_{\text{min}} + (1 - f_{\text{min}}) \cdot f(\rho) \cdot k$$

where:

- v_{max} is the occupant's maximum speed.
- f_{min} is the minimum speed fraction (default: 0.15).
- $f(\rho)$ is the speed-density curve based on the SFPE fundamental diagram.
- k is a terrain modifier (1 for level terrain; modified for stairs, etc.).

- ρ is the occupant density in the current room.

Movement through doors in SFPE Mode is constrained by flow rates defined by the SFPE guidelines, with the delay for each occupant to pass through a door calculated as:

$$t_{\text{pass}} = \frac{1}{(\text{specific flow} \cdot \text{door width})}$$

The *specific flow* depends on the densities of adjacent rooms and is bounded to ensure realistic flow rates [77].

The SFPE model often utilizes the concepts of RSET and ASET to ensure safety by predicting how long it takes for individuals to evacuate compared to the time available before conditions become untenable.

Steering Mode

In contrast, the Steering mode employs an agent-based approach, wherein each individual (agent) makes decisions based on their surroundings and interactions with others. This mode allows for the representation of complex behavioral dynamics, such as panic, flocking behavior, and individual route preferences. In *Steering Mode*, occupant motion is based on inverse steering behaviors, originally described by Reinolds [78] and refined by Amor et al. [79]. The base occupant velocity v depends on the modified maximum velocity v'_{max} and local density ρ' as:

$$v = v'_{\text{max}} \cdot f(\rho')$$

Here, ρ' is estimated from the local spacing of surrounding occupants using Fruin's spacing-density relationship [80]. This allows for smooth, natural motion in complex scenarios.

Acceleration in steering mode is split into tangential, radial, and separation components, computed as:

$$a_{\text{tangential}} = \frac{v - v_{\text{current}}}{\text{Acceleration Time}}$$

Movement direction is chosen by evaluating a cost function across multiple sample directions (e.g., avoiding walls, occupants, maintaining separation), with the final velocity and position computed via explicit Euler integration.

The inclusion of individual decision-making and interaction allows for a more realistic simulation of crowd dynamics, especially in cases of high stress or panic, leading to unpredictable outcomes such as bottlenecks or sudden directional changes.

Comparison of the Two Modes

Behavioral Dynamics:

- **SFPE Mode:** Utilizes averaged, aggregate behaviors which may overlook critical individual actions during emergencies. It is effective for estimating overall flow but may lack fidelity in portraying individual behaviors, potentially leading to underestimations of evacuation times in chaotic situations [81].
- **Steering Mode:** Captures the nuances of individual behavior, allowing for an analysis of how interactions within a crowd can influence flow and congestion. Research illustrates that the Steering mode can produce significantly different routing patterns and evacuation times compared to SFPE, particularly in complex environments where panic behaviors may arise [81].

Application Context:

- **SFPE Mode:** Best suited for scenarios where it is essential to maintain an overarching view of crowd dynamics, such as in building codes and fire safety regulations where general flow must be calculated rapidly based on fixed parameters.
- **Steering Mode:** More applicable in real-life situations where individual reactions can dramatically alter evacuation outcomes. This is particularly useful in large gatherings or high-density environments where the unpredictability of crowd behavior presents significant challenges [81].

SFPE mode offers a broader, simplified representation of crowd dynamics suitable for regulatory frameworks, the Steering mode incorporates the complexities of individual behavior, making it particularly valuable in scenarios where human factors significantly impact evacuation effectiveness. For this paper Steering mode was selected, as for the exit-cluster exercise it is essential to consider individual egress evaluations, to capture exit choice and rerouting.

5.2 Physical Layout

Pathfinder is a powerful tool capable of creating complex simulation environments, including multi-story structures, staircases, and elevators. However, to ensure simplicity and focus for the objectives of this study, only the fundamental components, rooms and doors, were utilized. This approach allows for a clear investigation of exit width and clustering effects without the additional complexities introduced by vertical movement or advanced architectural features.

A square-shaped layout was chosen to maintain a straightforward and consistent environment across all simulations. In the initial exit width experiment, a single door was positioned at the center of one of the square's sides to examine the influence of exit width on egress performance.

For the exit width experiment, three different square side lengths were considered: 100 m, 200 m, and 300 m. In each case, a constant occupant density was maintained, leading to occupancy levels of 1000, 4000, and 9000, respectively. This setup ensures that variations in egress performance could be attributed primarily to exit width rather than changes in crowd density.

For the exit clustering experiment, the clustered exits were treated as a single entity extending from the starting point of the first door to the endpoint of the last door. This entity was placed centrally on one side of the square layout, maintaining symmetry and simplifying analysis. The experiments for exit clustering were conducted in a 200 m sidelength square environment. For configurations with an odd number of exits, the middle exit aligned with the center of the square's side. For configurations with an even number of exits, the central gap between the two middle exits coincided with the square side's center. This ensures consistency in the placement of exit clusters, facilitating a fair comparison of their effects on egress performance.

5.3 Occupancy Settings

Despite this paper not intending to model a specific scenario or directly examine the effects of body dimensions, age, and walking speed in egress, it establishes an overview of the foundational settings in Pathfinder to reflect occupancy characteristics, so it can be set to be similar to a typical Danish festival environment. This ensures that the simulation results can be later fine-tuned to remain applicable and relevant to such festival settings. The chosen parameters, what mainly remains Pathfinder base settings,remain consistent throughout all simulations, providing a reliable baseline for future scenario-specific refinements.

Pre-Movement Time

Pre-movement time, defined as the delay between alarm activation and initial occupant movement, can significantly affect overall evacuation times. Studies show that occupants often hesitate or complete ongoing tasks before responding to evacuation signals. However, for this exercise, our focus is solely on movement time, as discussed in Methodology Section 4.3. Pre-movement time was therefore not set in Pathfinder, although it is fully supported by the software for concrete application modeling.

Gender Considerations

Gender differences in walking speeds have been documented in the literature. Males generally display slightly higher walking speeds compared to females. However, recent studies indicate that these differences are minimal in festival or crowd scenarios, where dense populations and shared space usage tend to equalize speeds between genders. Gender-specific movement profiles were not distinguished in this exercise. In addition for the body dimensions were left as the base setting in Pathfinder. This is based on validated world average data, which is in accordance with the high internationality of the festival scenarios as discussed in Section 2.5. In case of available statistics, different profiles can be set for genders, with varying body dimensions.

Age-Related Walking Speeds

Age plays an important role in determining walking speeds. Younger adults generally achieve the fastest walking paces, typically around 1.34 to 1.36 m/s. In contrast, older adults tend to move at slower speeds, with average values between 1.13 and 1.26 m/s due to age-related declines in mobility and agility [82]. Incorporating these variations is crucial when simulating evacuation scenarios with mixed-age populations to ensure that models mirror real-world behavior [83]. These data factors are sensitive and need validation before application, to reflect the geographical location and age distribution of the event. Since no exact statistics were available for this thesis scenario, and to keep focus on optimization, the occupant profiles were left as a base setting, which reflects a world average.

Exit Choice

The only behavior the behavior profiles must contain is the "Exit" behavior, therefore serving base of differentiation in behaviors. As this paper aims to capture rerouting and handle clusters, it does not wish to differentiate based on the preferences of occupants in choosing a specific door within a cluster. This was set in Pathfinder as leaving the base setting in place: Exit <any>.

Parameter Variability

Pathfinder offers multiple options for defining movement or physical parameters, including assigning constant values or utilizing statistical distributions such as normal or lognormal. For this exercise, constant walking speeds and body dimensions were applied to minimize variation in results, supporting better processing and data fitting later in the study. Future scenario refinements may incorporate probabilistic distributions better to represent individual differences within the same age group or to account for behavioral variability during large-scale evacuations.

Chapter 6

Experiment I. Door size

In evacuation scenarios for outdoor mass gatherings, the size of the exit plays a critical role in determining egress efficiency. This experiment aims to quantify the relationship between door (exit) width and the corresponding egress time in square venues of different sizes and occupancies. This foundational analysis informs later studies on exit clustering by establishing baseline relationships that serve as references for more complex exit arrangements.

Three primary scenarios are considered, representing small, medium, and large-scale outdoor event contexts:

- **1000 occupants in a 100×100 m (10,000 m^2) area**
- **4000 occupants in a 200×200 m (40,000 m^2) area**
- **9000 occupants in a 300×300 m (90,000 m^2) area**

6.1 Dataset Overview

The datasets capture the variation of **egress time**, **average egress time**, and **standard deviation** as a function of **door (exit) width**, ranging from narrow door widths (0.77 m) to wider exits (25 m). Table 6.1 provides a view into the structure of the raw data:

Occupants	Area (m^2)	Door Width (m)	Egress Time (s)	Avg. Egress Time (s)	Stdev (s)
1000	10,000	0.77	1108.7	553.1	316.9
⋮	⋮	⋮	⋮	⋮	⋮
9000	90,000	25	420.9	264	82.7

Table 6.1: Example of raw data [Own creation]

6.2 Data Visualization and Initial Observations

For all three scenarios, egress time decreases sharply as door width increases, particularly at smaller widths. This behavior aligns with crowd dynamics where narrow exits create bottlenecks, leading to the "faster-is-slower" phenomenon at high densities. See plotted egress data in Figure6.1

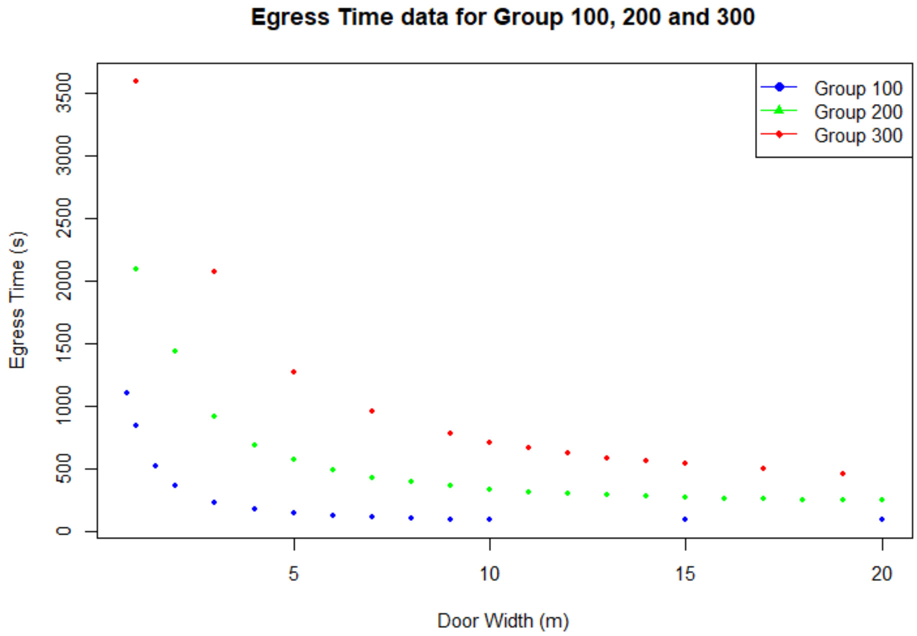


Figure 6.1: Egress Time plotted against Exit Width for the three scenarios, [Own creation]

Key trends:

1000 occupants (small scenario): egress time drops rapidly up to ∼4 m door width, beyond which diminishing returns appear.

4000 occupants (medium scenario): similar trend but higher absolute times and a more gradual decrease beyond ∼10 m door width.

9000 occupants (large scenario): significant initial improvements, with flattening beyond ∼15 m door width.

6.3 Model Fitting and Mathematical Interpretation

To model this relationship, a nonlinear regression approach was employed using the functional form:

$$\text{Egress Time} = \frac{a}{(\text{Door Width} + b)} + c$$

This function captures the hyperbolic decrease in egress time as door width increases, leveling off at a baseline time c.

Model Fits:

Small Scenario (10,000 m^2, 1000 occupants):

$$ET = \frac{636.2}{(W_{100} - 0.19)} + 25.8$$

High R^2 fit; parameters suggest rapid improvements up to ~3–4 m door width.

Medium Scenario (40,000 m^2, 4000 occupants):

$$ET = \frac{3026.1}{(W_{200} + 0.46)} + 62.8$$

Higher intercept; improvements in egress time extend up to ~10 m.

Large Scenario (90,000 m^2, 9000 occupants):

$$ET = \frac{7847.8}{(W_{300} + 1.2)} + 57.5$$

The largest absolute values indicate the significant impact of congestion in high-density settings.

6.4 Parameter Significance and Uncertainty

The **parameter estimates** from the fits (with their standard errors) highlight:

The scaling parameter a increases with occupancy and area size, reflecting larger crowd pressure in bigger venues.

The offset b, while small, adjusts the door width at which improvements become significant, accounting for behavioral and environmental variability.

The asymptotic baseline c captures the minimum achievable egress time given other physical and behavioral constraints.

Significance levels (p-values well below 0.01 for most parameters) indicate that these relationships are robust and not due to chance. The residual standard error is low, confirming the model's appropriateness.

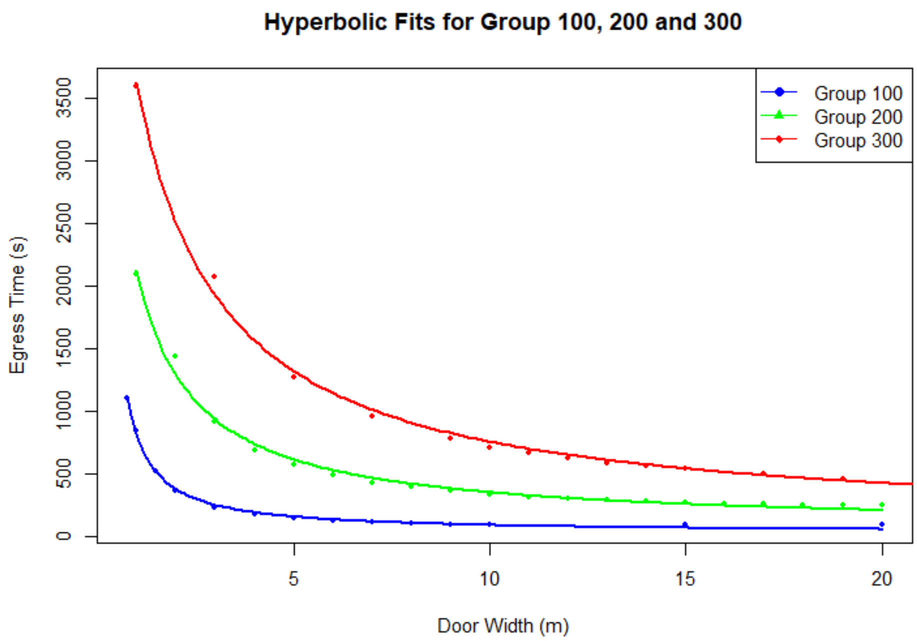


Figure 6.2: Fitted Models on Data for the 3 scenarios, [Own creation]

6.5 Practical Interpretation and Baseline Selection

The diminishing returns observed in the models show that simply increasing exit width has a point of diminishing safety benefits:

For smaller events (e.g., 1000 people), 3–4 m door widths already provide close to optimal egress times.

For larger events (e.g., 4000–9000 people), 10–15 m door widths are needed before the gains level off.

In line with these insights, the 12 m exit width in the 40,000 m^2 scenario (4000 occupants) was selected as the baseline exit configuration for subsequent clustering experiments. This width balances egress efficiency and practical feasibility (considering real-world spatial constraints and regulations).

6.6 Implications for Evacuation Planning

This chapter confirms that:

Door width is a critical factor for evacuation times, especially at narrow widths.

However, beyond a certain width, further widening provides limited benefit.

Occupancy density and crowd behavior amplify these effects, demanding careful, scenario-specific planning.

The relation between Egress Time and Exit Width is non-linear.

The findings provide a quantitative baseline for subsequent experiments on exit clustering (Chapter 7). They also offer practical guidance for event organizers and emergency planners: investing in optimal door widths tailored to expected crowd sizes can significantly reduce evacuation times and improve safety.

Chapter 7

Experiment II. Cluster

The evacuation efficiency of buildings is a critical aspect of safety design, and understanding how various architectural configurations influence egress time is essential for optimizing evacuation strategies. In this study, the influence of door clustering on egress time was investigated, focusing on two key factors:

- **Number of doors in the cluster**
- **Length of gaps between doors**

A systematic approach combining Design of Experiments (DOE) and the Response Surface Method (RSM) was used to model, analyze, and optimize these factors.

7.1 Experimental Design

Two factors were identified as primary variables:

- Number of doors: Ranging from 2 to 12, chosen to cover practical scenarios while maintaining a fixed cluster width of 12 m. This ensures that the total opening length does not itself bias egress performance, isolating the effect of door count.
- Length of gaps: Initially explored broadly from 0.1 m to 10 m to identify general trends and local optima.

The response variable was egress time, measured through simulation runs in Pathfinder.

The split of the cluster can be represented by:

Number of doors: direct count of door segments.

Length of doors: since total length = 12 m, this is simply:

$$\text{Length of doors} = \frac{12\,\text{m}}{\text{Number of doors}}$$

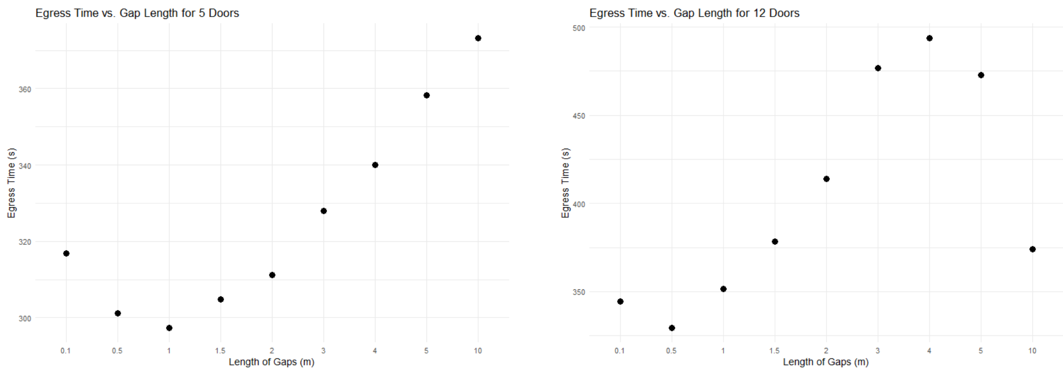
Both variables describe the same geometry, when the number of doors increases, the length of each door decreases, and vice versa, for the initial phase the number of doors were chosen as primary variable for the ease ofdata handling. All other factors, such as number of occupants, geometry of area, behavioral and profile settings of occupants were kept the same, to exclude them prom influencing factors. The Area was a 200 m side length square, with 4000 occupants, with behavior and profile identical as previously discussed in Section 5.3.

Exploratory Testing and Gap Refinement

An initial screening phase was conducted with sampling of gap lengths:

$$\{0.1\,\text{m},\ 0.5\,\text{m},\ 1\,\text{m},\ 2\,\text{m},\ 3\,\text{m},\ 4\,\text{m},\ 5\,\text{m},\ 10\,\text{m}\}$$

Examining the underlying dynamics for door counts 5 and 12. The plot of these results and the underlying data can be seen in Figure 7.1 and Table below.



(a) Explaratory testing on 5 doors

(b) Explaratory testing on 12 doors

Figure 7.1: Egress time in relation to gaps between doors for 5 and 12 door clusters [Own creation]

Early observations revealed a notable local minimum in egress time near a gap length of 1 m for the 5 door cluster and around 0.5 m for the 12 doors cluster. To refine this finding, additional data points were collected in the range 0.2 m–1.9 m, including all 0.1 m increments such as {0.2 m, 0.3 m, . . . , 1.8, 1.9 m.} This adaptive exploration ensured that the critical region around the observed local minimum was densely sampled. In addition on the 12 door cluster a potential maximum can be seen, to get a better understanding about this, but taking the already longer lengths into consideration, further data points were colected regarding {6 m, 7 m, 8 m, 9 m,} gaps.

Doors	Door length (m)	Gap length (m)	Egress Time (s)	Average Egress (s)	Stdev Egress (s)
5	2.4	0.1	316.9	185.8	74.4
5	2.4	0.5	301.1	178.6	69.6
5	2.4	1	297.3	176.4	67.9
5	2.4	2	311.2	180	70.7
5	2.4	3	327.9	182.2	73
5	2.4	4	340.1	183.2	74.7
5	2.4	5	358.3	184	77.4
5	2.4	10	373.2	182.5	80.9
12	1	0.1	344.4	195.9	80.8
12	1	0.5	329.3	183.1	71.6
12	1	1	351.7	186.1	75.2
12	1	2	414	197.1	86.1
12	1	3	476.8	206.3	96.2
12	1	4	493.7	209.8	100.6
12	1	5	472.9	206	95.2
12	1	10	374.2	198	89.8

Table 7.1: Summary of Egress Data for exploratory testing of gap length sampling [Own creation]

Final DOE Structure

The final dataset combined:

A broad exploration phase to capture global trends.

A dense, focused sampling around the identified local minimum.

For the number of doors, the following configurations were tested:

$$\{2, 3, 4, 5, 6, 8, 10, 12\}$$

This range balances practical relevance with model fidelity, covering typical and extreme door counts. Total cluster width: 12 m – constant throughout the experiments to isolate the effects of door count and gap length. Observations: Initial exploration revealed an S-shaped egress time trend, with local minima in the 0.5–1 m range and a potential maximum near 10 m. Adaptive refinement: Focused data collection in regions of greatest change to maximize modeling efficiency and precision.

Factor	Type	Levels
Number of doors	Discrete	2, 3, 4, 5, 6, 8, 10, 12
Length of gaps	Continuous	0.1 m to 10 m, with targeted sampling strategies: - **Initial exploration:** {0.1 m, 0.5 m, 1 m, 2 m, 3 m, 4 m, 5 m, 10 m} - **Refined sampling:** • 0.1–2 m region (dense sampling every 0.1 m: 0.1, 0.2, . . . , 1.9 m) • 2–10 m region (scattered sampling at 6 m, 7 m, 8 m, 9 m to capture global effects)

Table 7.2: Final Design of Experiments [Own creation]

Full factorial design for the discrete factor (number of doors). Dense and adaptive sampling for the continuous factor (gap length), balancing local detail with global trend coverage. Efficiecy: Prioritizing data where egress time variation is highest. Robustness: Sufficient coverage to enable reliable response surface modeling and optimization.

7.2 Application of RSM

7.2.1 Data Model Results

The results of the model can be seem below, as raw output from R.

```
    Call:
rsm(formula = Egress_Time ~ SO(Number_of_doors, Length_of_gaps),
    data = data.cluster.200)

                                Estimate Std. Error t value  Pr(>|t|)
(Intercept)                    276.68671    4.77047 57.9999 < 2.2e-16 ***
Number_of_doors                  1.07972    1.49356  0.7229  0.470418
Length_of_gaps                  14.91099    1.87003  7.9737 5.799e-14 ***
Number_of_doors:Length_of_gaps   1.11856    0.12356  9.0527 < 2.2e-16 ***
Number_of_doors^2                0.31939    0.10977  2.9097  0.003949 **
Length_of_gaps^2                -1.57536    0.18387 -8.5680 1.174e-15 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Multiple R-squared:  0.7976, Adjusted R-squared:  0.7935
F-statistic: 193.9 on 5 and 246 DF,  p-value: < 2.2e-16

Analysis of Variance Table

Response: Egress_Time
                                       Df Sum Sq Mean Sq F value    Pr(>F)
FO(Number_of_doors, Length_of_gaps)     2 295545  147773 402.926 < 2.2e-16
TWI(Number_of_doors, Length_of_gaps)    1  30055   30055  81.951 < 2.2e-16
PQ(Number_of_doors, Length_of_gaps)     2  30029   15014  40.939 4.492e-16
Residuals                             246  90220     367
Lack of fit                           246  90220     367     NaN       NaN
Pure error                              0      0     NaN

Stationary point of response surface:
Number_of_doors  Length_of_gaps
      -6.152527        2.548307

Eigenanalysis:
eigen() decomposition
$values
[1]  0.4721598 -1.7281314
```

```
$vectors
                      [,1]       [,2]
Number_of_doors -0.9646605 -0.2634961
Length_of_gaps  -0.2634961  0.9646605
```

Interpretation

The fitted model including all sampled points (0.1–10 m) was:

$$\text{Egress Time} = 276.69 + 1.08 \cdot N + 14.91 \cdot L_G + 1.12 \cdot (N \cdot L_G) + 0.32 \cdot N^2 - 1.58 \cdot L_G^2$$

where:

- N: Number of doors
- L_G: Length of gaps (m)

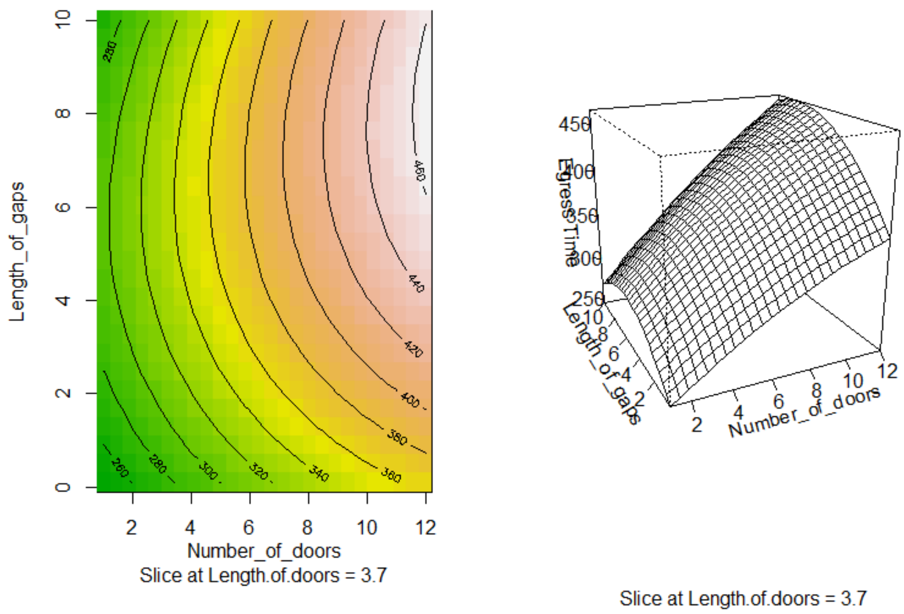
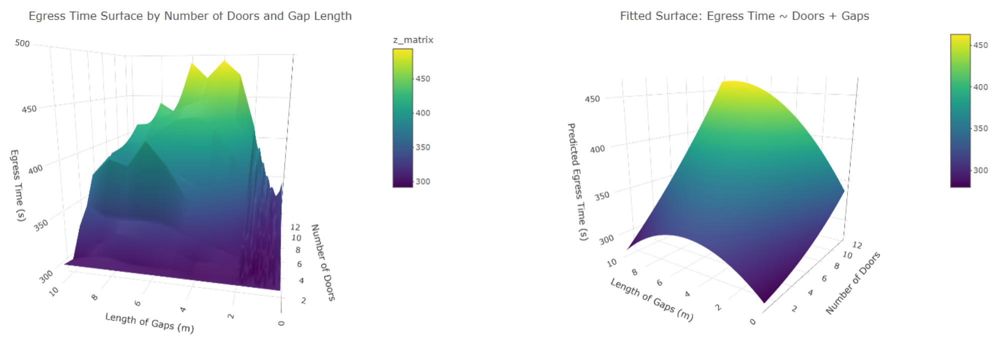


Figure 7.2: Fitted model to all data points observed, [Own creation]

Significant Effects:
Gap length has a strong positive linear effect (14.91, $p < 0.001$).
The quadratic term for gap length (-1.58) is negative, indicating an initial



(a) Simulation data plotted as surface

(b) Fitted surface

Figure 7.3: Visualisation of data and fitted surface [Own creation]

increase followed by a decrease after a turning point (evidence of a local maximum in the gap length effect).
The interaction term (1.12, $p < 0.001$) confirms that gap length and door count jointly influence egress time.

Weaker Door Count Effect:
The linear effect of the number of doors (1.08) is not significant ($p = 0.47$).
The quadratic effect (0.32, $p = 0.004$) suggests a mild non-linear influence.

Overall Model Fit:
Adjusted $R^2 = 0.7935$, explaining approximately 79% of variability.
The model provides a reliable framework for interpreting trends, especially in the critical region around the local minimum in gap length.

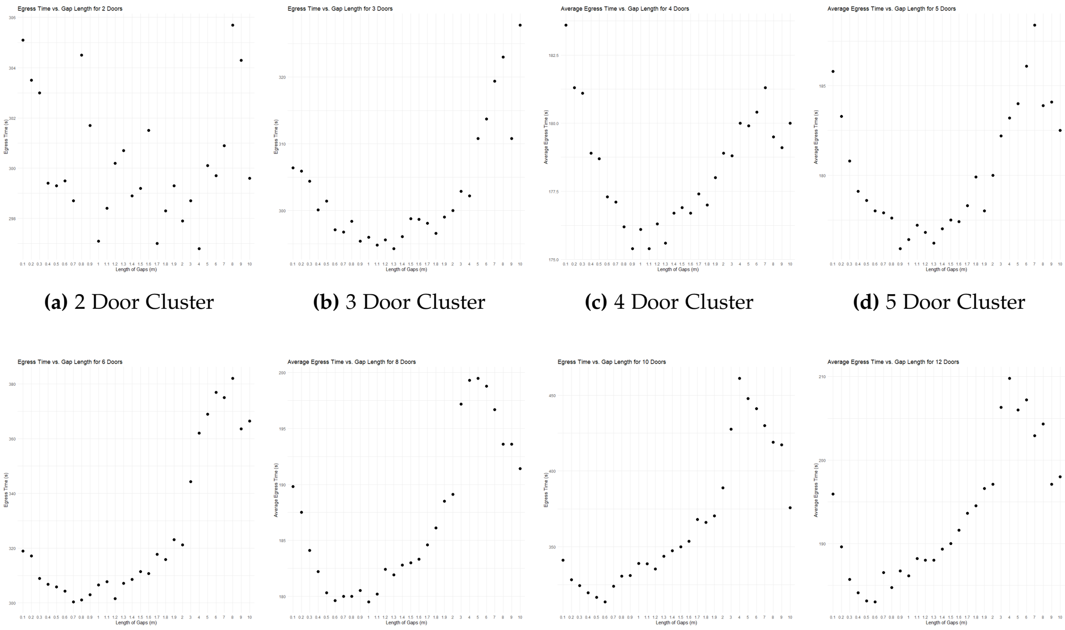
Stationary Point and Local Behavior

The stationary point of the response surface was identified at:

$$N \approx -6.15 \quad \text{(unrealistic, extrapolated)}$$

$$L_G \approx 2.55\,\text{m}$$

The negative door count value is not physically possible, indicating that the true minimum in the practical domain lies at the tested lower end (e.g., 2–3 doors). The eigenanalysis of the second derivative matrix yielded eigenvalues of 0.47 and -1.73, confirming that the stationary point is a saddle point (not a local minimum or maximum overall). This suggests that while locally there may be a minimum along gap length, globally the surface is more complex—consistent with the S-shaped behavior observed in earlier plots. This duality can still be seen in the detailed dataset in Figure 7.4.



(a) 2 Door Cluster **(b)** 3 Door Cluster **(c)** 4 Door Cluster **(d)** 5 Door Cluster

(e) 6 Door Cluster **(f)** 8 Door Cluster **(g)** 10 Door Cluster **(h)** 12 Door Cluster

Figure 7.4: Between Egress Time (ET) and Gap Lenght (L_G)for all Door Numbers (N) [Own creation]

7.2.2 Filtered Data Model Results

As the initially fitted model has a moderate fit and little real-life implications, and the detailed plots for each door number imply that two different mechanisms are in place regarding the egress time, data filtering was carried out. Only the gaps less than 2 m were considered.

The final fitted model was:

$$\text{Egress Time} = 328.13 - 6.49 \cdot N_F - 46.94 \cdot L_{GF} + 4.18 \cdot (N_F \cdot L_{GF}) + 0.59 \cdot N_F^2 + 15.81 \cdot L_{GF}^2$$

where:

- N_F: Number of doors in filtered data
- L_{GF}): Length of gaps in filtered data (m)

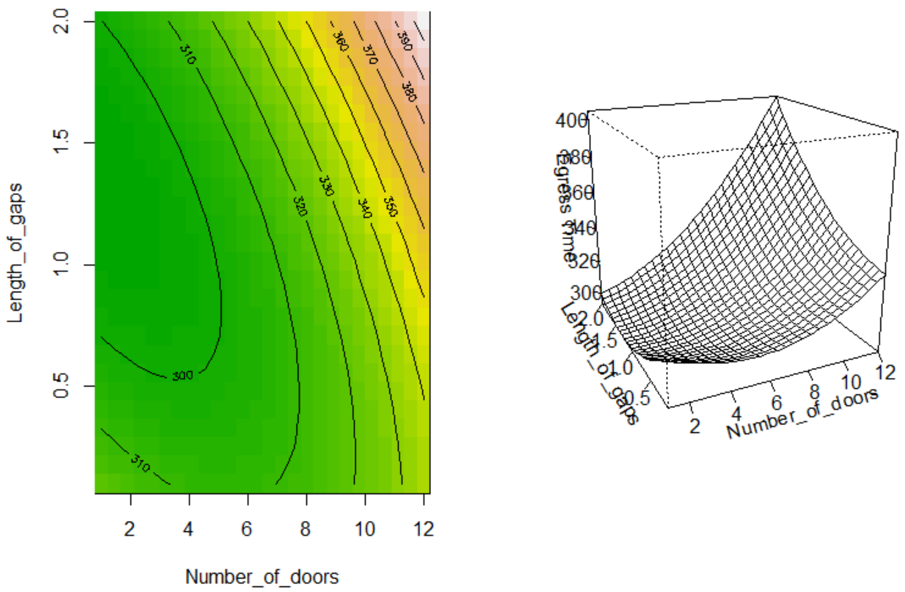
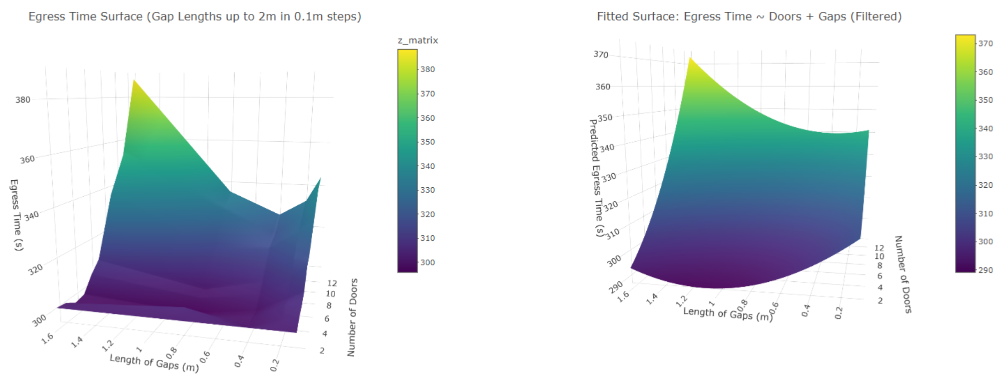


Figure 7.5: Fitted model to the filtered data points, [Own creation]



(a) Caption for Image 1

(b) Caption for Image 2

Figure 7.6: Relation between Egress Time (ET) and Gap Lenght (L_G) for all Door Numbers (N) [Own creation]

All terms were highly significant ($p < 0.001$), and the model achieved an **ad-**

justed R^2 of 0.942, indicating that it explains **94% of the variability** in egress time.

Key Insights

Main effects:

- **Number of doors**: Increasing the number of doors generally reduces egress time.
- **Gap length**: Egress time initially decreased as gap length increased, but only up to a point.
- **Quadratic terms**: Both factors exhibited diminishing returns. The quadratic terms confirmed that beyond certain gap lengths and door counts, the improvements in egress time level off or reverse.
- **Interaction**: The significant positive interaction term indicates that the effectiveness of adding more doors depends on gap length (and vice versa). This underscores the importance of jointly optimizing both factors rather than treating them independently.

Stationary Point and Local Minimum

The stationary point (local minimum) of the response surface was identified at:

$$\text{Number of doors} \approx 0.46$$
$$\text{Length of gaps} \approx 1.42\,\text{m}$$

While the gap length minimum of 1.42 m is physically plausible, the calculated minimum door count below 1 is not. This highlights that while the quadratic model accurately captures the trends within the observed data range, it extrapolates mathematically beyond physically meaningful values. In practice, this suggests that 2-3 doors are sufficient for optimal performance at the best gap length.

Eigenanalysis and Confirmation

The eigenanalysis of the second derivative matrix confirmed that:

- Both eigenvalues were positive (16.08 and 0.31), indicating a true local minimum.
- The response surface is more sensitive to changes in gap length (larger eigenvalue) than to the number of doors, suggesting that precise control of gap length has a greater influence on egress time reduction.

The response surface analysis identified significant linear, quadratic, and interaction effects for the number of doors and gap length. The quadratic terms confirm the existence of an optimal gap length (1.4m), while the interaction indicates that the benefit of increasing the number of doors depends on the gap length. Despite the mathematical minimum suggesting a door count below one, this is physically implausible and highlights that the model extrapolates beyond the feasible domain. Instead, the analysis should be interpreted as evidence that the optimal number of doors lies at the lower tested end (e.g., 2 or 3 doors) for minimal egress time at optimal gap lengths.

7.2.3 Comparation of Wide and Filtered data

Aspect	Full Data Model	Filtered Data Model
Intercept	276.69	328.13
Linear Effect of Doors	1.08 (not significant)	-6.49 (significant)
Linear Effect of Gap Length	14.91 (significant)	-46.94 (significant)
Interaction	1.12 (significant)	4.18 (significant)
Quadratic Doors	0.32 (significant)	0.59 (significant)
Quadratic Gap Length	-1.58 (significant)	15.81 (significant)
Adjusted R^2	0.7935	0.942
Stationary Point (Doors)	-6.15	0.46
Stationary Point (Gap)	2.55 m	1.42 m
Eigenvalues	0.47, -1.73 (saddle point)	16.08, 0.31 (local minimum)

Table 7.3: Comparison of Full Data vs. Filtered Data Surface Fit [Own Creation]

Interpretation of Table 7.3 The filtered data model provides a much better fit ($R^2 = 0.942$ vs. 0.7935) and identifies a physically realistic local minimum, suggesting more robust and interpretable results. This improved performance indicates that focusing on the smaller gap lengths (<2m) better captures the main evacuation dynamics and interactions relevant to practical exit clustering in mass gathering scenarios.

7.2.4 Possible Door Length Considerations

Door Length instead of Gap Length

Initially, it was considered to represent the number of doors in terms of total door length for the response surface modeling. However, this alternative fit did not yield results as robust as the original door count representation. The model using door length as a factor showed a slightly lower adjusted R^2 of 0.8947 compared to 0.942 for the filtered data model using door count.

Door Length incorporation in addition

An additional modeling attempt included both the number of doors and the total length of doors as predictors alongside the gap length. However, this approach faced severe issues with multicollinearity, leading to singularities in many model terms. The results showed that only the gap length and its quadratic term could be estimated, while the coefficients for door number and door length (and their interactions) were not defined:

```
Call:
rsm(formula = Egress_Time ~ SO(Number_of_doors, Length_of_doors,
    Length_of_gaps), data = filtered_data)

Residual standard error: 16.75 on 25 degrees of freedom
Multiple R-squared:  0.9025, Adjusted R-squared:  0.8947
F-statistic: 115.7 on 2 and 25 DF,  p-value: 2.316e-13
```

Given that the majority of model terms could not be estimated and the adjusted R^2 was similar to the simpler door length model (0.8947) and worse than the Door Number model (0.942), this three-factor approach was not considered further. .

In the course of regression modeling for the evacuation simulation analysis, a phenomenon known as singularities was encountered. In regression analysis, singularities arise when the model's design matrix becomes singular, meaning it cannot be inverted due to perfect multicollinearity among predictors. In practice, this occurs when one or more predictor variables (or their combinations) are exact linear combinations of others, making it mathematically impossible for the model to uniquely estimate their effects.

In this study, the inclusion of both the number of doors and the length of doors as separate predictors led to this issue. Since the length of doors is inherently linked to the number of doors (by design, as explained in Section 7.1), the predictors exhibit perfect or near-perfect collinearity. Consequently, the regression model was unable to differentiate the individual contributions of these predictors to the egress time. As a result, these coefficients were reported as "NA" in the output tables, indicating that the regression algorithm could not compute unique, meaningful estimates for these terms.

This occurrence underscores the importance of ensuring that predictors are not redundant or perfectly correlated in regression models, particularly in RSM applications. In this specific case, the inability to distinguish the individual effects of the number and length of doors justified the decision to focus the parametric analysis on the number of doors and the gap length only. These variables were sufficiently independent, allowing for reliable estimation of their effects on egress time without introducing singularities in the model. Because of these issues and to maintain a clear and interpretable model, focusing only on the number of doors (rather than also including door length) provided a more stable and interpretable fit, aligning with the study's goal of evaluating exit clustering configurations in mass gathering scenarios

7.3 Practical Implications and Recommendations

The RSM analysis provides a robust framework for design optimization:

- **Gap length optimization**: The optimal gap length for minimal egress time was identified as approximately 1.4 m.
- **Number of doors optimization**: Adding more doors helps up to a point, but the benefit tapers off due to quadratic effects and practical constraints.
- **Joint consideration**: The significant interaction effect means that optimal configurations must be determined by jointly considering gap length and door count.

These findings can guide the design of clustered door arrangements in buildings, ensuring that egress time is minimized while maintaining practical and architectural constraints.

By combining DOE with RSM, this study successfully identified and quantified the key factors and their interactions that govern egress performance in door clustering scenarios. The methodology, broad exploration followed by local refinement, ensured that both global trends and local optima were accurately captured. This approach and its findings can serve as a foundation for further work in evacuation safety design and contribute to developing data-driven, optimized building configurations.

7.4 Crowdflow Behind the Data

7.4.1 Congestion Maps

This figure below (Fig. 7.7) presents the maximum congestion maps, which illustrate the highest density of crowding (i.e., the peak "clogging factor" or congestion level) occurring throughout the evacuation in the 12-exit scenario. This means that the congestion that occurred is layered onto each other, regardless of the time at which they occurred. The congestion is defined here as the maximum movement-hindering effect of occupants due to density within a given area during the entire evacuation period, providing a clear visualization of crowd bottlenecks and flow patterns.

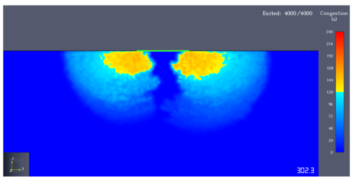
The 12-exit scenario was selected for this visualization as it demonstrated the most extreme congestion values, making it an effective example to illustrate the dynamic effects of gap lengths on evacuation performance. In this figure, we can observe a progression of congestion patterns:

Minimal gap lengths (0.1 m and 0.5 m): The exits effectively function as a single large opening. The congestion maps in these cases exhibit a fan-shaped pattern radiating from the exits, resembling the congestion fields typical of a single wide exit.

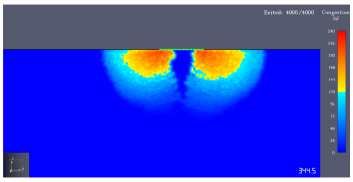
Gap lengths of 2 m and 4 m: The exits begin to operate more independently, though they still share a contiguous congestion field. The outer exits show larger congestion zones, while the inner exits develop smaller, localized bottlenecks that overlap with the outer zones, maintaining a single congestion field overall.

Gap length of 10 m: The congestion fields fully separate, with each exit developing its own distinct congestion zone. This indicates that at these larger gap lengths, the exits no longer act collectively as a single cluster but function as independent egress paths.

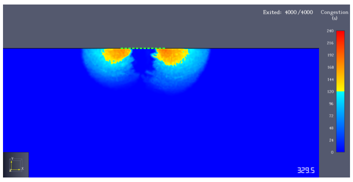
The figure below (Figure 7.7)illustrates the gradual transition from a dual, unified congestion field to separated, individual congestion zones as the gap length increases. Such insights are critical for understanding the interplay between exit clustering and crowd dynamics, offering evidence-based recommendations for optimizing exit placement and gap design in outdoor mass gathering scenarios.



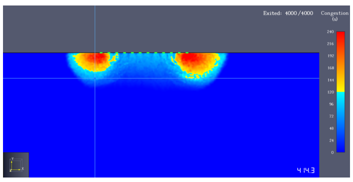
(a) Single open exit



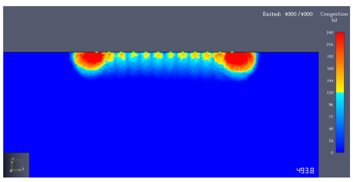
(b) 0.1m Gap Length



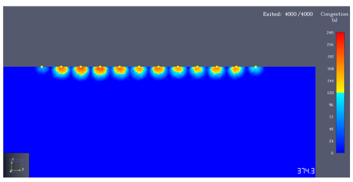
(c) 0.5m Gap Length



(d) 2m Gap Length



(e) 4m Gap Length



(f) 10m Gap Length

Figure 7.7: Max Congestion Maps for 12 Door Clusters for multiple scenarios [Own creation]

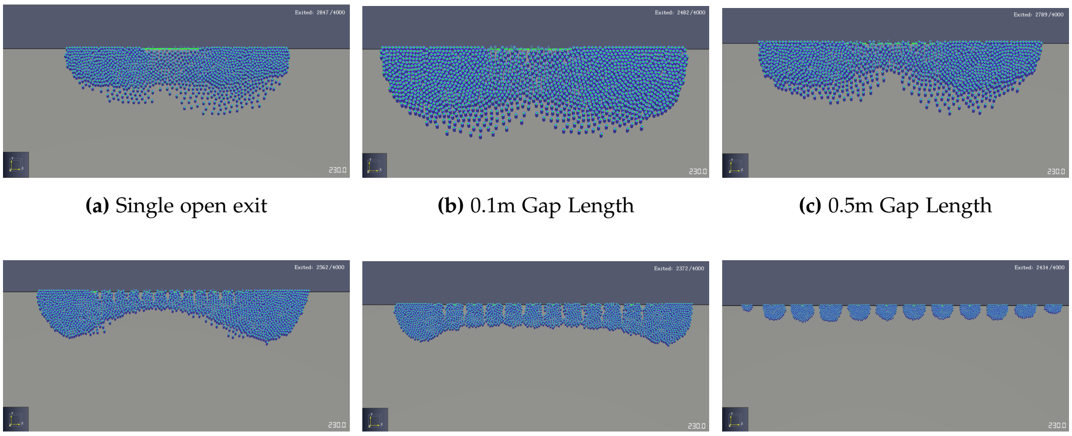
7.4.2 Occupant Flow Mid-Evacuation

In this next figure (Figure 7.8), the occupants and their movement directions are visualized. The examined scenario is still the 12-door configuration, and these images are snippets from the video result of the simulation, each captured at 230 seconds into the evacuation.

This visualization provides valuable insights into how different gap lengths affect crowd behavior and spatial patterns:

> One exit scenario: A uniformly outlined field of occupants is formed, with lower density in the middle of the crowd. This uniform shape reflects a highly utilized single exit with consistent crowd pressure across the exit width.
>
> 0.1 m and 0.5 m gap lengths: These scenarios are similar to the one-exit scenario; however, with the central density reduction more pronounced. The lower density in the middle indicates that while these gaps still act as a single opening, there is some tendency for occupants to avoid the absolute center.
>
> 2 m and 4 m gap lengths: The shape becomes narrower and transitions into a half hourglass-like configuration. Although the overall density remains similar to the smaller gaps, the crowd shape suggests reduced utilization of the middle doors, redused LoS, hinting at partial separation of the flows at the clustered exit.
>
> 10 m gap length: This scenario clearly shows that the exits act as separate, independent doors rather than as a cluster. Instead of one continuous crowd, there are distinct groups of occupants moving through each exit independently. Interestingly, at this stage, all exits are almost equally utilized, similar LoS, but the scenario also shows the formation of multiple small bottlenecks at each individual exit, rather than a single large congestion zone.

These visual snapshots offer an intuitive understanding of how exit clustering and gap lengths influence crowd behavior, complementing the quantitative analyses and congestion maps presented earlier. They highlight the gradual transition from a unified cluster to separate exit usage as the gap length increases, revealing the complex trade-off between exit separation and local congestion.



(a) Single open exit **(b)** 0.1m Gap Length **(c)** 0.5m Gap Length

(d) 2m Gap Length **(e)** 4m Gap Length **(f)** 10m Gap Length

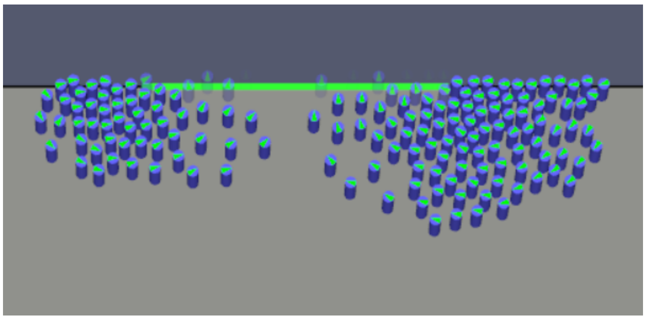
Figure 7.8: Crowd pattern for for 12 Door Clusters for multiple scenarios at 230s timestamp [Own creation]

7.4.3 Occupant Flow towards the End of Evacuation

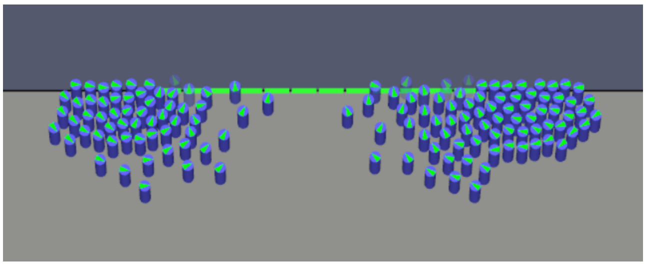
To evaluate how these crowds shape and evolve throughout the evacuation, screenshots were taken towards the end of the evacuation process. Comparing the one open exit scenario with the 0.5 m gap length cluster, we observe that they exhibit very similar flow patterns. In both cases, occupants initially gather at the sides of the exit or clustered exit, but as they are blocked by the density, they later redirect towards the emptier middle area. This adaptive behavior ensures that all available doors are utilized consistently up until the end of the evacuation (Figure 7.9), thus equalizing the LoS.

In the other figure (Figure 7.10), which visualizes the end stages of the 2 m and 4 m gap length scenarios, the impact of clustering on egress times becomes clearer. As the distance between exits increases, the redirection towards other exits becomes less common. While some occupants still redirect towards the closer side doors, the middle doors remain largely unutilized. This phenomenon leads to longer egress times, with the 4 m gap length scenario resulting in the longest evacuation duration, as only 4 doors are utilized in the final stages. In contrast, the 2 m gap length scenario sees 6 doors being used to various degrees by the end of evacuation.

These end-stage visualizations provide important insights into how exit spacing and clustering influence occupant behavior. They highlight the trade-off between exit separation and the adaptive flexibility of occupants to redirect towards less crowded doors, ultimately shaping overall evacuation performance.



(a) One exit



(b) 0.5 Gap Length

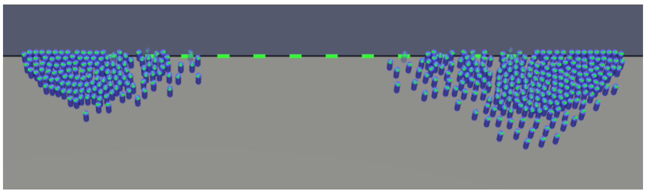
Figure 7.9: Crowd flow pattern late stage of evacuation [Own creation]

7.4.4 Optimal Situation

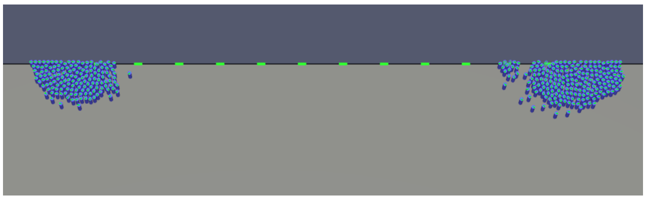
One of the optimal configurations identified through the RSM involves placing three doors 1.4 m apart. This arrangement still behaves as a single exit flow in practice, but instead of the standard 12 m net exit area, it effectively functions as a 14.8 m open exit. This slight increase in effective exit width directly contributes to reducing the overall egress time.

There is no need to visualize the 10-m gap length scenario towards the end of the evacuation, as the crowd configuration at that point closely mirrors the snapshot taken at 230 seconds and is consistent with the patterns shown in the congestion maps. In this scenario, the crowd is clearly separated into distinct groups, with the exits functioning independently rather than as a cluster. Occupant door selection appears to be primarily driven by their initial physical location relative to the exits, resulting in relatively balanced usage of all available doors despite forming several smaller congestion zones.

Interestingly, while the 4 m gap length scenario produced the longest egress time due to limited door utilization, increasing the gap length beyond this point led to a reduction in total egress time. This phenomenon underscores a critical insight: although clustering might initially seem beneficial, many safety guidelines



(a) 2m Gap Length

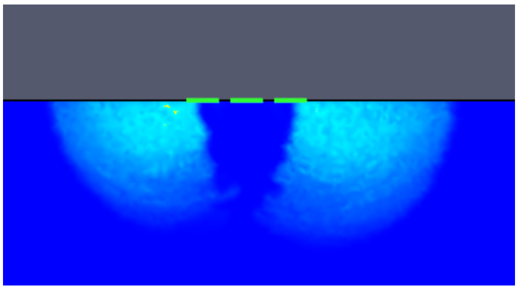


(b) 4m Gap Length

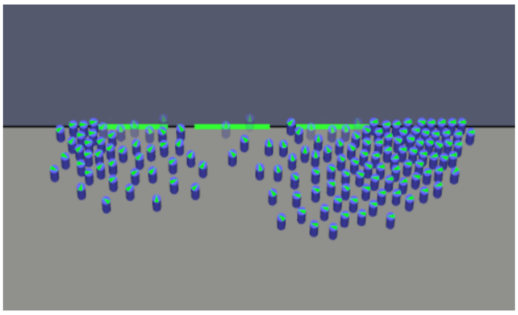
Figure 7.10: Crowd flow pattern late stage of evacuation [Own creation]

do not recommend clustered exit configurations, particularly in the 2 m to 10 m gap length range—precisely because it tends to hinder evacuation performance rather than improve it.

This improvement is also evident in the maximum congestion visualizations. The flow of occupants in this scenario is not significantly hindered, with the congestion map showing a continuous, well-utilized exit field. These observations highlight how carefully configured small gap lengths can enhance evacuation efficiency without introducing significant bottlenecks or congestion zones.



(a) Max Congestion



(b) Crowdflow at late stage of evacuation

Figure 7.11: Congestion and crowd flow of optimized configuration [Own creation]

Chapter 8

Discussion

One of the key findings of this work is that while exit clustering can reduce egress distances for some occupants, it can also create congestion bottlenecks if not optimally configured. The analysis of different gap lengths and exit counts has highlighted that there exists an optimal gap length of approximately 1.4 m, beyond which the marginal benefits of additional exits decrease or even become counterproductive. This insight aligns with broader observations in evacuation modeling literature, where excessive exit clustering can lead to uneven crowd pressures and delays rather than facilitating smoother egress.

The Danish regulations and EU directives offer a solid framework for ensuring the safe and effective placement of exits. However, there is no explicit mention of exit clustering in the Danish regulations, suggesting a potential gap in national guidance. EU directives and guidelines generally discourage clustering of doors, which is related to the adverse effect of 2 m-10 m clustering. This study showcased that indeed these scenarios lead to unutilized exits; still, closer clustering can be proven beneficial, as with the optimal distance, the separate doors, despite separation, exhibit the characteristics of one big opening. The findings from this study provide practical recommendations for event organizers and venue designers to consider clustering effects in their emergency planning, moving beyond simple regulatory compliance towards evidence-based optimization.

The use of Pathfinder simulation software proved instrumental in exploring these complex dynamics. Pathfinder's agent-based framework enabled detailed simulations of crowd movement, accounting for both individual and group behaviors. Despite its strengths—intuitive usability, flexibility, and robust validation (as highlighted in Thunderhead Engineering's documentation)—it became apparent that simulations with higher occupancy and more complex configurations demanded significant computational power. This computational challenge suggests the need for powerful hardware or cloud-based solutions when planning evacuations for large-scale events.

While the initial data fitting was not perfect and contained some outliers, the application of Pathfinder has a built-in Monte Carlo feature that can help account for these stochastic variations, providing more robust estimates of evacuation times and flow rates. In an extended scope study, the utilization of this data stabilizing feature is recommended.

While the simulations were validated against peer-reviewed literature and Pathfinder verification documentation, the absence of large-scale real-world evacuation exercises or field experiments represents a limitation. Future studies could address this gap by collaborating with event organizers or emergency services to conduct controlled evacuation drills, thereby enhancing the external validity of these findings.

The limitations of this work—such as focusing only on exit clustering, using a single crowd profile, and considering only the Danish context—should be acknowledged. Nevertheless, these constraints also present opportunities for future research. For instance, future studies could explore how clustering interacts with other exit characteristics (e.g., signage, lighting, or accessibility features), demographic variations (e.g., age or mobility impairments), and environmental factors (e.g., weather conditions at outdoor events).

Additionally, the methodology employed in this study—integrating systematic parameter variation with simulation-based analysis—can be extended to other aspects of crowd safety. There is substantial scope for developing a comprehensive framework that incorporates multiple factors influencing evacuation performance, such as exit width, crowd density, and social behaviors. Moreover, the dynamic interplay between psychological responses and environmental triggers (e.g., how people perceive exit availability during emergencies) could be modeled to better understand real-world crowd behavior during critical incidents.

8.1 Further Research Directions

As with any focused research study, the scope of this thesis was necessarily limited by practical constraints, including time and available resources. Consequently, several areas of potential extension and refinement remain open for future investigation.

1. **Expand the Exit Clustering Model:** The current study focused on a single scenario of exit clustering using a uniform square-shaped area and fixed

occupant density. Future work could enrich the model by incorporating a broader set of variables, such as variations in area size, area side lengths, and total occupancy levels. This would allow for a more nuanced understanding of how clustering interacts with other spatial and crowd-density factors, and how these interactions affect egress performance in a wider range of real-world scenarios.

2. **Integrate with Exit Positioning Studies:** Building on previous work, such as the mentioned studies on exit positioning [64], future research could compare the effects of exit clustering directly with exit positioning strategies. This would help to evaluate whether exit clusters can be treated as one continuous egress point across different spatial positioning scenarios, or whether the clustered exits' effects vary based on their placement within the event area.

3. **Investigate Behavioral Differences in Exit Clustering:** Future studies could examine how behavioral factors—such as substance abuse, panic reactions, or varying levels of situational awareness—might influence the utilization of exit clusters. Understanding these human factors is crucial for refining simulation models and improving the real-world applicability of exit clustering strategies in dynamic and unpredictable festival environments.

4. **Application in Real-world Events:** Finally, a logical next step would be to validate the simulation-based findings by applying the recommended exit clustering configurations in a real-world event scenario. This would involve collaborating with event organizers to implement the recommended configurations at an actual festival and using video-based crowd monitoring systems to collect empirical data on flow rates, congestion, and overall evacuation efficiency. Such an empirical validation would bridge the gap between theoretical modeling and practical application, contributing valuable insights to both the research community and the event management industry.

These future research directions are good ways to build upon the insights developed in this thesis, and to develop practical, evidence-based strategies for improving crowd safety and evacuation efficiency in mass gatherings.

Chapter 9

Conclusion

This thesis has provided a thorough investigation into how exit clustering affects evacuation efficiency and crowd dynamics in outdoor mass gatherings in Denmark. The analysis demonstrated that there is an optimal gap length for clustering that minimizes evacuation times and avoids detrimental bottleneck effects. By using Pathfinder simulations, this study generated quantitative insights that can support safer venue designs and emergency plans for large-scale events.

Despite some data inconsistencies and the inherent challenges of simulation-based approaches, this work underscores the potential of advanced modeling tools like Pathfinder to inform real-world decisions. Importantly, the conclusions drawn here highlight the necessity of considering both spatial configurations and human behaviors in crowd safety planning.

In the future, this research can serve as a foundational framework for more comprehensive studies that incorporate additional parameters and real-world data. By bridging the gap between simulation modeling and practical event management, this work aims to contribute to the ongoing improvement of crowd safety in outdoor events, aligning with broader goals in emergency management and public safety.

List of Figures

List of Tables

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Vancouver-based hybrid style was applied for referencing. [1]

[1] All ideas, arguments, and interpretations in this paper are entirely my own. Upon conducting research I only used ChatGPT purely to help with sentence flow and refining structure, LaTeX coding, ensuring my original content was clear and well-organized.