Emergency exit layout planning using optimization and agent-based simulation

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Abstract

Evacuation preparedness includes ensuring proper infrastructure, resources and planning for moving people from a dangerous area to safety. This is especially important and challenging during mass gatherings, such as large concerts. In this paper, we present the Emergency Exit Layout Problem (EELP) which is the problem of locating a given number of emergency exits and deciding their width such that the time it takes to evacuate the crowd from an arena is minimized. The EELP takes into account the geography of the arena and its surroundings, as well as the number of pedestrians in the crowd and the distribution of these within the arena. The EELP is formulated as a two-stage stochastic mixed integer linear program to handle the uncertainty related to the location of the possible incidents and the distribution of the pedestrians. Two cases are studied, a large concert planned at the Leangen trotting track in Trondheim and a smaller indoor arena. For each case, the EELP is solved for different scenarios, and the suggested layouts are evaluated using an agent-based simulation model. In particular, the potential of incorporating detailed assessment regarding the location and probability of specific incidents and the distribution of pedestrians are investigated. The computational study shows that making a more detailed risk assessment has little effect on the large concert, but a significant impact on the location of the emergency exits for the smaller indoor case. The results also indicate that it is more important to consider the location and probability of specific incidents rather than the pedestrian distribution.

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1 Introduction

Evacuation preparedness includes ensuring proper infrastructure, resources and planning for moving a crowd (of people) from a dangerous area to safety. This is especially important and challenging during mass gatherings, such as large concerts and other events. One vital component is the layout of emergency exits, including determining how many exits are needed and how large (wide) they should be. A good emergency exit layout shortens the evacuation time and gives firefighters and paramedic personnel faster access to the fire and the people injured by the fire.

When planning for a large event, ensuring the safety and security of the visitors includes assessing the risk and consequence of different incidents and planning the emergency exit layout among other things. For example, in Norway, risk advisors would create a comprehensive risk and safety assessment, including which scenarios are most likely to occur and how to prepare for them. Additionally, the advisors prepare calculations and arguments to motivate the number of tickets sold and a design for the safety arrangements. Then, the assessment is sent to the Police for evaluation to ensure that all safety requirements are met, and to the Fire department which approves the fire safety arrangements. The municipality also organizes a meeting in which the emergency services meet with the event organizer to contribute to the risk and safety assessment and general preparation prior to the event (H. Vidarsson, personal communication, September 2020).

Previous related research includes studies on how people behave during an evacuation, e.g., how they interact with each other and how they choose which exit to use. There are also studies on how to improve the evaluation flow, e.g., through architectural design, exit locations, signs and other information.

Simulation is commonly used to study pedestrian evacuation, and approaches can be divided into macroscopic, social force-based, Cellular Automata-based and agent-based modeling (Chen et al. 2021). In a macroscopic approach, evacuees are in general not modeled individually, but represented as flows between nodes or zones. In social force modeling, each pedestrian is viewed as an entity, subject to social forces, e.g., from other pedestrians (Helbing and Molnár 1995). For instance, in Helbing and Molnar (1998), evacuation from a room with limited visibility is simulated with so called evacuation leaders, who are the only ones aware of the exact location of the exits. Then there is a social force that pulls the other evacuees to follow the leaders. In a Cellular Automata model, the geography may be divided into discrete cells, where each cell can fit only one individual. At each time interval, the states of the cells evolve, which e.g., in Zhang et al. (2018) means that an individual in a cell might move to an adjacent cell if this is beneficial. In agent-based modeling, each pedestrian is an agent who interacts with the environment and other agents according to specific rules. For example, in Yang et al. (2009), emergency evacuation of a public square is simulated, where each agent has different characteristics, e.g., in terms of speed and familiarity with the environment.

Vermuyten et al. (2016) describe three different problem types where the first consists of developing optimal evacuation plans for large buildings with multiple

exits. The second type of problem is concerned with improving pedestrian flow through a bottleneck (as e.g., Helbing et al. (2007) and Seyfried et al. (2009)) and the third type of problem is improving the safety of pedestrians at mass gatherings through the study of crowd management. The last problem type is not necessarily related to disasters, but aims to prevent injuries caused by crowd phenomena such as congestion and clogging (Selim and Al-Rabeh 1991).

Most relevant for our paper are studies aiming to evacuate pedestrians from an area with multiple exits. Ronchi et al. (2016) present a model that simulates three different disaster evacuation scenarios at a festival arena. The results can be used to identify factors, e.g., bottlenecks, that affect the evacuation. Shi et al. (2009) provide a model that simulates the evacuation of large buildings in the event of a fire. Both papers aim to provide models for decision support when designing architectural plans for buildings or large outdoor areas. However, they do not specifically compare different solutions or suggest optimal solutions.

On the other hand, Abdelghany et al. (2014), Zhang et al. (2016), Duives and Mahmassani (2012) and Tissera et al. (2014) introduce models that provide optimal route plans for a given environment with emergency exits and evaluate these according to selected key performance indicators. Abdelghany et al. (2014) do this by giving people in different subareas of a concert venue evacuation instructions, such as time to start the evacuation and where to leave the building. Zhang et al. (2016) aim to optimally direct pedestrians from a metro station during evacuation, based on calculations such as the length of the path and the density of people. The objective of Duives and Mahmassani (2012) is to build a realistic model that evaluates four exit choice strategies. Equivalently, Tissera et al. (2014) compare the performance of two exit choice strategies for a given environment.

Another objective of several papers is to compare the performance of different exit designs. Wagner and Agrawal (2014) presents a prototype to simulate fire disaster scenarios for concert events and compare the performance when adding exits and varying the size of the audience. Similarly, the model developed by Kasereka et al. (2018) compares the performance of different exit layouts during the evacuation of a supermarket. Liu (2015) also compares different exit designs, but in addition, other factors in the environment are altered, such as staircases. The model developed by Şahin et al. (2019) is used to test the influence of exit width on congestion and total evacuation time. Their results show that in the general case, evacuation time, as can be expected, will increase when the exit width decreases and when the number of evacuees increases. However, in some instances, the evacuation time increases even when the number of evacuees decreases, and the authors explain that this may be due to herding, arching and clogging. Related to this phenomenon is the "faster-is-slower effect", which means that when people are in a hurry to get out (thus highly competitive), the risk is greater that narrow exits become clogged. Zhang et al. (2017) study this problem by forcing crowds of mice through exits of varying width, and conclude that if the exit is wide enough to allow for two mice passing through at the same time, the faster-is-slower effect can be avoided. It may be noted that this effect was not observed by Seyfried et al. (2009), who conducted similar experiments, but with people instead of mice, and without introducing a highly competitive

state (evacuation was calm and controlled). Their results showed a linear growth of the flow with the exit width.

In much of the previous work on optimized emergency exit location and design, different layouts are constructed by hand (trial and error) and tested using computer simulation. For example, Tavares (2009) aim to find the optimal positions of one or two exits from a square room and simulate the evacuation time for a set of different scenarios. The results show, among other things, that two 1-meter wide exits can (depending on the position) give a shorter evacuation time than one 2-meter wide exit. Lei and Tai (2019) also show that when having an equivalent total width, two exits are more efficient than one. Selin et al. (2019) build a game-engine-based simulation model to study emergency exit planning. They incorporate customized user profiles to simulate the movement of handicapped and elderly people, and simulate a fire incident in a shopping center. Ma et al. (2021) develop a simulation model that incorporates a pedestrian exit selection strategy model. Testing different exit designs, they discover that the total utilization of two exits drop if they are placed too close to each other, since the pedestrians may sway in choice between the two. In general, having two exits on different walls seems better than having two exits on the same wall. Gao et al. (2022) also focus on exit choice modeling and identify four factors that influence exit choice preference: age, gender, distance to exit, and crowdedness of the exit. This is combined with system-level exit assignment optimization and used to study evacuation from an outdoors museum using agent-based simulation.

Some recent studies have also been done, in which mathematical models have been used to obtain suggestions on where to locate emergency exits. Gao et al. (2020) use a constraint-based approach and a branch-and-bound solution methodology to find the optimal locations of the exit doors in a building. They test their method on two different real cases, museums, and find that it is possible to reduce the evacuation times between 7.5% and 16.2%, using optimized door locations. Another example is Khamis et al. (2020) who find the optimal locations of emergency exits in a multi-room building using artificial bee colony optimization. From the original designs with which they compare their results, they show a decrease in evacuation time by up to 39%.

More examples of studies trying to optimize crowd evacuation can be found in Haghani (2020), who indicates that more work is needed in the prescriptive domain, trying to find ways to actually improve the way people evacuate, rather than just studying how it is done today.

The purpose of our paper is to give additional insight into how emergency exit planning affects the efficiency of an evacuation due to a major incident at an event. To do this, we define the Emergency Exit Layout Problem (EELP) as the problem of locating a given number of emergency exits around an arena and deciding their width so that the time it takes to evacuate the crowd is minimized. The EELP takes into account the geography of the arena and its surroundings, as well as the number of pedestrians in the crowd and the distribution of these within the arena. We formulate the problem as a two-stage stochastic mixed integer linear program to handle the uncertainty related to the location of the possible incidents and the distribution of the pedestrians. The behavior of the pedestrians is incorporated by defining two

objectives of the model and solving it using a lexicographic approach. To evaluate different locations, we also develop an agent-based simulation model. Using this tool when preparing for events, it is possible to get suggestions for emergency location layouts and also compare different layouts and evaluate different scenarios.

Compared with previous research, we explicitly model the exit layout problem, incorporating the number, width and location of the exists together with the behavior of the pedestrians, into one optimization model, something that has not been done before, to the best of our knowledge. Thus, the gap we are addressing is the lack of models for getting suggestions on how to locate and design emergency exits, as compared with models for evaluating existing or manually produced designs.

The paper is organized as follows. Section 2 presents the problem and gives a formal description of the EELP. Furthermore, the two-stage stochastic mixed integer linear programming formulation of the problem is given. Section 3 presents the simulation model used to assess the suggested layouts. In Sect. 4, the cases used to test the models are presented. The first case is a large concert by the band Rammstein in the Norwegian city Trondheim and the second is a smaller indoor arena. The associated input data is also described in the section. Then comes the computational study in Sect. 5 before the conclusions are given in Sect. 6.

2 Problem description and formulation

The Emergency Exit Layout Problem (EELP) is defined over an arena with a given boundary. A given number of emergency exits with a bounded total width can be placed along the boundary. The total width is divided into equally sized modules, and an integer number of modules can be placed at an emergency exit. The number of modules allocated to different exits can vary. The maximum number of pedestrians that can leave through an exit in a given time period is linear in the width of the exit, in consistence with previous studies, e.g., Seyfried et al. (2009).

The crowd is distributed over the arena from a given distribution function. Incidents, such as a fire alarm or an explosion, can occur that force the crowd to evacuate through the emergency exits. The evacuation time is counted from the time of the incident until a predefined number of pedestrians have left the arena through the emergency exits. The decisions in the EELP are where to locate the emergency exits, the width of each exit and which exit each pedestrian should use. The goal is to minimize the expected evacuation time.

The decisions can clearly be divided into design decisions and execution decisions. Design decisions, that is, locating exits and deciding their width, are made by the organizer prior to the incident, while execution decisions, that is, choosing the exit and the path to it, are made by pedestrians after the incident. This decision structure can be captured in a two-stage stochastic formulation where the first stage is the design stage and the second stage is the execution stage. The multitude of possible incidents and pedestrian distributions can be expressed through scenarios in the formulation so that the expected evacuation time can be approximated.

We formulate the EELP as a two-stage stochastic mixed integer linear program. First, we discretize the arena and divide it into a set of zones $\mathcal{Z}$ and the boundary into
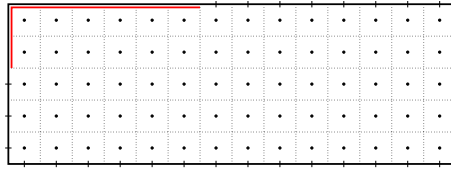
Fig. 1 The arena, marked with the solid black rectangle, is divided into zones, marked with thin dotted lines. The black dots are the centers of the zones, and the ticks on the boundary are the set of possible exit points. The part of the boundary marked in red cannot be used for emergency exits

a set of possible exit points $\mathcal{P}$, see Fig. 1. We also introduce $\mathcal{T}$ as the set of time periods and $\mathcal{S}$ as the set of scenarios. The predefined number of exits to locate is N, and B modules of width W can be placed at the exits to determine their width. The maximum number of pedestrians that can leave through a module per time period is denoted by K. The number of pedestrians in zone i in scenario s just before the incident is R_{is}. We use H to indicate the number of pedestrians that must have left the arena for it to be considered evacuated. The probability of scenario s is ρ_s.

We introduce y_p which is 1 if an emergency exit is located at exit point p, and 0 otherwise, and s_p for the number of modules used for exit point p. We take a macroscopic view on the pedestrians and do not model them individually, but as continuous flows. The flow through an emergency exit is modeled using queues and f_{ipts} is the number of pedestrians from zone i entering the queue of exit point p in time period t and scenario s. The number of pedestrians in the queue at exit point p at the beginning of time period t in scenario s is denoted by q_{pts} and the number of pedestrians exiting through exit point p in time period t and scenario s is denoted by e_{pts}. Finally, w_{ts} is 1 if at least H pedestrians have left the arena at time period t in scenario s and 0 otherwise. The problem can now be formulated in the following way

$$z^T = \min \sum_{s \in \mathcal{S}} \rho_s \sum_{t \in \mathcal{T}} t w_{ts} \tag{1}$$

$$\sum_{p \in \mathcal{P}} y_p = N \tag{2}$$

$$\sum_{p \in \mathcal{P}} s_p = B \tag{3}$$

$$s_p \leq B y_p \quad p \in \mathcal{P} \tag{4}$$

$$\sum_{p \in \mathcal{P}} \sum_{t \in \mathcal{T}} f_{ipts} = R_{is} \quad i \in \mathcal{Z}, s \in \mathcal{S} \tag{5}$$

$$\sum_{t\in\mathcal{T}} f_{ipts} \leq R_{is}y_p \quad i\in\mathcal{Z}, p\in\mathcal{P}, s\in\mathcal{S} \tag{6}$$

$$\sum_{i\in\mathcal{Z}} f_{ipts} + q_{pts} = e_{pts} + q_{p,t+1,s} \quad p\in\mathcal{P}, t\in\mathcal{T}, s\in\mathcal{S} \tag{7}$$

$$e_{pts} \leq Ks_p \quad p\in\mathcal{P}, t\in\mathcal{T}, s\in\mathcal{S} \tag{8}$$

$$\sum_{p\in\mathcal{P}} \sum_{\tau\in\mathcal{T}|\tau\leq t} e_{p\tau s} \geq Hw_{ts} \quad t\in\mathcal{T}, s\in\mathcal{S} \tag{9}$$

$$\sum_{t\in\mathcal{T}} w_{ts} = 1 \quad s\in\mathcal{S} \tag{10}$$

$$f_{ipts} \geq 0 \quad i\in\mathcal{Z}, p\in\mathcal{P}, t\in\mathcal{T}, s\in\mathcal{S} \tag{11}$$

$$q_{pts}, e_{pts} \geq 0 \quad p\in\mathcal{P}, t\in\mathcal{T}, s\in\mathcal{S} \tag{12}$$

$$s_p \in \{0,\dots,B\} \quad p\in\mathcal{P} \tag{13}$$

$$y_p \in \{0,1\} \quad p\in\mathcal{P} \tag{14}$$

$$w_{ts} \in \{0,1\} \quad t\in\mathcal{T}, s\in\mathcal{S} \tag{15}$$

The objective function (1) minimizes the probability weighted evacuation time. Constraint (2) and (3) state the number of emergency exits and modules available, respectively. Constraints (4) make sure that no modules are used at exit points without exits. The total flow from a zone is handled in constraints (5). Constraints (6) ensure that there is no flow to an exit point without an exit. The flow through an exit point is balanced in constraints (7), while the capacity of an exit is given by constraints (8). The relationship between the flow through the exits and the number of pedestrians that must have left the arena for it to be considered evacuated is stated in constraints (9). Constraints (10) make sure that exactly one evacuation time is chosen for each scenario. Finally, constraints (11) to (15) define the variables.

A scenario is a combination of a pedestrian distribution, i.e. the number of pedestrians in each zone just before the incident, and a cause for evacuation. The cause can be a general evacuation without visible indications, caused by, for example, a fire alarm, or an incident such as an explosion or fire. A fire is modeled with a center position and a radius and can limit the line of sight of the pedestrians. Figure 2 shows a small example where the arena has a boundary, marked with a thick black line, and two emergency exits, e_1 and e_2. For a pedestrian standing at i, the fire at f with radius r blocks the line of sight of the boundary marked in red. Therefore, the pedestrian cannot use e_1 in this scenario, but must leave the arena through e_2.
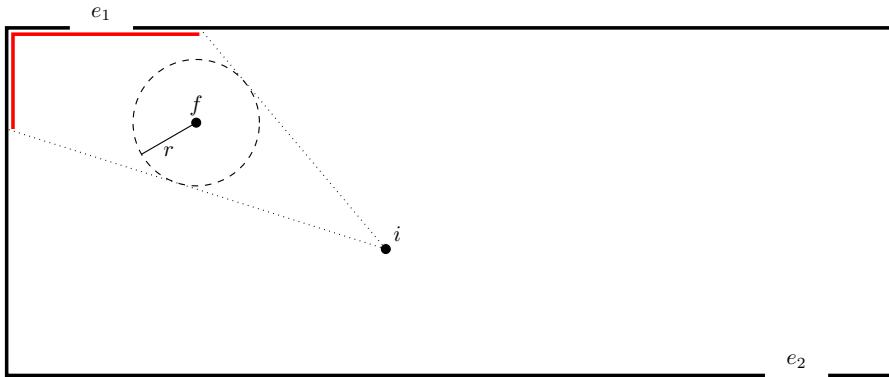
Fig. 2 An example of a fire limiting line of sight. The pedestrian at i cannot use e_1 in this scenario but must leave the arena through e_2

We have analyzed the formulation to reduce the number of variables and thus strengthen it. We can calculate the part of the boundary that is out of sight from the center of each zone in each scenario a priori and define $\mathcal{P}_{ip}$ as the set of exit points on the part of the boundary that is out of sight from the center of zone i in scenario s. If we also use the distance D_{ip} from the center of zone i to p and the average speed of the pedestrians V, then we can restrict f_{ipts} and change variable declaration (11) to

$$f_{ipts} \geq 0 \qquad i \in \mathcal{Z}, s \in \mathcal{S}, p \in \mathcal{P} \setminus \mathcal{P}_{is}, t \in \mathcal{T} \mid t = \lceil D_{ip}/V \rceil \tag{16}$$

The variables from constraints (11) which are not declared in constraints (16) are set to 0. The total number of pedestrians in the crowd and the capacity of the exits are used to restrict w_{ts} and we change variable declaration (15) to

$$w_{ts} \in \{0, 1\} \qquad t \in \mathcal{T}, s \in \mathcal{S} \mid t \geq \sum_{i \in \mathcal{Z}} R_{is}/(K \cdot B) \tag{17}$$

Also here, the w_{ts} not declared are set to 0.

The model defined by constraints (2)-(10), (12)-(14), (16) and (17) and objective function (1) does not take the behavior of the crowd into consideration and can therefore give unrealistic solutions where pedestrians are sent to emergency exits far away. To remedy this, we assume that each pedestrian leaves the arena through his or her closest emergency exit. To model this we introduce the new objective function

$$z^D = \min \sum_{s \in \mathcal{S}} \rho_s \sum_{i \in \mathcal{Z}} \sum_{p \in \mathcal{P}} \sum_{t \in \mathcal{T}} D_{ip} f_{ipts} \tag{18}$$

The objective function (18) locates the exits such that the total probability weighted distance is minimized, but does not consider the evacuation time. To minimize the evacuation time given that each pedestrian leaves the arena through his or her closest emergency exit, two solution strategies are tested.

In the time-centered (*TC*) strategy, the model defined by constraints (2)-(10), (12)-(14), (16) and (17) and objective function (1) is solved first. This gives a theoretical minimal evacuation time T^E. Then, the objective function is changed to (18) and the constraint

$$\sum_{s \in \mathcal{S}} \rho_s \sum_{t \in \mathcal{T}} t w_t \leq (1 + T^\epsilon) T^E \tag{19}$$

is included where T^ϵ is the largest acceptable increase in evacuation time compared with the minimal. The optimal locations of the exits y_p^* and the flows f_{ipts}^* from this solution are fixed and then the objective function is changed back to (1) and the problem reoptimized. The last problem optimizes the width of the exits.

In the distance-centered (*DC*) strategy, the first step in the *TC* strategy is left out and the model defined by constraints (2)–(10), (12)–(14), (16) and (17) and objective function (18) is solved. The optimal locations of the exits y_p^* and the flows f_{ipts}^* from this solution are fixed, then the problem is reoptimized with objective function (1).

Both strategies give emergency exit layouts, that is, the locations for the emergency exits y_p^* and their corresponding widths s_p^*. The results are colored by the assumptions made in the optimization models. Since the dynamics of an evacuation and most of the interaction between pedestrians in the crowd are not included in the optimization models, the layouts are evaluated by simulation. Introducing complex dynamics and interactions between the pedestrians in the simulation makes it possible to compare the results from the optimization model with the simulated results and assess if the optimization model gives satisfactory results or if a more complex representation of the dynamics is needed. Since the true dynamics of an evacuation situation cannot be captured (not even in a simulation model), striking the right balance between applicability and solubility is paramount.

3 Simulation model

This section describes the agent-based simulation model used to evaluate emergency exit layouts. We start by presenting the objective of the model, before we provide a description of the main components and logic of the model in accordance with the STRESS guidelines proposed by Monks et al. (2019).

3.1 Objective of the simulation model

The objective of the agent-based simulation model is to simulate evacuations to evaluate the performance of emergency exit layouts, and thus the model is constructed to imitate human behavior and dynamics during an emergency. The simulation model is general for single floor venues with an arbitrary number of static obstacles. Additionally, it can be applied to different incidents by adjusting the extent of damage caused by the incident. The key performance indicators (KPIs) of the model are the

total evacuation time and the number of agents evacuated through the different exits at each time step.

3.2 Model components

The model consists of a defined environment with agents representing individual pedestrians. The model environment consists of an arena and its immediate surrounding area. The arena is a closed area, including a set of obstacles. Further, the arena is represented as a two-dimensional continuous space, enabling the agents to move in any direction. A number of exits are also part of the model. An exit is an opening in the wall enabling agents to evacuate the arena and thereby enter the surrounding area for further evacuation.

Each pedestrian is modeled as a unique agent with its own behavior. Moreover, the agents are divided into three agent groups based on the roles they take during an emergency situation, such as an evacuation. According to Massazza et al. (2021), about 20% of the pedestrians take a leader role, and 20% act irrational due to panic. About 60% are confused and find it hard to make their own decisions. Based on this fact, the simulation model includes three different personality types, referred to as *Leader*, *Follower* and *Panic* respectively. The behavior of the different agent types is reflected in the choice of emergency exit.

Regardless of the personality of an agent, the attributes are the same for all agents. Table 1 presents the attributes of agent *n*. The first four attributes are static and do not change during the simulation, while the last five are dynamic. At the beginning of the simulation each agent is given a triage label based on their distance to the epicenter of the incident. The triage labels include deceased, acute, urgent, minor injuries and unharmed. The closer to the incident, the higher the probability for severe damage of an agent. Deceased, acute, and urgent labeled pedestrians become static from the start of the simulation, and are thereby treated as obstacles

Table 1 Attributes of agent *n*

Attribute	Symbol	Description
Radius	r	Radius of a circle-shaped agent, equal for all pedestrians (0.3 m)
Type	–	Personality type of agent (*Leader*, *Follower* or *Panic*)
Triage label	–	Health status of an agent (Deceased, Acute, Urgent, Minor injuries or Unharmed)
Desired speed	v_n	The speed agent *n* maintains in free space (1.1−1.3 m/s for Leader, Follower, 1.27−1.5 for Panic)
Horizontal position	x_n	Horizontal position of agent *n* within the continuous space
Vertical position	y_n	Vertical position of agent *n* within the continuous space
Strategic goal	–	The overall goal of an agent (i.e. one of the exits)
Tactical goal	–	A point on the path towards the strategic goal. Crowds and obstacles are considered when determining this goal
Desired direction	θ_n	The direction agent *n* desires to follow disregarding collision with other agents

by moving agents. Unharmed agents move with their desired speed throughout the simulation, while pedestrians with minor injuries keep a speed 20% lower than desired to reflect their restricted physical abilities.

3.3 Topology

At the core of the agent-based simulation model is the topology of the decision-making and actions performed by each agent. These actions are based on individual preferences, interactions between agents, and between an agent and the environment. The movement of an agent is carried out through a three-level decision-making process in a top-down approach. First, the strategic level is executed, followed by the tactical and operational levels. The processes of the operational level are performed in each time step during the simulation. The tactical level is revised less frequently, and the strategic level is performed rarely to reflect the time intervals between major decisions. Figure 3 illustrates the decision process at each level, which leads to the final action taken by an agent in a step in the simulation. τ_1, τ_2 and τ_3 are the number of time steps between each time a decision on the given level is made. $\tau_1 = 1$ means that the agent's position is updated each time step based on the surroundings, the direction decided on the tactical level and the exit decided on the strategic level.

The purpose of the strategic level is for an agent to choose an emergency exit. This decision is based on the distance to exits, crowding around exits, the position of the exit with regard to the incident epicenter, obstacles on the path towards the exits, and the exit choice of neighboring agents. The exit choice is performed by selecting
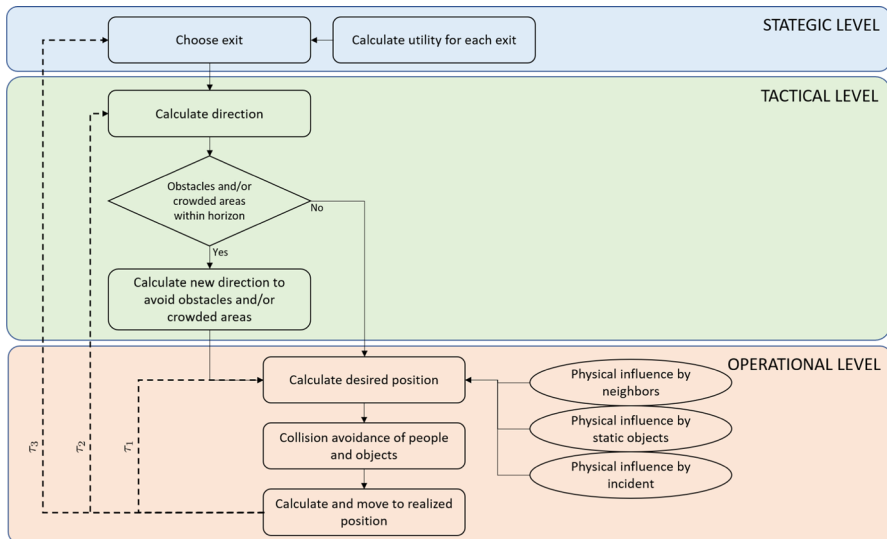
Fig. 3 Three-level decision-making process of an agent. The feedback loops, presented with dashed lines, show when the agent makes decisions on different levels. τ_1, τ_2 and τ_3 are the number of time steps between each time a decision on the given level is made

the exit that maximizes a weighted utility function. The utility for exit point i for agent n in time step t, U_{nit}, is calculated as

$$U_{nit} = \beta_{n,d} \cdot D_{nit} + \beta_{n,\rho} \cdot \rho_{it} + \beta_{n,\alpha} \cdot \alpha_{nit} + \beta_{n,\delta} \cdot \delta_{nit} + \beta_{n,f} \cdot f_{nit} + \beta_{n,\epsilon} \cdot \epsilon_{nit} \quad (20)$$

where D_{nit} is the Euclidean distance from agent n to exit point i in time step t, ρ_{it} is the crowd density in front of exit point i in time step t, α_{nit} is the angle between exit point i and the incident spot seen from position of agent n in time step t. We also have δ_{nit} which equals 1 if an obstacle obstructs the path from the position of agent n to exit point i in time step t, f_{nit} which is the share of neighboring agents of agent n with exit point i as its strategic goal in time step t and ϵ_{nit} which is a random error component of utility for agent n in time step t for exit point i. The rationality of an agent, determined by the agent type, is reflected through the magnitude of the weight $\beta_{n,\epsilon}$. Each variable has an associated weight represented by the β-parameters. The βs for an agent are set from a uniform distribution that depends on the agent type.

At the tactical level, an agent plans a route to approach the exit point selected at the strategic level. The agent scans its neighborhood for static obstacles and high-density crowded areas. In case of blockages, locations surrounding the obstacles and crowds are set as intermediate destinations, becoming the tactical goals of an agent. In the absence of obstructions, the tactical goal equals the strategic.

At the operational level, the position for the next step in time is computed for an agent. This computation takes the direction given by the tactical level as input and adds physical forces and collision avoidance to calculate a new realized position. The first step at the operational level is to include social forces. According to Helbing and Molnar (1998), a pedestrian reacts to the perceived information about its environment by producing a physical acceleration or deceleration. This effect of the environment, including other pedestrians and physical objects, is referred to as social force. Since social forces are not exerted on a pedestrian body, these are seen as a motivation to act rather than physical forces. The model in this paper includes a simplification of the social forces introduced by Helbing and Molnar (1998). Forces are applied to an agent by neighboring agents, static objects, and the incident modeled in the simulation. Each agent is influenced by agents within its own local neighborhood to move in their direction. Additionally, when an agent is close to a wall or static object, the movement direction is influenced in a magnitude inversely proportional to the distance to the object. Furthermore, the incident influences the direction of agents close to the incident epicenter to imitate both physical and psychological repulsion. The influence becomes stronger the closer to the incident the agent is positioned. The inclusion of social forces and incident avoidance results in a direction, called desired direction, potentially deviating from the tactical direction.

Further, collision detection and avoidance are applied to ensure that an agent does not collide with other agents by moving to the desired position. Collision detection is executed by scanning the neighborhood for agents having their center closer than $2r$ from the desired position. In the case of multiple colliding agents, the intersection point between the $2r$ circles of the two closest neighbors is set as the new position. If an agent detects one single neighbor in collision, the desired direction is maintained while the distance moved is shortened. After all forces are included and collisions

Fig. 4 Collision avoidance between agents at the operational level
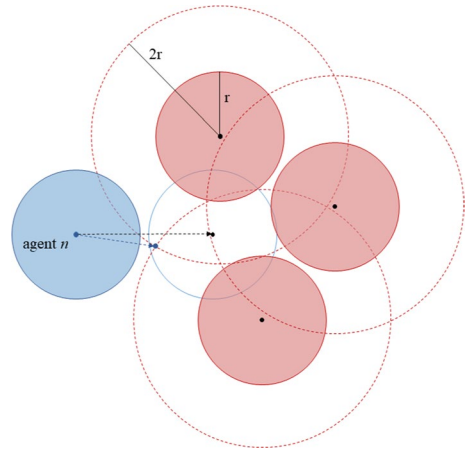
are avoided, the operational level gives its output as the realized position, which the agent moves to in the next time step. Figure 4 shows a situation where there are three colliding agents following the black dashed arrow to the desired position for agent n. Agent n is illustrated as a blue-filled circle, and the empty blue circle marks the desired position. Colliding neighbors are portrayed as red-filled circles. The blue point is chosen as the new position, and the agent follows the dashed blue arrow.

4 Case description and data

We have tested the proposed methodology on two different cases, a large concert at the Leangen trotting track in Trondheim and a fictitious smaller indoor arena. Section 4.1 presents the case of the large concert and Sect. 4.2 presents the smaller case.

4.1 Leangen trotting track in Trondheim on 25.07.2021

Data from a concert that was planned at the Leangen trotting track in Trondheim on 25.07.2021 with the German industrial rock band Rammstein is utilized to test the developed model in a real case study. Figure 5 gives an overview of the trotting track and the surrounding area. With 60,000 tickets put out for sale, the concert has been referred to as potentially the largest concert with a paying audience that has ever been arranged in Norway (Talseth 2020). Unfortunately, the concert was postponed and eventually moved to a new location due to the Covid-19 pandemic.

The concert was planned by the local concert organizer, Livesentralen, in collaboration with the national concert organizer, All Things Live Norway. As part of the preparation phase before any major concert, Livesentralen do incident planning, including hiring international risk advisors that create a comprehensive risk and safety assessment. Among other things, this assessment includes which scenarios that are most likely to occur and how to prepare for them. When 60,000 people are gathered close to the city center, a wide range of scenarios can occur including

**Fig. 5** Leangen trotting track (Lynum 2016)

man-made incidents, such as terror attacks and natural disasters, such as extreme weather (Vidarsson 2020).

Interviews with the three emergency services (Police, Emergency medical services and Fire and rescue services) revealed that they were most concerned with the pyrotechnical effects at the Rammstein concert and saw this as the most probable threat to safety. Additionally, food trucks were expressed as a general threat to fire safety during large events.

Based on data from the preparation before this concert we created the following case. The arena is roughly a 280×110 meter rectangle divided into three sections with different crowd density. Due to the surroundings of Leangen trotting track, parts of the arena boundary are not suited for emergency exits. Figure 6 shows an overview of the arena. The red lines mark the boundary where no emergency exit can be located. The approximate crowd densities ρ (# pedestrians/m^2) in each section are used to distribute the crowd over the arena.

To evaluate the effect of taking a more detailed risk assessment into consideration when planning, we created three instances. In the first instance, I1, a general evacuation is studied. This instance only have one scenario, S0, in which there is no fire. Instead, an evacuation signal is sent and all pedestrians start to evacuate. In the

Fig. 6 Overview of the original arena
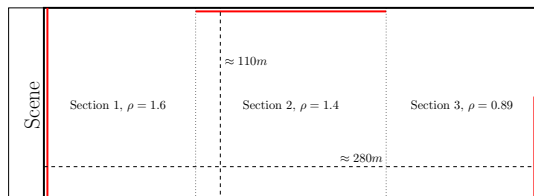
Table 2 Probabilities of the different scenarios for the three instances

Name	Probabilities								
I1	1.00	–	–	–	–	–	–	–	–
I5	0.30	0.23	0.23	0.12	0.12	–	–	–	–
I9	0.30	0.20	0.20	0.09	0.09	0.03	0.03	0.03	0.03
Scenario	S0	S1	S2	S3	S4	S5	S6	S7	S8
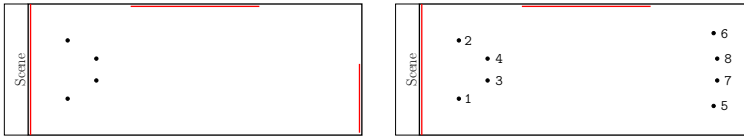
(a) Instance I5 with four potential incidents at the pyrotechnics.

(b) Instance I9 with eight potential incidents. Four at the pyrotechnics and four at the food trucks.

Fig. 7 Instance I5 and I9. The numbers indicate the location of the fire in the corresponding scenario

second instance, I5, risk of fires caused by the pyrotechnical effects are included. This gives four scenarios, S1-S4. We have assessed the likelihood and consequence of a fire in each of the four towers containing pyrotechnics and I5 contains these four scenarios and the general evacuation. In the third instance, I9, the risk of fire in the food trucks at the back of the arena is also incorporated. This gives another four scenarios, S5-S9. This instance has nine scenarios, four from the pyrotechnics, four from the food trucks and the general evacuation. The location of the fires caused by the pyrotechnical effects is based on the blueprint of the stage setup and the food trucks are evenly spread at the back of the arena. Table 2 gives the information about the instances and Fig. 7 shows the location of the incidents. In Table 2, the probability of an incident is stated, either a general evacuation (S0), or a fire in location 1–8. e.g., in I9, the probability of a general evacuation is 30%, a fire in location 2 is 20%, and in location 6 it is 3%.

Due to very long simulation times during preliminary testing we decided to reduce the size of the arena and the crowd. Doing this downscaling, we kept the breadth/width ratio and divided both breadth and width by 3. Correspondingly, the speed of the pedestrians is divided by 3 and the number of pedestrians in the crowd is divided by 9. This gave an arena that is 93×36 meters.

A computational study regarding the effect of different granularities used in the optimization models is performed. We create three grids, defined by the size of the zones created. The grids have zones with size 1×1, 3×3 and 5×5 meters respectively. Information about the number of zones and the number of possible emergency exits for each grid is given in Table 3. With a zone size of 1×1, we get $93 \cdot 36 = 3348$ zones. Since emergency exits cannot be placed everywhere, the number of possible emergency exits is less than the length of the boundary.

Today there are no specific rules for emergency exits at outdoor arrangements in Norway (Direktoratet 2017). Together with local authorities, the concert organizers

Table 3 Information about the grids

Name	□	$|\mathcal{Z}|$	$|\mathcal{P}|$
G1	1×1	3348	167
G3	3×3	372	56
G5	5×5	133	34

have suggested that the total width of the emergency exits should be 80 ms. Considering the downscaling of the arena, this gives approximately 27 ms for the studied arena.

We name the cases we test by concatenating the instance and the grid followed by information about the total width of the emergency exits and the number of exits according to Gc_Ii_Ww_Nn. For example, G1_I5_W30_N6 means grid G1 and instance I5 with 30 ms as the total width of the emergency exits and 6 exits.

4.2 L-shaped arena

The arena in the smaller case is L-shaped and shown in Fig. 8. On two sides of the arena it is not possible to locate emergency exits. The arena is divided into three sections, A_1, A_2, and A_3, with different crowd densities. Three different incidents, marked with dots in the figure, are defined together with a general evacuation.

Unlike the first case, the distribution of pedestrians is uncertain in this case. We have defined three different distributions shown in Table 4. In the first distribution, D1, the number pedestrians in each section is the same. In the second distribution, D2, there are considerably more pedestrians in section A_1 and in the third distribution, D3, there are considerably more pedestrians in section A_3. This reflects a situation where the pedestrians move during the event, for example a festival with two stages.

Fig. 8 Overview of the L-shaped arena
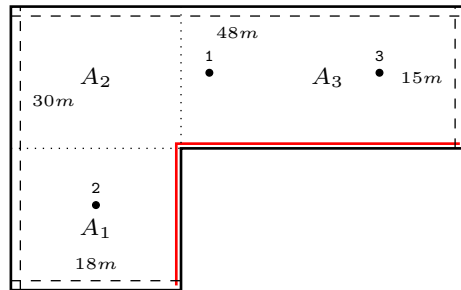
Table 4 Information about the different pedestrian distributions

Name	A_1	A_2	A_3
D1	1/3	1/3	1/3
D2	0.7	0.2	0.1
D3	0.1	0.2	0.7

With four different incidents and three different pedestrian distributions, we generate 12 scenarios combining an incident and a distribution.

5 Computational study

The optimization model is implemented in the programming language (Fair Isaac Corporation 2023) and the models are solved using Xpress-Optimizer Version 8.13. The simulation model is programmed in Python using a library named Mesa. Mesa is a modular framework for creating, analyzing, and visualizing agent-based modeling in Python (Masad and Kazil 2015; Project Mesa Team 2022). All software is run on Lenovo NextScale nx360 M5 computers with the specifications below.

CPU:	2x 3.4 GHz Intel E5-2643v3 – 6 core
RAM:	512 Gb
Disk:	120 Gb SATA SSD

The questions that we want to answer through this computational study are:

- How is the performance affected by different grid sizes?
- What is the effect of taking a more detailed risk assessment into consideration?
- How is the performance affected by different numbers of emergency exits and their total width?

5.1 Grid sizes

We answer our first question by testing different grid sizes when solving the first case, presented in Sect. 4.1. We take `G1_I1_W30_N8` as the base case and compare it with `G3_I1_W30_N8` and `G5_I1_W30_N8`. We use a module width of 1, i.e. $B = 1$, 6700 pedestrians in the crowd and $H = 5025$ which means that 75% of the crowd must have left the arena for the evacuation to be finished. Each time period is 5 s and the time horizon is 600 s. For the *TC* strategy, we use $T^\epsilon = 0.03$. Each problem has a time limit of 36,000 s. The metric of comparison is statistics from the optimization model. Table 5 shows the results where z^T and z^D are the evacuation time and total distance according to objective functions (1) and (18) respectively, and *TC* and *DC* are the time-centered and distance-centered solution methods. The last two columns show the total solution time.

Table 5 Results from changing the size of the grid

Name	z^T (TC)	z^T (DC)	z^D (TC)	z^D (DC)	T (TC)	T (DC)
G1_I1_W30_N8	280.0	280.0	76174.7	76203.3	36106.6	36053.2
G3_I1_W30_N8	280.0	280.0	75844.6	75844.6	50.9	58.4
G5_I1_W30_N8	280.0	280.0	77761.6	77761.6	6.1	6.5

A detailed analysis of the results shows that it is the model with objective function (18) that is the most time consuming. Starting by solving the model with objective function (1) and then adding constraint (19) before solving the model with objective function (18) slightly improves the performance. We note that none of the problems with `G1` are solved to proven optimality. Based on the detailed analysis and the results we conclude that `G3` and *TC* strike the best balance between solution quality and solution time. We therefore continue the computational study with these settings.

5.2 Detailed risk assessment

To answer the second question, we do a computational study on both cases. In the first case, we take `G3_I1_W30_N8` as the base case and compare it with `G3_I5_W30_N8` and `G3_I9_W30_N8`. When generating the scenarios we assume that the radius of the fires is 7 ms. All other settings are as in Sect. 5.1 and *TC* is used as solution method. The results from the optimization models are shown in Table 6; the columns show the evacuation time and total distance according to objective functions (1) and (18) respectively as well as the lower bound, $\underline{z}^D(DC)$, of the problem solved with objective function (18) and the total solution time. We note that these problems are not solved to proven optimality for `I5` and `I9` but the optimality gaps are small.

The resulting emergency exit layouts are shown in Fig. 9. The first thing we notice is that the layouts are very similar. The layout for `I1` and `I5` have the exits on the same location, but the bottom left exit is slightly larger and the back exit slightly smaller in the `I5` layout compared with the `I1`. In the `I9` layout, some of exits are moved away from the scene and the bottom left exit is slightly smaller and the top right slightly larger in the `I9` layout compared with the `I5`. These similarities are also apparent in the results in Table 6.

To assess the value of taking a more detailed risk assessment into consideration, we take the layout for all cases and simulate each incident defined in `I9`. Even though not all incidents are taken into consideration in the `I1` and `I5` instances, the incidents can happen. Each combination of layout and incident is simulated 15 times and Table 7 and Fig. 10 present the results. The columns T^i give the median evacuation time counted when 75% of the crowd is outside the arena for each incident. Index 0 is the general evacuation without incidents and 1-8 are shown in Fig. 9c.

The results indicate that the weighted evacuation times for `I1` and `I5` are similar and slightly worse than `I9`. We see that the general evacuation `S0` and fires corresponding to `S5` and `S7` have similar evacuation times and that the evacuation time

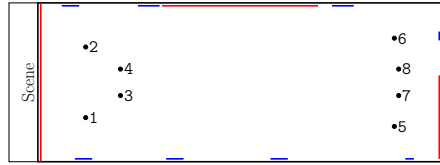| Table 6 Results from changing the number of scenarios	Name	z^T (*TC*)	z^D (*TC*)	$\underline{z}^D$ (*TC*)	T (*TC*)
	`G3_I1_W30_N8`	280.0	75844.6	75844.6	50.9
	`G3_I5_W30_N8`	284.7	79005.8	78931.7	36083.9
	`G3_I9_W30_N8`	280.0	80959.9	80429.4	36348.1
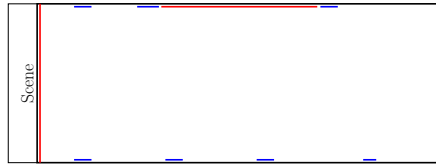
(a) Layout from instance I1.
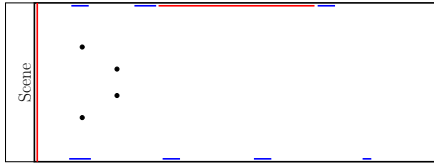
(b) Layout from instance I5.

(c) Layout from instance I9.

Fig. 9 Layouts from the three instances of G3_Ii_W30_N8

Table 7 Results from simulating the three layouts

Name	T^0	T^1	T^2	T^3	T^4	T^5	T^6	T^7	T^8
G3_I1_W30_N8	189.4	243.6	234.8	250.2	238.6	191.8	246.4	195.8	212.8
G3_I5_W30_N8	183.2	252.6	244.4	255.4	242.8	184.8	239.6	183.8	202.8
G3_I9_W30_N8	176.8	242.4	235.2	243.8	241.6	181.8	260.8	192.0	213.2

Fig. 10 Evacuation times for I1, I5, I9 and S0-S8
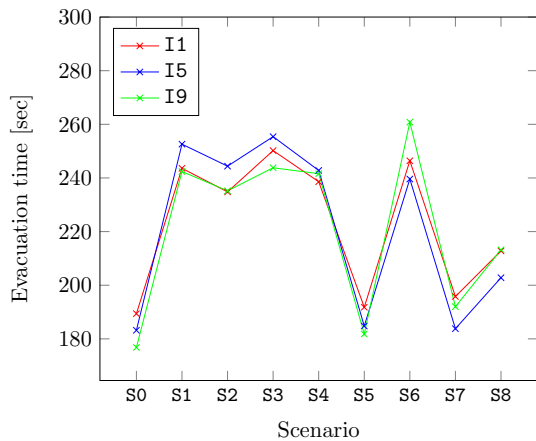
for fires close to the stage S1-S4 have a higher evacuation time. The reason why S6 and to some degree S8 experience higher evacuation times than S5 and S7 is probably because they make the top right and back exits unavailable for many pedestrians in the crowd. This is especially apparent in I9 where the top right exit is both wider and closer to 6 than in I1 and I5.

Table 8 Information about the
different instances generated for
the small case

Name	Distributions	Incidents
In1	D1	I0
In2	D1-D3	I0
In3	D1	I0-I3
In4	D1-D3	I0-I3

Fig. 11 The four layouts from
the instances In1-In4

(a) Layout In1.   (b) Layout In2.

(c) Layout In3.   (d) Layout In4.
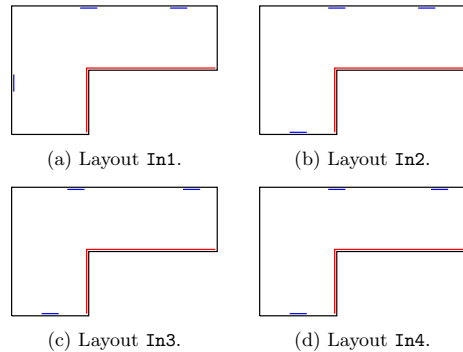
The weighted simulated evacuation time is lower than the evacuation time from the optimization model (approximately 20% lower). This indicates that the speed used in the optimization model is probably too low. Preliminary testing showed that speed does not affect the layout to a large extent, so we have chosen not to adjust it in the optimization models. Besides this, the results from the simulation are well aligned with the results of the optimization model.

In the second case, presented in Sect. 4.2, we use a grid size of 3×3 meter giving 111 zones and 37 possible exit points. We use a fixed size for the emergency exits of 4 ms and locate 3 exits, i.e. $N = 3$, $B = 3$, and $W = 4$. There are 1500 pedestrians in the crowd and $H = 1425$, which means that 95% of the crowd must have left the arena for the evacuation to be finished. Each time period is 5 s and the time horizon is 600 s.

We define four instances to optimize. In the first instance, only pedestrian distribution D1 and the general evacuation I0 are used. This means that no risk assessment regarding pedestrian distributions or incidents is made. In the second instance, all pedestrian distributions, D1-D3, and the general evacuation I0 are used. This represents a situation where different pedestrian distributions are assessed but not the incidents. In the third instance, pedestrian distribution D1 and all incidents, I0-I3, are used. This means that the crowd is considered fairly evenly distributed when assessing the incidents. In the final instance, all pedestrian distributions, D1-D3, and all incidents, I0-I3, are used. The instances are summarized in Table 8.

The *TC* solution method was used and all instances are solved to optimality within two hours. The layouts generated for each instance are shown in Fig. 11. We see that there are design differences between the layout for instance In1 and the other instances. This shows that making a more detailed risk assessment have an

Table 9 Results fixing the layouts and solving instance `In4`

Layout	z^T	z^D	noExit
In1	286.5	14154.8	121.2
In2	306.5	15062.4	48.8
In3	328.4	16322.1	0.0
In4	320.2	16229.5	0.0
La	321.8	15901.0	48.8

Fig. 12 The heuristic layout `La` based on an equidistant location
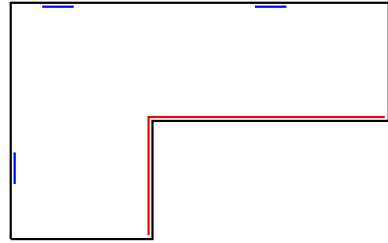
effect on the proposed layout. When comparing instances `In2` and `In3` we see that both have moved an emergency exit from the left side to the bottom. For instance `In2` it is probably to have it closer to the possible large number of pedestrians in the A_1 section. For instance `In3` it is probably to move it away from the possible incident in the A_2 section. We also see that the emergency exits at the top part are moved away from the incidents in instance `In3`. Finally, we note that the layout for instance `In4` very similar to the layouts of `In2` and `In3`. The location of the emergency exit at the bottom is the same, the top left location is the same as for instance `In3` and the top right location is the same as for instance `In2`.

We compare the layouts for the instances by fixing the location of the emergency exits and then solving instance `In4`. This gives the total distance for all pedestrians for each incident and for each pedestrian distribution. It also gives the expected evacuation time for each layout. The results are presented in Table 7. The table shows the expected evacuation time z^T and the total distance z^D when 95% of the pedestrians have evacuated. The table also shows the number of pedestrians that are not able to reach an emergency exit, noExit. This happens if all emergency exits are unreachable for a zone. We see that when the incidents are not considered, i.e. in instance `In1` and `In2`, there are pedestrians that cannot reach an emergency exit. z^T and z^D are calculated from the pedestrians that have evacuated and are therefore biased for these instances.

As a final comparison, we have generated a layout heuristically. The layout, `La`, has the exits located equidistant from each other on the part of the boundary with possible exit points. The results of the evaluation of the layout are also in Table 9 and the layout is shown in Fig. 12. We see that the layout fails to provide an emergency exit for all pedestrians.

We see that not making a detailed risk assessment when locating the emergency exits can have large consequences and can lead to pedestrians not reaching

emergency exits in case of incidents. In the instances where the incidents are taken into consideration, i.e. instance `In3` and `In4`, we only see a small effect of taking the pedestrian distribution into consideration.

5.3 Number of exits and total width

The last analysis is done on the large case and study how the number of exits and the total width of the exits affect the evacuation time. The optimization model has been solved for all combinations of number of exits (`N8`, `N10`, `N12`) and total width (`W20`, `W30`, `W40`). All other settings are as in Sect. 5.1 and *TC* is used as solution method. The evacuation times are presented in Table 10.

We cannot draw any certain conclusions regarding how the number of exits affect the evacuation, but it is clear that the inverse of the total width has an almost linear relation with the evacuation time. Considering the rather simple modelling of queues around the emergency exits, this is not unexpected.

6 Conclusions

We have presented the Emergency Exit Layout Problem (EELP) which is the problem of locating a given number of emergency exits and deciding their width such that the time it takes to evacuate the crowd from an arena is minimized. The EELP is formulated as a two-stage stochastic mixed integer linear program to handle the uncertainty related to the location of the possible incidents and the distribution of the pedestrians. The layouts suggested by the optimization model are are evaluated using a social force agent-based simulation model.

Two cases are studied, a large concert planned at the Leangen trotting track in Trondheim and a smaller fictitious indoor arena. In the computational study we aim to answer three questions:

– *How is the performance affected by different grid sizes?*

We see that the complexity of the model is very dependent on the grid size and a too fine grid makes the problem very time-consuming to solve. The results from the optimization model indicate that the quality of the solutions is equal for the grid sizes tested.
– *What is the effect of taking a more detailed risk assessment into consideration?*

There is no clear indication in our results that the layout is particularly affected by a more detailed risk assessment in the large case, but the most com-

Table 10 Evacuation times for different number of exits and total width

	N8	N10	N12
W20	426.374	434.864	426.474
W30	280.868	282.464	280.000
W40	210.000	209.864	210.336

plex instance, I9, shows a 2% lower weighted evacuation time than the other instances. In the small case, we see that not making a detailed risk assessment when locating the emergency exits can have large consequences and can lead to pedestrians not reaching emergency exits in case of incidents. Another observation is that the evacuation time is very sensitive to where the incident takes place and that a well-functioning model should take this into consideration.

We also notice that the surrounding of the arena influences the evacuation time and should be part of the overall risk assessment.

– *How is the performance affected by different number of emergency exits and their total width?*

We cannot see any clear trends in the evacuation time related to the number of emergency exits, but it is very clear that the total width of the exits affect the evacuation time.

To carefully assess the arena, its surroundings and potential incidents is adamant when planning the layout of emergency exits at large events. The small case shows that taking the pedestrian distribution into consideration is important, but also that not including potential incidents can give bad results. A main consideration is to locate the emergency exits close to the majority of the crowd, but also not close to potential incidents. Finding the critical locations that balance this trade-off is at the core of the EELP. In this work we have shown that the combination of optimization and simulation provides a powerful planning tool in this context.

We see that the simulation model can be developed further to better cope with the dynamics in the very dense areas around the emergency exits, and also to incorporate medical personnel entering the arena to provide help for the people injured by the incident. The optimization model use a very simple crowd behavior where everyone go to the closest exit. Introducing more of the dynamics from the simulation into the optimization is definitely an important development. Finally, assessing the possibility of guiding the crowd through directed messages to improve the evacuation time is another interesting avenue for future research.

References

Abdelghany A, Abdelghany K, Mahmassani H, Alhalabi W (2014) Modeling framework for optimal evacuation of large-scale crowded pedestrian facilities. Eur J Oper Res 237(3):1105–1118. https://doi.org/10.1016/j.ejor.2014.02.054

Chen J, Shi T, Li N (2021) Pedestrian evacuation simulation in indoor emergency situations: approaches, models and tools. Saf Sci 142:105378. https://doi.org/10.1016/j.ssci.2021.105378

Direktoratet for samfunnssikkerhet og beredskap: Veileder for sikkerhet ved store arrangementer. https://www.dsb.no/veiledere-handboker-og-informasjonsmateriell/veileder-for-sikkerhet-ved-store-arrangementer/. Accessed 31 May 2022 (2017)

Duives DC, Mahmassani HS (2012) Exit choice decisions during pedestrian evacuations of buildings. Transp Res Rec 2316(1):84–94

Fair Isaac Corporation: (2023) FICO®Xpress Optimization Help. https://www.fico.com/fico-xpress-optimization/docs/latest/overview.html. Accessed 02 Feb 2023

Gao H, Medjdoub B, Luo H, Zhong H, Zhong B, Sheng D (2020) Building evacuation time optimization using constraint-based design approach. Sustain Cities Soc 52:101839

Gao F, Du Z, Werner M, Zhao Y (2022) An improved optimization model for crowd evacuation considering individual exit choice preference. Trans GIS 26(7):2850–2873. https://doi.org/10.1111/tgis.12984

Haghani M (2020) Optimising crowd evacuations: mathematical, architectural and behavioural approaches. Saf Sci 128

Helbing D, Molnár P (1995) Social force model for pedestrian dynamics. Phys Rev E 51:4282–4286. https://doi.org/10.1103/PhysRevE.51.4282

Helbing D, Johansson A, Al-Abideen HZ (2007) Dynamics of crowd disasters: an empirical study. Phys Rev E 75:046109

Helbing D, Molnar P (1998) Social force model for pedestrian dynamics. Phys Rev E 51

Kasereka S, Kasoro N, Kyamakya K, Doungmo Goufo E-F, Chokki AP, Yengo MV (2018) Agent-based modelling and simulation for evacuation of people from a building in case of fire. Procedia Comput Sci 130:10–17. https://doi.org/10.1016/j.procs.2018.04.006

Khamis N, Selamat H, Ismail FS, Lutfy OF, Haniff MF, Nordin INAM (2020) Optimized exit door locations for a safer emergency evacuation using crowd evacuation model and artificial bee colony optimization. Chaos Solitons Fractals 131:109505

Lei W, Tai C (2019) Effect of different staircase and exit layouts on occupant evacuation. Saf Sci 118:258–263

Liu Y (2015) Optimizing gymnasium evacuation performance by agent-based simulation. Spectator 27:30–8

Lynum S (2016) Nå blir det rundt 1500 boliger på Travbanen. Adresseavisen. https://www.adressa.no/pluss/okonomi/2016/11/09/N Accessed:2021-05-04

Ma G, Wang Y, Jiang S (2021) Optimization of building exit layout: combining exit decisions of evacuees. Adv Civ Eng 2021(6622661):1–16. https://doi.org/10.1088/1674-1056/26/8/084504

Masad D, Kazil J (2015) Mesa: an agent-based modeling framework. In: 14th PYTHON in science conference, pp 53–60

Massazza A, Brewin CR, Joffe H (2021) Feelings, thoughts, and behaviors during disaster. Qual Health Res 31(2):323–337

Monks T, Currie CS, Onggo BS, Robinson S, Kunc M, Taylor SJ (2019) Strengthening the reporting of empirical simulation studies: introducing the stress guidelines. J Simul 13(1):55–67

Project Mesa Team: (2022) Mesa Documentation Release .1. https://mesa.readthedocs.io/_/downloads/en/latest/pdf/. Accessed 31 May 2022

Ronchi E, Uriz FN, Criel X, Reilly P (2016) Modelling large-scale evacuation of music festivals. Case Stud Fire Saf 5:11–19. https://doi.org/10.1016/j.csfs.2015.12.002

Şahin C, Rokne J, Alhajj R (2019) Human behavior modeling for simulating evacuation of buildings during emergencies. Phys A Stat Mech Appl 528:121432. https://doi.org/10.1016/j.physa.2019.121432

Selim SZ, Al-Rabeh AH (1991) On the modeling of pedestrian flow on the jamarat bridge. Transp Sci 25(4):257–263

Selin J, Letonsaari M, Rossi M (2019) Emergency exit planning and simulation environment using gamification, artificial intelligence and data analytics. Procedia Comput Sci 156:283–291. https://doi.org/

10.1016/j.procs.2019.08.204. 8th International young scientists conference on computational science, YSC2019, 24-28 June 2019, Heraklion, Greece

Seyfried A, Passon O, Steffen B, Boltes M, Rupprecht T, Klingsch W (2009) New insights into pedestrian flow through bottlenecks. Transp Sci 43(3):395–406

Shi J, Ren A, Chen C (2009) Agent-based evacuation model of large public buildings under fire conditions. Autom Constr 18(3):338–347. https://doi.org/10.1016/j.autcon.2008.09.009

Talseth T (2020) Rammstein slår sammen to utsatte Trondheim-konserter til én. VG. https://www.vg.no/rampelys/musikk/i/RRVLWa/rammstein-slaar-sammen-to-utsatte-trondheim-konserter-til-en. Accessed 14 Oct 2020

Tavares RM (2009) Finding the optimal positioning of exits to minimise egress time: a study case using a square room with one or two exits of equal size. In: Building simulation, vol 2. Springer, pp 229–237

Tissera PC, Castro A, Printista AM, Luque E (2014) Simulating behaviours to face up an emergency evacuation. arXiv preprint arXiv:1401.5209

Vermuyten H, Beliën J, De Boeck L, Reniers G, Wauters T (2016) A review of optimisation models for pedestrian evacuation and design problems. Saf Sci 87:167–178. https://doi.org/10.1016/j.ssci.2016.04.001

Vidarsson H (2020) Personal communication

Wagner N, Agrawal V (2014) An agent-based simulation system for concert venue crowd evacuation modeling in the presence of a fire disaster. Expert Syst Appl 41(6):2807–2815. https://doi.org/10.1016/j.eswa.2013.10.013

Yang B, Wu Y-g, Wang C (2009) A multi-agent and gis based simulation for emergency evacuation in park and public square. In: 2009 International conference on computational intelligence and security, vol 1, pp 211–216 . https://doi.org/10.1109/CIS.2009.234

Zhang L, Liu M, Wu X, AbouRizk SM (2016) Simulation-based route planning for pedestrian evacuation in metro stations: a case study. Autom Constr 71:430–442. https://doi.org/10.1016/j.autcon.2016.08.031

Zhang Y-C, Ma J, Si Y-L, Ran T, Wu F-Y, Wang G-Y, Lin P (2017) Required width of exit to avoid the faster-is-slower effect in highly competitive evacuation*. Chin Phys B 26(8):084504. https://doi.org/10.1088/1674-1056/26/8/084504

Zhang X, Zhong Q, Li Y, Li W, Luo Q (2018) Simulation of fire emergency evacuation in metro station based on cellular automata. In: 2018 3rd IEEE international conference on intelligent transportation engineering (ICITE), pp 40–44 . https://doi.org/10.1109/ICITE.2018.8492555