A new integrated agent-based framework for designing building emergency evacuation: a BIM approach

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Abstract

Today, safety control is considered one of the most important pillars of building construction processes due to maintaining security in major incidents such as fire, earthquake, and flood, and placing a basis of mutual trust between builders and residents for building design and construction. The evacuation process is a key aspect of safety control in case of an emergency such as a fire. This study develops a new integrated agent-based framework for designing building emergency evacuation by using Building Information Model (BIM). Three main steps of the framework include data collection, building model development, and evacuation simulation with a combination of Revit-MassMotion. The methodology is demonstrated through its application to a real case of a multi-story commercial building located in Iran. The building model is simulated through three scenarios with a different number of floors (i.e., one, two, and three floors). In each scenario, the safety of evacuation is evaluated for three designs of stairs in the building. The results show the best performance of the building evacuation in all scenarios can be achieved when two individual stairs are designed for each floor. Other influential factors including the maximum density, vision time, and agent count are more acceptable compared to other design factors. These parameters can also be used to design a control system by using smart conceptual models based on both decision tree and auto-work break structure methods.

Keywords: Agent-based modeling; Building Information Models; Decision Tree; Emergency Evacuation; System Safety.

1. Introduction

Although nowadays, the energy crisis and green technologies have become the main concerns in the construction and building industry (Mousavi et al. 2023), building safety has always been one of the most important pillars of building construction processes (Aleksandrov et al. 2019). One of the challenges for safety control of high-rise public buildings is to manage building evacuation in a short time during an emergency due to its inherent hazards to human life. Studies found exposure to multiple life-threatening crises could be prevented with contingency planning and effective decision-making (Xiong Q, et al., 2017). Duration and efficiency of evacuation are important parameters of a safe and effective emergency evacuation which is also influenced by the behaviour of residents within the evacuation (Bohannon, 2005; Miao, 2011). The evacuation process cannot be easily tested experimentally due to the nature of the incident and other factors such as cost constraints and implicit hazards hence during recent decades numerical solutions for the environment and human behaviour have been incorporated in finding an optimised design for building evacuation (Lovreglio et al., 2022).

According to Fig. 1, the largest number of major fatalities are due to earthquakes as a main natural hazard between 1900 and 2022. One of the main reasons for such high fatalities during these hazards e.g., fire and earthquake is mainly linked to the interaction of citizens and buildings (Xiao et al., 2022). In other words, fast reactions in the buildings can be useful due to reliable evacuations from buildings, and by taking this concept, the rate of death and damages can be considerably decreased (Haghani and Lovreglio, 2022).

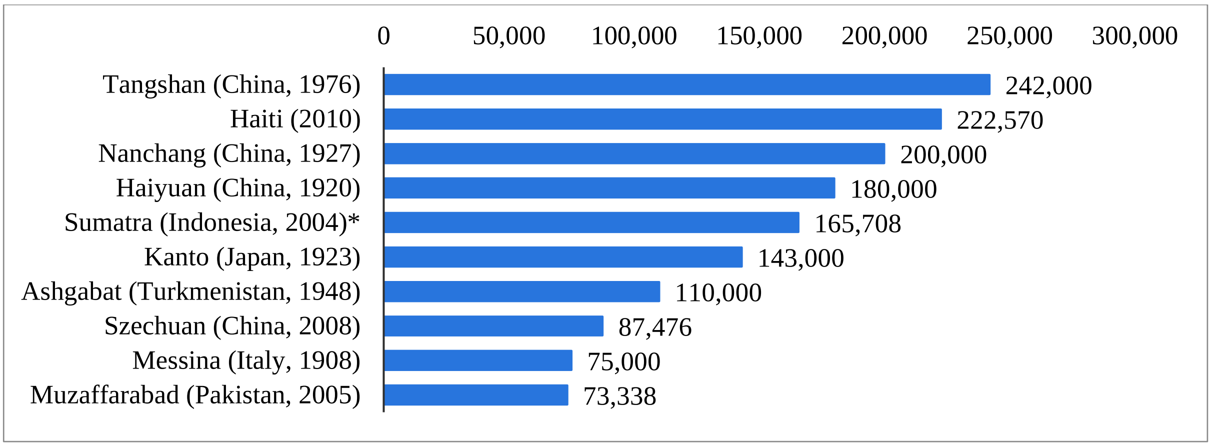
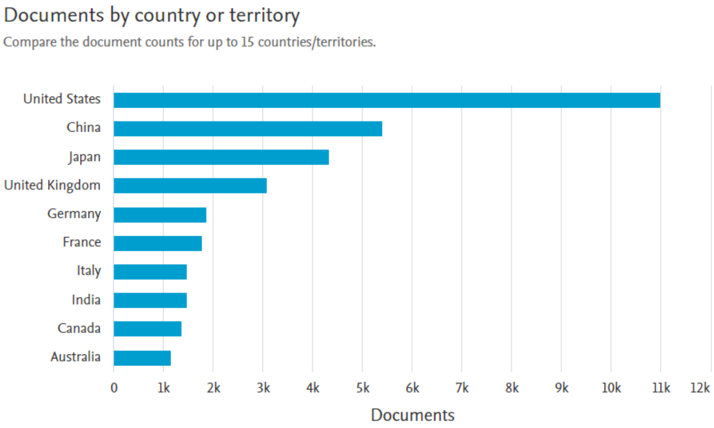


Fig. 1. Earthquakes with the highest death toll worldwide from 1900 to July 2022, inspired by CRED; BBC; ID 266325.

Based on the bibliometric search in the literature, a databank from Scopus is provided for the evacuation in buildings that are analysed by the Bibliometrix toolbox in R software as demonstrated in Fig. 2. The tool collects more than 47,000 research items (1837-2024) in the databank. As can be seen in Fig. 2a, the spatial distribution of publications in the field is mainly for the US with more than 10k papers, followed by China, Japan, and UK. Besides, according to the analysis of the keywords shown in Fig. 2b, it is evident that the main hazards for buildings are related to fire, smoke, and building evacuations that are contributed more than other aspects. Meanwhile, Fig. 2b shows that the evacuation process is evaluated in tsunami and flood disasters in the next step.



(a)

(b)

Fig. 2. Bibliometrix analysis of evacuation in buildings based on (a) Sankey diagram and (b) word cloud (AU: Authors, AU-CO: Authors countries, DE: Authors keywords).

Two significant features influencing each other in the evacuation process sequentially are Building Information (BI) and the Behaviour of Residents (BR) as shown in Fig. 3 that create feedback-based interaction during the evacuation process in both fire and earthquake events (Hassanpour et al., 2022; Eom et al., 2022; Alam et al., 2022). Likewise, this interaction can lead to facing Dynamic and Event Information (DEI) (Makinoshima et al., 2022, Hassanpour et al., 2022). The DEI contains event intensity, sensor systems, and building resilience online detection (Song et al., 2022; Abir et al., 2022; Ghafoori et al., 2022; Cao et al., 2022).

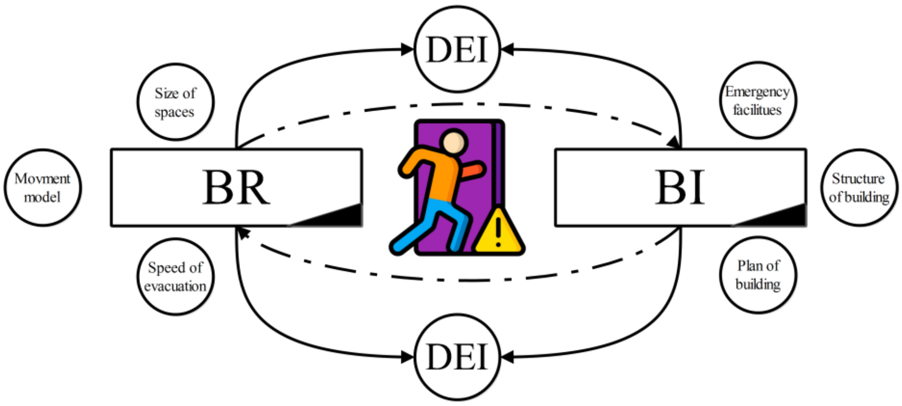


Fig. 3. Interactions of BR and BI during the evacuation process (Makinoshima et al., 2022, Hassanpour et al., 2022).

Recently developed research works related to building evacuation and emergency reaction systems in 2022 are summarised in Table 1. It is evident that some different aspects of building evacuation are developed but fire accident events are accounted for the majority of these studies as a hot topic for safety systems against human-made and natural phenomenon control. In addition, to the best of the authors' knowledge, none of the previous research studies developed a combination of agent-based models and Building Information Models (BIM). Some examples of similar cases are briefly discussed and analysed here. As can be seen in Table 1, the application of the Decision Tree model integrated into Revit and MassMotion as an agent-based method was not applied for evacuation management in buildings. However, after finding the best condition of design at the end of the feasibility study, an early decision-making platform needs to be developed for the supervision process in a fast reaction system. As per Table 1, some of the studies evaluated the social aspects of the evacuation process in buildings and controlled the secondary side effects as the cost of simulation practices (Makinoshima et al. 2022). Some studies analysed the 3D simulations of the evacuation process to find the best design framework (Song et al., 2022; Xiao et al., 2022; Li et al., 2022).

Table 1. Recent studies in the field of building evacuations through human made and natural incidents

Crisis type	Methods	Authors
Tohoku tsunami	Social networks communicational numerical model	Makinoshima et al. (2022)
Fire accident	Hazard and time enhancement in the evacuation process by the indoor network model	Song et al. (2022)
Fire accident	Evacuation simulation by PyroSim in prefabrication buildings	Xiao et al. (2022)
Fire accident	3D modelling, Random Forest, and Non-dominated Sorting Genetic Algorithm III for simulation, prediction, and control system of the evacuation process	Guo and Zhang (2022)
Fire accident	Application of Evolutionary Virtual Reality Platform	Lorusso et al. (2022)
Fire accident	Integration of Cellular Automata (CA) and a 2D Building Information Model (BIM)	Hassanpour et al. (2022)
Fire accident	Pathfinder and GCFM (generalised centrifugal-force model) techniques	Ren et al. (2022)
All types of disasters (Concentration on fire accidents)	Integration of social force model-based software and MassMotion	Li et al. (2022)
Natural or anthropogenic disasters	Integration of the CA model and Cumulative Prospect Theory (CPT)	Gao et al. (2022)

Some software tools have been used by researchers for analysing evacuation in buildings. For example, MassMotion as an Agent-Based Modelling (ABM) software, which was created based on human science and refined by data collection, can predict people's choices and behaviour in real-time. Vensim, as a system dynamic modeler, can be used to understand the complexity of the variable of time, and Arena for the prediction of discrete events for separate periods. The literature review illustrates the different capabilities of MassMotion, which include testing the evacuation process, behaviour in fire, BIM capabilities, and testing of different designs (Wang et al., 2016). Anvari et el., (2017) utilised MassMotion software to investigate the performance indicators such as mean total evacuation times, standard deviations, maximum evacuation times and minimum evacuation times during rapid evacuation of passengers in trains. ABM, and virtual and augmented reality are simulation tools that appoint 3D environments and characterise human behavioural patterns to predict the given scenarios (Wang et al., 2016; González-Méndez et al., 2021). Similarly, Lovreglio et al., (2021) employed virtual reality experiments to investigate, in controlled settings and how crowd decisions are made. Li et al., (2020) evaluated the emergency evacuation of some nursing homes in China especially when the eldery are in higher floors using MassMotion Software. As the complexity of a process rises, it requires a computational system for prediction and analysis, for instance, ABM's prestigious benefit is its ability to capture emerging circumstances with flexibility (Wang and Jia, 2021). Marzouk and Al-Daour (2018) proposed a system that, by simulating the right construction method alternatives, helps contractors and safety managers plan labour evacuation for building sites using BIM and computer simulation. The suggested methodology computes, while taking safety into account, the execution time, total cost, and evacuation time for building projects. The behaviour of workers in evacuation scenarios is modelled using agent-based simulation using MassMotion software. Xie et al., (2022) used Mass Motion software to create an evacuation simulation scene and study the effects of various evacuation methods on evacuation behaviour and evacuation efficiency. That study aimed to explore a reasonable evacuation strategy, i.e., to increase the safety of people traveling on the stairs without affecting the evacuation efficiency. Lorusso et al., (2022) presented a specific platform to create a fire emergency scenario and evaluated their platform through conducting fire emergency in an existing school. They employed MassMotion software in one the sections of the platform to simulate the crowd.

Elliott and Smith (1993) evaluated the causes of injuries and accidents during emergency evacuation and represented two factors of loss of control due to surrounding pressure and difficulties rising after a fall. Helbing et al. (1995) analysed people in movement, and their interaction with the environment and proposed an equation concerning Newton’s second law. This mathematical model was in proportion to the distance of the person with obstacles or other people, there are compressive forces, repulsion, and friction that are the basis for reducing or increasing the speed of movement. Sime et al. (1995) studied aggressive behaviour in crowds and examine the influencing factors for safe evacuation. Ghafori et al. (2015) simulated emergency evacuation in the building using AnyLogic during a crisis and estimated the time of evacuation including different effective variables. Aleksandrov et al., (2019) introduced a new method to find optimal evacuation strategies in tall buildings. Their method incorporates stochastic nature of people’s behaviour, modelling the randomness in decisions of people, and the capacities of egress components. Aleksandrov et al., (2021) proposed a BIM method to automatically evacuate a building needed for pedestrian dynamics from any building configuration. The method evaluates the usability of the navigation mesh to carry out a realistic simulation of a pedestrian while considering the walker's physical capabilities. Haghani and Sarvi (2023) conducted a sensitivity analysis to find the most important factors of crowd motion behaviour.

Ensuring safety in building construction processes is essential for maintaining security and trust between builders and residents especially in the events of emergencies such as fires, earthquakes, and floods, a well-designed evacuation plan is critical. In recent years, using BIM has become increasingly popular for designing building emergency evacuation plans. BIM provides a digital representation of a building's physical and functional characteristics, which can be used to simulate and analyse different evacuation scenarios. This study proposes an integrated agent-based framework for designing building emergency evacuation using BIM. The objective is to evaluate the safety of evacuation in a multi-story commercial building by simulating the evacuation process using a combination of Revit-MassMotion software tools. Furthermore, this study evaluates the impact of various design factors such as the number and location of stairs, maximum density, vision time, and agent count on the safety of evacuation. While previous studies (reviewed in Table 1) applied existing theories, methods and tools (such as, Li et al., 2020; Anvari et al., 2017; Marzouk and Al-Daour 2018; Lorusso et al., 2022; Xie et al., 2022) to design building emergency evacuation plans, this study offers a novel approach by integrating these existing techniques and software tools to develop a comprehensive framework for evacuation design of commercial buildings. The integration of agent-based modeling, BIM, decision tree, and auto-work break structure methods is expected to provide a unique and valuable contribution to the field of building safety control. To sum up, this research work develops the best design parameters for evacuation in public buildings using ABM based on the following main steps:

- An attempt is made to find the most effective parameters in building emergency evacuation for occupants by modeling a real-world case study building.
- The identified parameters, including emergency stair size, door position, and size were analysed and simulated to achieve the best values for the parameters in the simple designed plan.

- Modeling and simulation of different arrangements in stairs include 1-3 services and their influences on evacuation time.
- Assessment of evacuation time in three floors and their behaviour during the evacuation process based on discharging time and accumulative width of stairs.
- In the large-scale and real-field evaluations, the evacuation time is then examined for three floors of buildings including three stairs in 12 different widths as a sensitive analysis of the evacuation framework.
- Both maximum density and agent counts are then evaluated in the case study map according to the three states of maximum, optimum, and minimum times of evacuation.
- Four Decision Tree (DT) and Auto Work Break Structure (AWBS) conceptual models are finally developed for smart fast reaction systems.

This study also aims to identify and find the best key design parameters for the rapid and safe evacuation of the building during an emergency. Revit software is used to create a 3D model of the case study building and MassMotion software is applied to simulate the emergency evacuation process. The proposed agent-based model can be used in other public buildings with the same number of populations. The methodology presented in the next section entails specifying the simulation and finding the best design parameters and the flowchart to generate ideal solutions. The results are discussed in Section 3 followed by presenting smart control systems in Section 4. Some recommendations for future studies and conclusions are finally made in Section 5.

2. Research methodology

The flowchart of the proposed methodology in this study is shown in Fig. 4. The first step entails data collection simulation assumptions of the case study building. Then, the collected data are used for modeling the building evacuation process in the Revit software tool as BIM for a simulation model connected to a two-way loop with an agent-based model. Agent-based simulations typically rely on established behavioural models and empirical observations to model the behaviour of agents in certain situations. This can be a major source of uncertainty for the results obtained when dealing with building evacuation. In this study, the agent behaviour in the evacuation simulation was assumed based on those in the literature and empirical observations of human behaviour in emergency situations. For instance, previous studies have shown that people may follow the crowd during evacuations, especially in unfamiliar environments, and that they may experience anxiety, panic, or confusion in high-stress situations (Haghani, 2021). Furthermore, people may display different behaviours based on factors such as age, physical ability, and familiarity with the building layout. To include those reactions in the model, we used established behavioural models such as the Social Force Model and the Flee Model, which account for social interactions and physical forces, as well as panic in evacuations. These models were also calibrated based on the empirical observations of human behaviour in similar emergency situations to ensure the agent reactions are included based on previously developed models. In addition, additional parameters were incorporated that affect agent behaviour, including maximum density, vision time, and agent count. These parameters reflect the physical characteristics of the building and the environment during an emergency, and they are informed by building codes, safety regulations, and empirical data on evacuation dynamics.

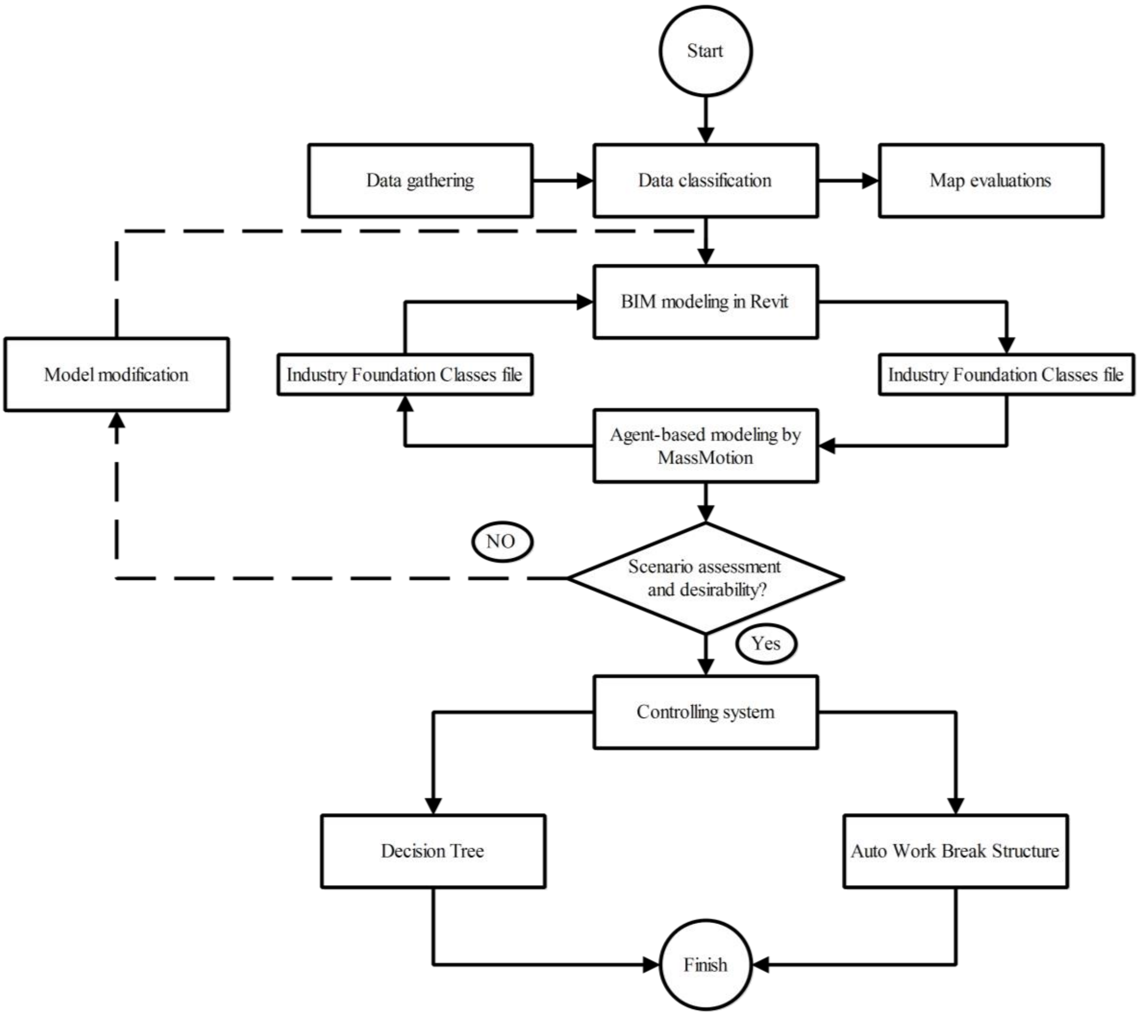


Fig. 4. Research methodology flowchart presented in this study

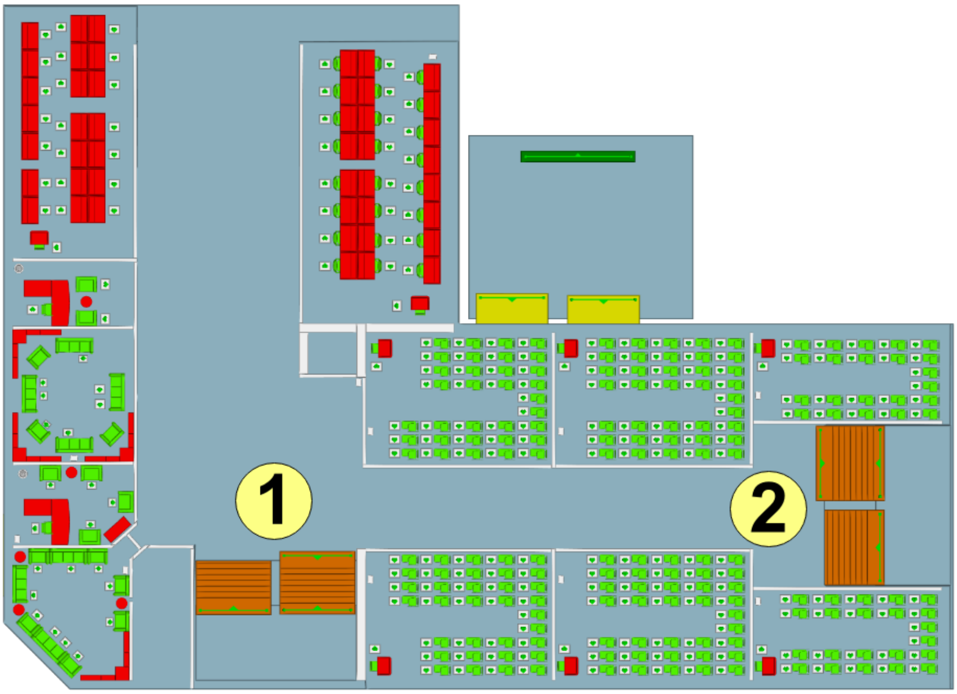
The loop in the flowchart given in Fig. 4 is repeated until converging to ideal solutions for the objectives of building evacuation. After reaching desirable conditions, control systems for evacuation process management are generated to be used for future applications. The proposed methodology is demonstrated by its application to an educational building at Sajjad university in Mashhad in eastern Iran and illustrating the best-case scenarios during the analysed periods. More details of the methodology are presented in the following.

2.1. Data collection

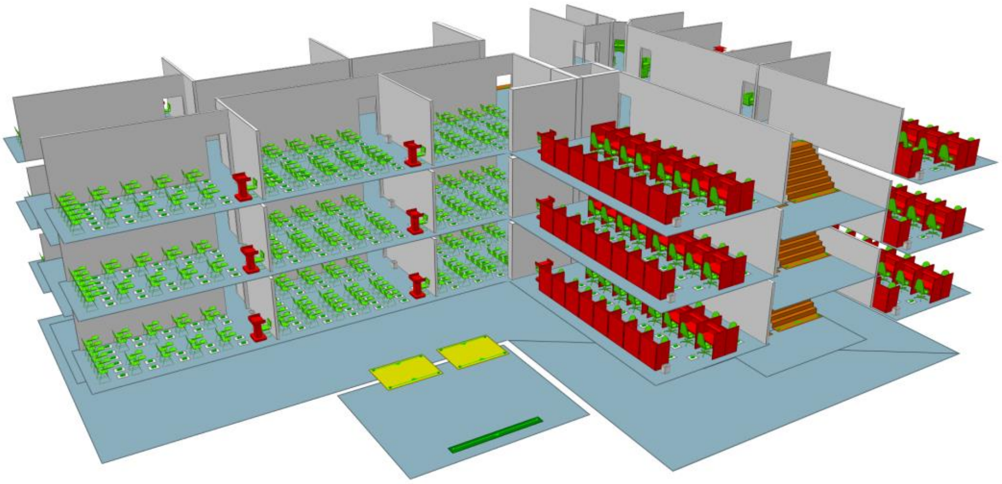
Building data and information are collected in the first step from any sources including the approved plans, as-built drawings, and archived maps. The data collection is accompanied by a site visit to create 3D model materials in BIM. Some information is also assumed based on the literature/previous studies and standards/norms in building construction in Iran (Building Standards of Iran, part 22). A review of strategies and scenarios in similar building types is also conducted to specify different feasible scenarios that can be effective for this study.

2.1.1. Case study

An educational building with a plan and 3D maps as shown in Fig. 5 based at the Sajjad University in Mashhad, Iran is selected as the case study of the building evacuation in this study. The building has a concrete structure on four floors including the underground with a geometry of 41m × 28m. The functions of the building spaces were designed for educational activities such as classrooms, computer workshop rooms, and offices. The building evacuation is simulated in this study for three floors above the ground and with a uniform plan for each level as shown in Fig. 5a.



(a)



(b)

Fig. 5. The case study building at Sajjad University used in this study (a) plan of floors, (b) 3D view

2.1.2. Modelling assumptions

The simulation modeling of the building evacuation needs to assume some parameters based on the most possible state when an emergency evacuation is performed with a focus on the effect of executing scenarios to improve the discharge time. The assumptions used in this study are given in Table 2, which include individuals' distance from each other, movement speed, agents' colour, proportion, delay period for evacuation, class arrangements, discharge time starting point, elevator situation, and weight of paths. In the next step, due to the assessment of floors' evacuation time and more population effects on the evacuation process, the fundamental of men's and women's evacuation mechanism is assumed similar. The number of persons on each floor and the furniture arrangements are considered such as other floors.

2.2. Building simulation and modeling

This study employs Revit software for physical building modeling and MassMotion for the simulation of the emergency exit process. According to ISO 29471-1, the process of BIM by Revit represents a digital image of the physical and functional characteristics of a structure to provide a reliable basis for decision-making during the life cycle of the structure with IFC output (Ren et al., 2022). MassMotion is designed to evaluate and analyse people's speed in different environments, by creating 3D environments, defining operational scenarios, performing dynamic simulations, and developing powerful analytics. The components modelled in these tools include a) adding a floor with stairs and links, b) a portal for agents to enter and exit, c) a barrier to block the agents, d) a server to model processes, and is the main factor in building process chains.

Table 2. The assumption for the evacuation simulation in this study

Assumption	Value
Width of shoulder	(40-50 cm)
Speed of movement	(0.9-1 m/s)
Agent's colour	Men and women (orange) Staff (black)
Delay duration for people	Men and women (immediately after simulation) and staff (30 s)
Class arrangement	Chair (r=50 cm) Distance to adjusting (50 cm)
Starting time of discharge	Evacuation 1st second of simulation
Number of elevators	0
Weight of path	0

After preparing the physical model of the building and preparing the environment for the evacuation process and the movement of agents, the type of movement activities needs to be evaluated. These movements include movement from one point to another, rotational movement between several destinations, and the characteristics of the factors such as colour, speed, individuals' radius, and how they are distributed (Hassanpour et al., 2022). Movement activation tools in this modeling are assumed to be as follows:

I) Profile involves physical and motor characteristics of the model, such as body radius. As the people inside the building (called agents in the model) have a competitive behaviour and influence each other in the emergency evacuation movement, it is necessary to determine the body radius of individuals by gender, as shown in the model assumptions. Another characteristic that needs to be specified for the agents is their speed during the escape period which is influenced by some factors such as the distance to the exit point, the location of other agents, and the location of obstacles.

II) Journey creates a trip for the agents by specifying the path between the beginning and destination points given a certain speed of the agents and minimum distance to the destination. When the agents arrive at their destination, their task is complete, and they leave the model.

III) Agent circulation starts with movement from one point and passes through several intermediate destinations and finally leaves the model when arriving at the destination. A new mission can be defined for the agents at the end, and after completing the initial round, they can proceed to a secondary mission.

IV) Evacuation command is employed by the agents to leave the building immediately. Hence, after the alarm goes off, those agents are activated and will find the nearest exit route to move towards it, moreover, path selection is adjusted to the real situation environment.

The agents choose their route toward the exit points based on their feeling and measure the distance according to their feeling, and finally, when they feel close to those points, they choose it and will be steadfast in it. However, it is noted that this waiting queue commitment can be changed by setting, for example, increasing the weight of a route to increase the likelihood that agents will select it so that agents will be more willing to choose that route.

Three graphical outputs of MassMotion, i.e., maximum density, agent count, and vision time are simulated in this study, which is described in detail below. The maximum density is related to the number of agents in the specific area at each point to reach a special time range.

Eq. (1) is used to compute the parameter. Due to the complexity of calculating the maximum density, this parameter is surrogated by calculating the Level of Service (LOS) expressed in Eq. (1). Hence, the LOS is an index for computing maximum density in the time range. The calculations of maximum density in the different places such as walkways, stairways, queuing, and wait/circulations are summarised in Table 3. Note that Fruin is the name of the main researcher in the evacuation analysis and all the categories are conveyed based on his experiments in standard conditions (Zarnke, 2015). LOS for a total simulation period of t can be calculated as below:

$$LOS(t) = \sum_{n=1}^{t} density\ (n) \tag{1}$$

where density (n) is the number of agents in a specific area.

Note that "maximum density" refers to the maximum number of agents (i.e., people) that can be present in each area, such as a room or a corridor, without overcrowding or hindering the evacuation process. Furthermore, the maximum density is typically determined based on local building codes, fire safety regulations, and other relevant standards. However, "agent count" refers to the actual number of agents present in each area during the evacuation simulation. This parameter is determined by the initial conditions set out by the simulation model, such as the number of occupants in the building and their distribution across different floors and rooms. In this study, both maximum density and agent count are considered as influential factors affecting the performance of building evacuation. As such, this study evaluates the evacuation safety for different combinations of these factors by simulating the evacuation process through three different scenarios with a different number of floors and various designs of stairs. The results indicate that the combination of two individual stairs for each floor can achieve the best performance in all scenarios, and other influential factors such as maximum density, vision time, and agent count are also important for designing a control system based on smart conceptual models.

Table 3. The parameters and legends used to calculate LOS as an index for maximum density

Fruit’ s Walkways	The area of the circle used to calculate density: 3.24 m^2			
	LOS	Density (person/m^2)	Space (m^2/person)	Colour
	A	x <= 0.309	x >= 3.24	🟦
	B	0.309 < x <= 0.431	3.24 > x >= 2.32	🟦
	C	0.431 < x <= 0.719	2.32 > x >= 1.39	🟩
	D	0.719 < x <= 1.075	1.39 > x >= 0.93	🟨
	E	1.075 < x <= 2.174	0.93 > x >= 0.46	🟧
	F	2.174 < x	0.46 > x	🟥
Fruin’ s Stairways	The area of the circle used to calculate density: 1.81 m^2			
	LOS	Density (person/m^2)	Space (m^2/person)	Colour
	A	x <= 0.541	x >= 1.85	🟦
	B	0.541 < x <= 0.719	1.85 > x >= 1.39	🟦
	C	0.719 < x <= 1.076	1.39 > x >= 0.93	🟩
	D	1.076 < x <= 1.539	0.93 > x >= 0.65	🟨
	E	1.539 < x <= 2.702	0.65 > x >= 0.37	🟧
	F	2.702 < x	0.37 > x	🟥
Fruin’ s Platforms (Queuing)	The area of the circle used to calculate density: 1.21 m^2			
	LOS	Density (person/m^2)	Space (m^2/person)	Colour
	A	x <= 0.826	x >= 1.21	🟦
	B	0.826 < x <= 1.075	1.21 > x >= 0.93	🟦
	C	1.075 < x <= 1.538	0.93 > x >= 0.65	🟩
	D	1.538 < x <= 3.571	0.65 > x >= 0.28	🟨
	E	3.571 < x <= 5.263	0.28 > x >= 0.19	🟧
	F	5.263 < x	0.19 > x	🟥
IATA Wait/ Circulate	The area of the circle used to calculate density: 2.70 m^2			
	LOS	Density (person/m^2)	Space (m^2/person)	Colour
	A	x <= 0.370	x >= 2.70	🟦
	B	0.826 < x <= 0.435	2.70 > x >= 2.30	🟦

	C	0.435 < x <= 0.526	2.30 > x >= 1.90	🟩
	D	0.526 < x <= 0.667	1.90 > x >= 1.50	🟨
	E	0.667 < x <= 1.00	1.50 > x >= 1.00	🟧
	F	1.00 < x	1.00 > x	🟥

Agent count is an expression of how many agents apply different walkable objects on the map. The vision time is also a concept about the environment that can be seen by agents during movement in the building. While looking at different objects is defined by a voxel. Voxel presents the vision capability of each agent in 15 degrees, a long 20m, and with 1.75m height. The vision capability of a typical agent in the MassMotion is presented in Fig. 6.

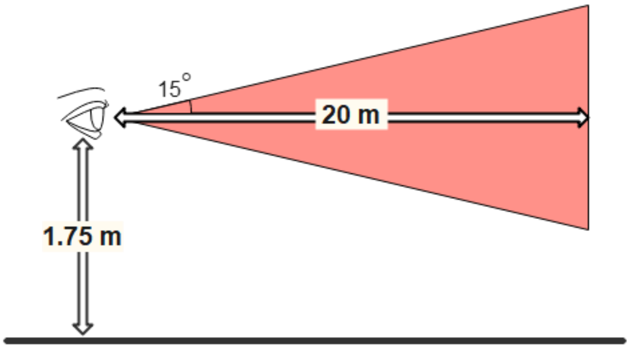


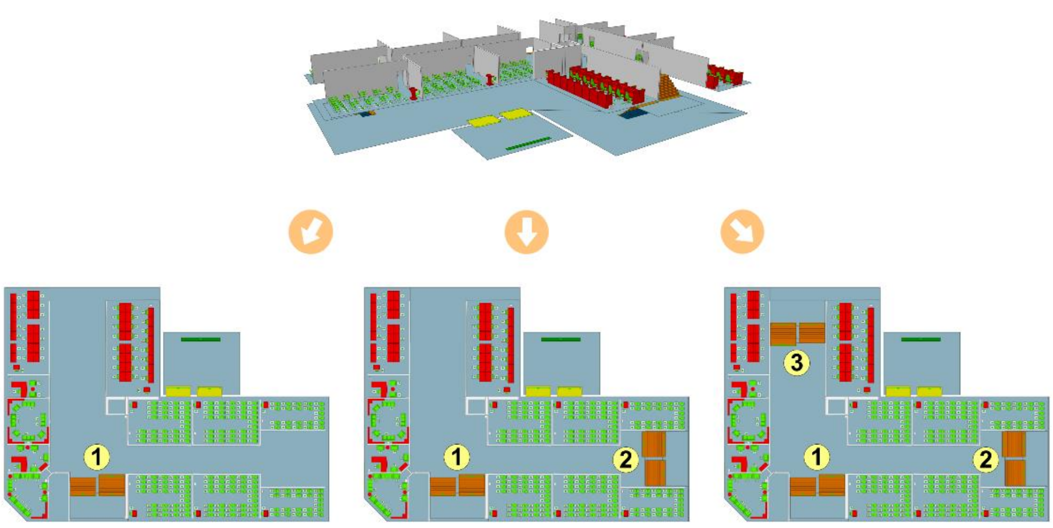
Fig. 6. The voxel position in vision time of MassMotion simulation.

2.3. Evacuation scenarios

This study evaluates three scenarios for the building design parameters that have an impact on the evacuation time. These scenarios are 1) the Width of the Classroom Doors (WCD) (initial WCD: 90 cm), 2) the Number of the Main Exit Doors (NMED) of the building (initial NMED: 1), and 3) the Width of the Staircases (WS) (initial NSSs contain 120 and 100 cm, respectively). Due to the evaluation of each parameter's effects and determination of evacuation time fluctuations, based on engineering judgment and available standards, features no. 1 to 3 are changed as secondary values contain WCD: 120 cm, NMED: 2, and WS: 200, 130. Each time the parameters are changed, the model is simulated followed by the sensitivity analysis to assess the impact of the changes on the design parameters in the scenarios. Thus, evacuation time is calculated for each set of new parameters and the most sensitive factor is selected for the crowd density and period. The procedure of finding ideal solution is performed in the next step to find the most effective parameters. All the simulations for the declared parameters are done in the one floor and plan of Fig. 5a.

2.4. Impacts of floor and population

The effects of the number of floors and population on each floor are also analysed in this study by defining new scenarios. Hence, the building design is reviewed for all plans and the impacts of the size of the staircase are scrutinised in different states. The staircases are simulated for a range of stair width between 1.10m and 3.30m on all the floors followed by sensitivity analysis based on a different number of staircases and different floors. In this simulation, the population on each floor is considered 260 people. Therefore, nine scenarios are analysed in this study as three states of stair designs for each of the three floors as shown in Figure 7. More specifically, the three states of stairs are simulated for a two-story building (Fig. 7a), a three-story building (Fig. 7b), and a four-story building (Fig. 7c).



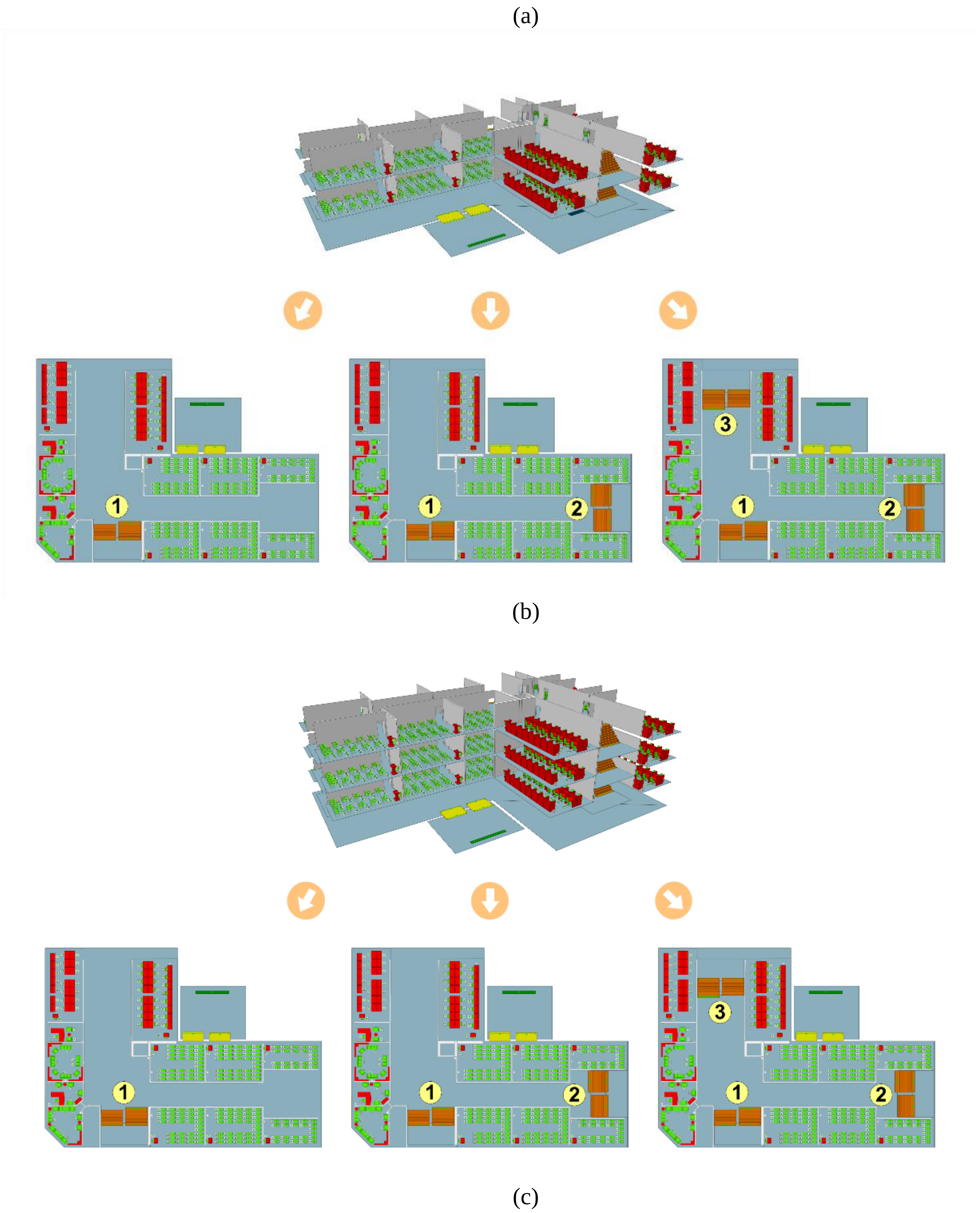


Fig.7. Nine scenarios of the building evacuation simulation according to three states of staircases on each floor for (a) two floors, (b) three floors, and (c) four floors.

2.5. Control conceptual modeling

This study employs four techniques for controlling systems including DT and AWBS during the evacuation process. More specifically, DT is used for prioritised control of design parameters to reduce injuries during the building evacuation process (Lee et al. 2022) while

AWBS is used for determining the re-engineering priorities of the studied building to increase the safety level in control systems (Chethan et al. 2022).

3. Results and Discussions

The data used in this study were obtained from a real-world multi-story commercial building in Iran with a great care to ensure the accuracy and reliability of the data. the building information model and evacuation simulation data. The data collected were used for building models in a combination of Revit and MassMotion software tools to simulate the evacuation of the building. Two simulation models in Revit (S.1 as uni.rvt) and MassMotion (S.2 as 03-floor-03-stair-cases-330.mm) are available in the supplementary materials. The main stages used in this study for modelling in Revit software are summarised as follows:

1. Setting up the project: a new project file is created, and the project settings are adjusted including units of measurement, levels, grids, and other project parameters.

2. Creating basic elements: the basic elements of the structure are created such as walls, columns, beams, floors, roofs, and stairs. Some predefined Revit families can be used or customised families can be created based on specific design requirements.

3. Adding details: more details can be added to the model, such as doors, windows, finishes, and fixtures. Revit's annotation tools can also be used to add dimensions, tags, and text notes.

4. Analysing the structure: the structural performance of the model can be analysed, such as load-bearing capacity, stresses, and deflections. Revit's analysis tools or third-party add-ins can be used to perform structural analysis.

5. Documenting the design: construction documents can be created including plans, sections, elevations, schedules, and details. Revit's documentation tools can be used to generate these documents automatically or manually based on the 3D model.

Once the Revit model was built, the following steps were used for modelling in MassMotion software tool in this study:

1. Creating the model geometry: the model geometry is created for the building or space in which the evacuation will take place. This involves creating floors, walls, doors, and any other architectural features necessary to define the space.

2. Defining the pedestrian flow paths: the pedestrian flow paths can be defined in the model geometry, including the location of exits, entry points, and any obstructions that might affect the flow of people during an evacuation.

3. Assigning the pedestrian properties: properties of the pedestrians are assigned in the model, including their walking speeds, densities, and preferred paths. This allows MassMotion to simulate how the pedestrians will move through the space during an evacuation.

4. Running the simulation: the model can be run to simulate the evacuation process. MassMotion uses a combination of agent-based modeling and simulation to model the movement of individual pedestrians in real time.

5. Analysing the results: the simulation results can be analysed to evaluate the effectiveness of the evacuation plan and identify any areas where improvements can be made. MassMotion provides a range of tools for visualising and analysing the simulation data, including heat maps, flow diagrams, and pedestrian density plots.

After running the evacuation model simulation, the evacuation time is first obtained by simulating different scenarios. The scenario presenting the shortest evacuation period is then selected as the best solution. The results are finally correlated to comply with the third topic of National Building Regulations.

3.1. Effective factor of evacuation time

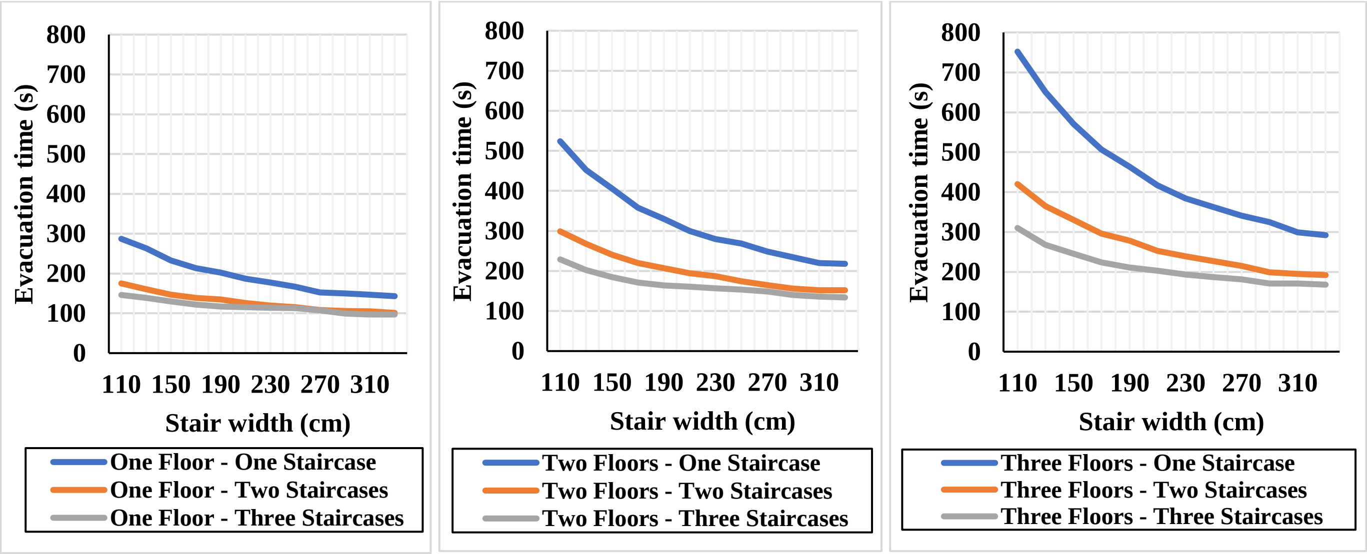
Table 4 illustrates the time reduction after changing effective parameters, as well as the total time after the application of all parameters together. The maximum reduction in evacuation time is achieved when all scenarios are applied simultaneously, however, by individual examination of each variable, it is found that the maximum reduction time, is achieved by widening the stairs, and the second effective variable is adding a second exit door to the building. Increasing the classroom door size has no significant impact on evacuation time reduction due to timing that the crowd leaves the classroom, which is before the classroom door disappears. Another important point that must be considered is that there are certain standard ranges regarding the door size of the classroom, that must be followed. The effective variable for time enhancement is related to the width of the stairs, hence other parameters are maintained as a constant value, while the width of the stairs and their number is enhanced in the next step.

Table 4. The first analysis of evacuation time in the case study

No.	Building component	Initial evacuation time (s)	Exit duration (s)	Change (%)
1	Base case	3.38	3.38	0
2	Door width improvement		3.33	5
3	Increase in the number of doors		3.30	8
4	Stair 2		3.08	30
5	Stair 1		2.50	48
6	2 staircases		2.43	55
7	Application of all parameters		2.32	66

3.2. The best stair condition

Based on the defined situations of model testing which are defined in the materials and methods section, the outputs of simulation for three states of staircases in the building with a different number of floors are depicted in Fig. 8. As can be seen, the performance of evacuation time for two and three staircases in almost three-floor numbers are relatively similar whereas the evacuation time increase significantly when there is only staircase in the building. Moreover, by increasing the floors from one to three, the performance of one staircase is decreased strongly due to increasing the agent junction points in critical zones. This can also be due to the fact when evacuating by more than one floor, agent interference occurs more frequently which will slow down the evacuation process. In addition, by increasing the stair width, the evacuation time in all states starts to level off, and specifically for two and three staircases, it is converted into a constant amount for a specific number of floors, i.e., around 100s for one floor, 150s for two floors and 190s for three floors. This can show the maximum stair size required for those specific designs and floor numbers in which the agents are safely discharged from the building and hence the building designers have the options to select either of these numbers of staircases.

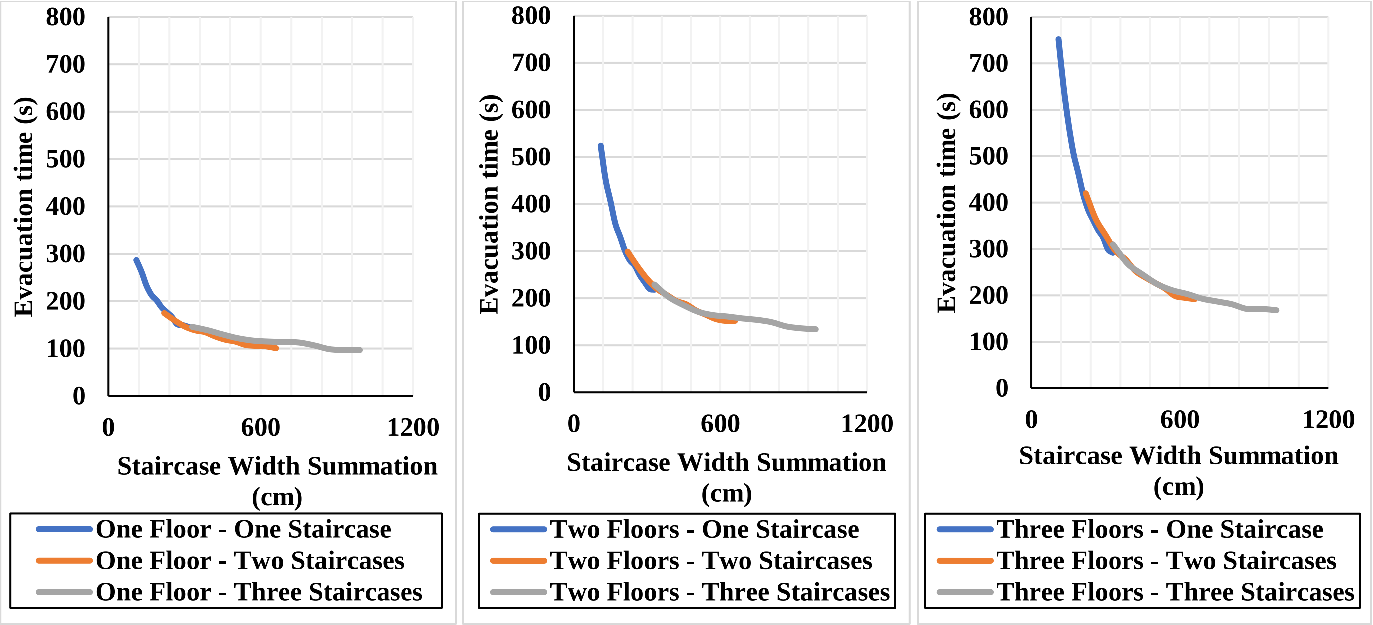


(a) (b) (c)

Fig. 8. The evacuation time versus the stair width in (a) one floor, (b) two floors, and (c) three floors above the ground

The best evacuation time in buildings is considered in this section based on engineering judgment and existing experiences in Iranian internal standards. The assumption linked to the best performance of the evacuation process is that when discharging on one floor, two floors, and three floors is 80% of the best evacuation time. Based on the model simulations, the minimum evacuation time from the building is 97s for one floor, 134s for two floors, and 138s for three floors above the ground. The best condition of the Staircase Width Summation (SWS) is determined based on both maximum performance and minimum evacuation time. The results of this analysis are shown in Fig. 9. For the case of a building with one floor above the ground (Fig. 9a), the best performance of SWS occurs in two staircases which is equal to three ones with a total width of 500cm and 115s evacuation time. Meanwhile, the three staircases with a total width of 570cm SWS (i.e., 190cm for each staircase) have the same evacuation time in the best performance (i.e., 80% minimum evacuation time). Therefore, the best condition on one floor occurred with two staircases with 250cm width for each staircase. For the case of a two-floor scenario (Fig. 9b), the best performance can be achieved by the evacuation time of 163s which is related to the two staircases with a total width of 560 SWS (280 for each staircase), equivalent to three staircases with a total width of 630cm (210cm for each staircase).

For the case of three floors scenario (Fig. 9c), the best performance of two staircases (i.e., evacuation time of 199s) is for a total width of 580cm SWS (i.e., 290cm for each stair) is more preferred to equivalent performance for the three staircases with a total width of 660 SWS due to the economic perspectives. Hence, comparing all three-floor scenarios shows that the best safest design for the minimum evacuation time is related to the building when two staircases with the width of 250cm, 280cm, and 290cm for one, two, and three floors scenarios, respectively, are designed in each floor. If more safety factor is included in the design process, three staircases can be considered. Although three staircases for each floor can slightly reduce the evacuation time, this improvement can be neglected for increasing safety as analysed above.



(a) (b) (c)

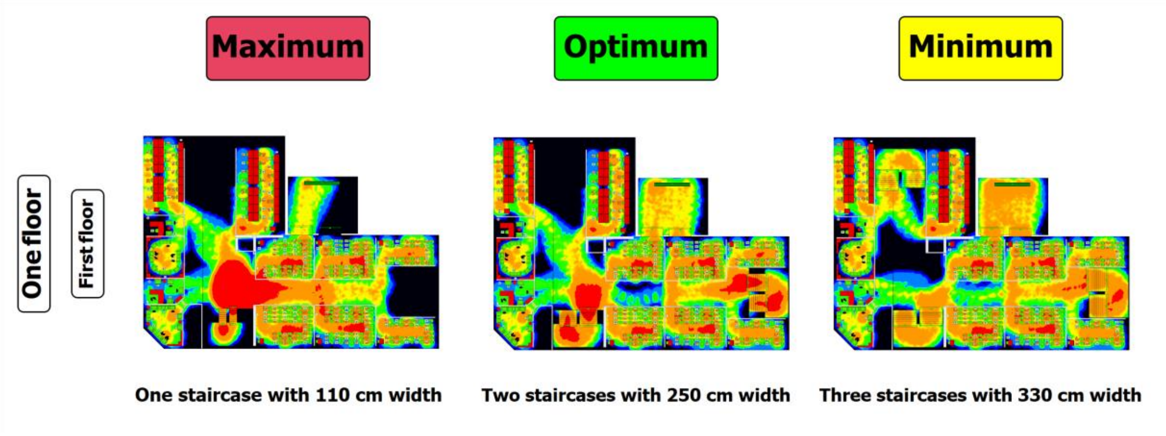
Fig. 9. The evacuation time versus Staircase Width Summation (SWS) in (a) one floor, (b) two floors, and (c) three floors above the ground

The results show that the best performance of building evacuation in all scenarios can be achieved when two individual stairs are designed for each floor. This finding contrasts with the common practice of using one central stair or three individual stairs. This can be due to several reasons. First, as stairs seem to be an expensive part of the building construction, it is much more cost-effective to build two staircases with a longer width instead of three. Secondly, the total width of the stairs is also an important factor affecting the performance of evacuation. The study shows that the total width of the stairs should be around 600 cm to achieve best performance. This width allows for a comfortable and safe passage of occupants, reducing the risk of accidents, such as falls or collisions. It is much more comfortable when compared to three staircases with lower total width. Furthermore, two staircases are more attractive and enhance the attractiveness of the construction as it can be in a symmetric way.

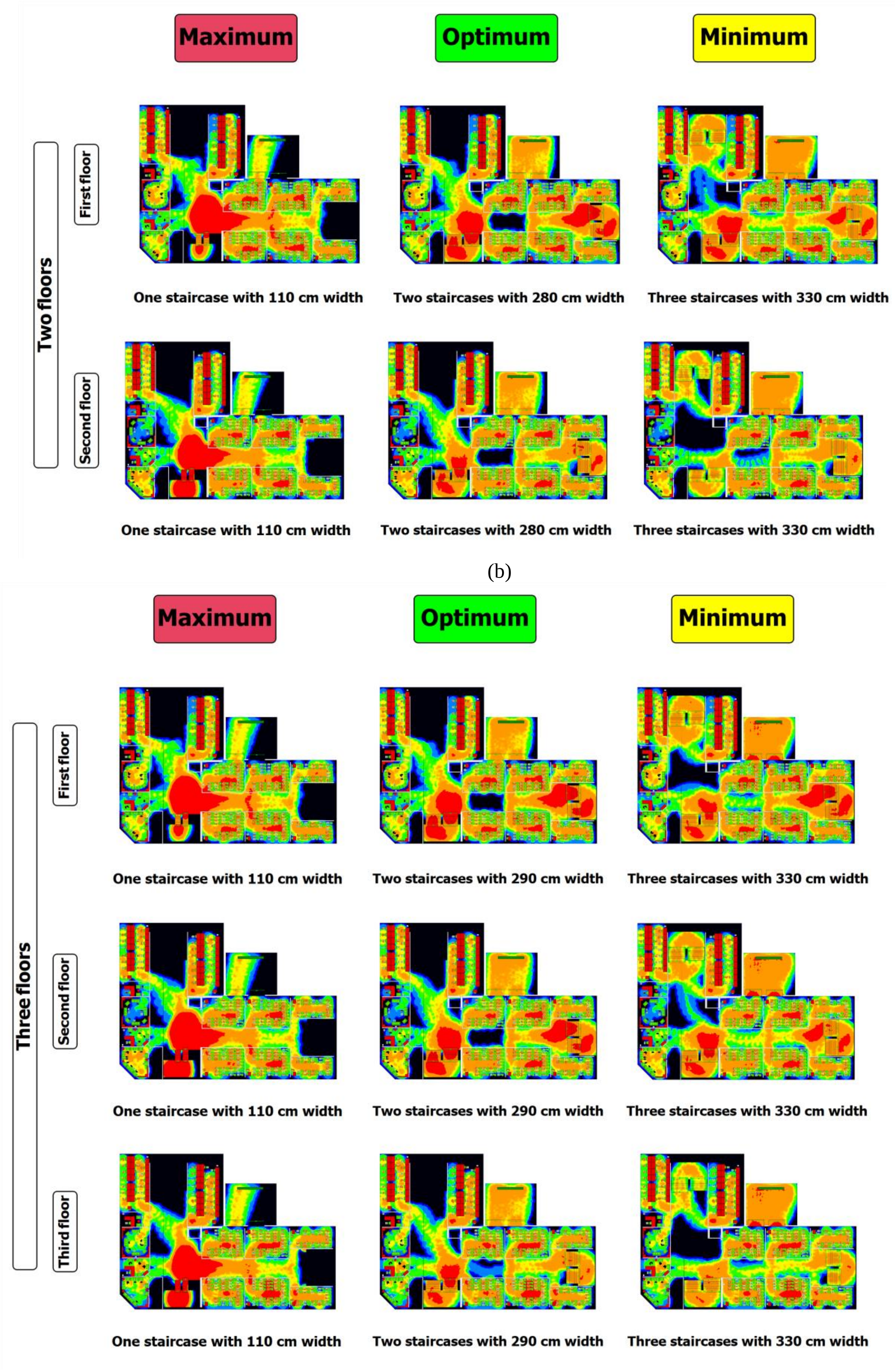
3.3. Map analysis

MassMotion software is used as an illustration map to show the movements made in the simulated models with different parameters. These parameters include agent count, agent path, dynamic path, density (maximum, experience, instantaneous, and average), time (agent to exit, occupied, and until clear), and vision (count and time). Both the agent count, and density significant models are selected here for analysis, including agent count, density in three different situations (minimum, maximum, and the best evacuation times), and time vision output.

Fig. 10 shows the maximum density of the evacuation process in all three scenarios (one, two, and three floors) based on maximum, minimum, and best evacuation time. The figures show that the maximum evacuation time occurs in the smallest staircase width in all cases. Therefore, the waiting time is increased for exiting the persons from the building. This phenomenon causes the density of agents to be raised in stairs. The changes in maximum density consideration to different conditions of this study are demonstrated in Video A1.



(a)

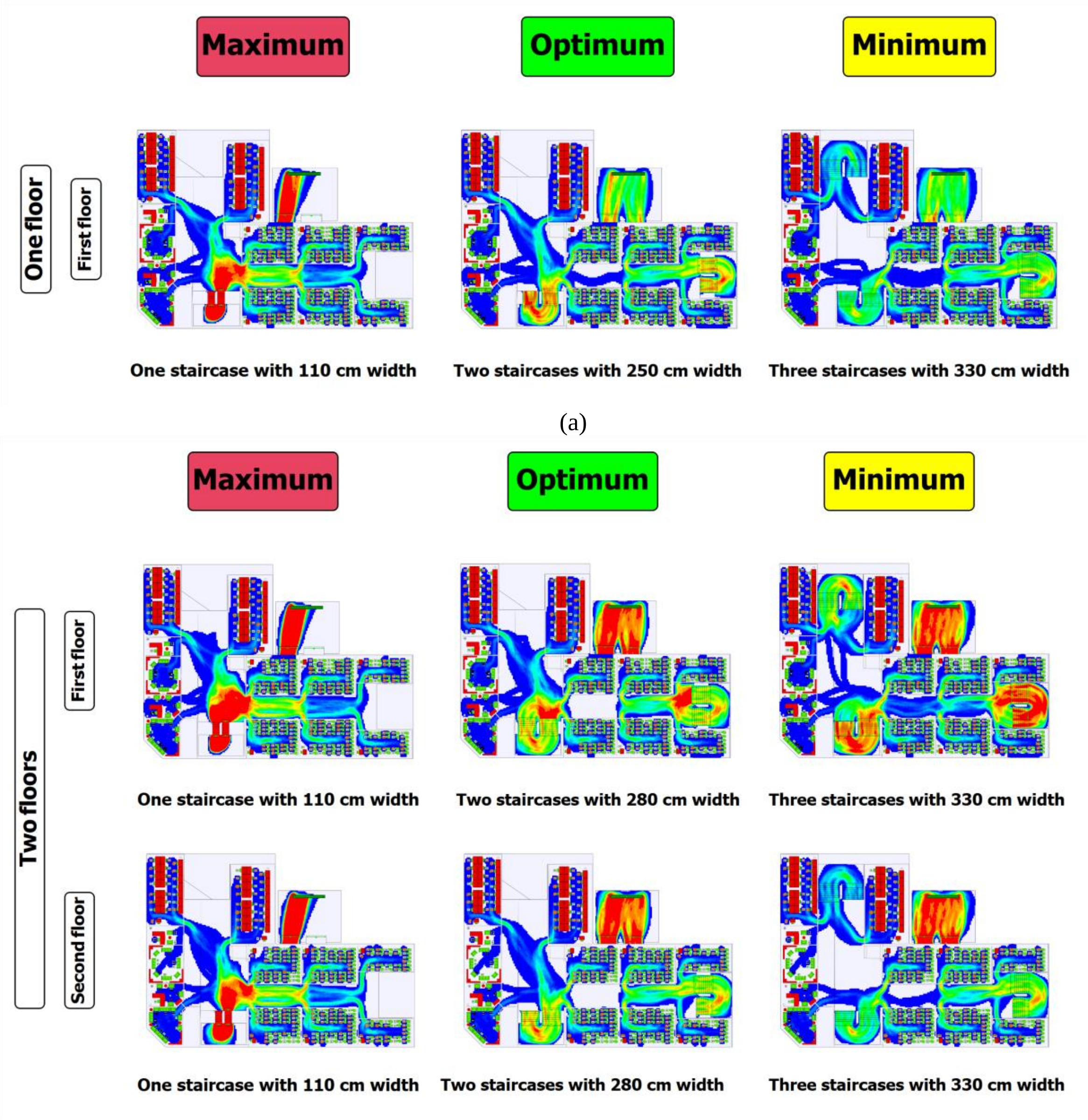


(b)

(c)

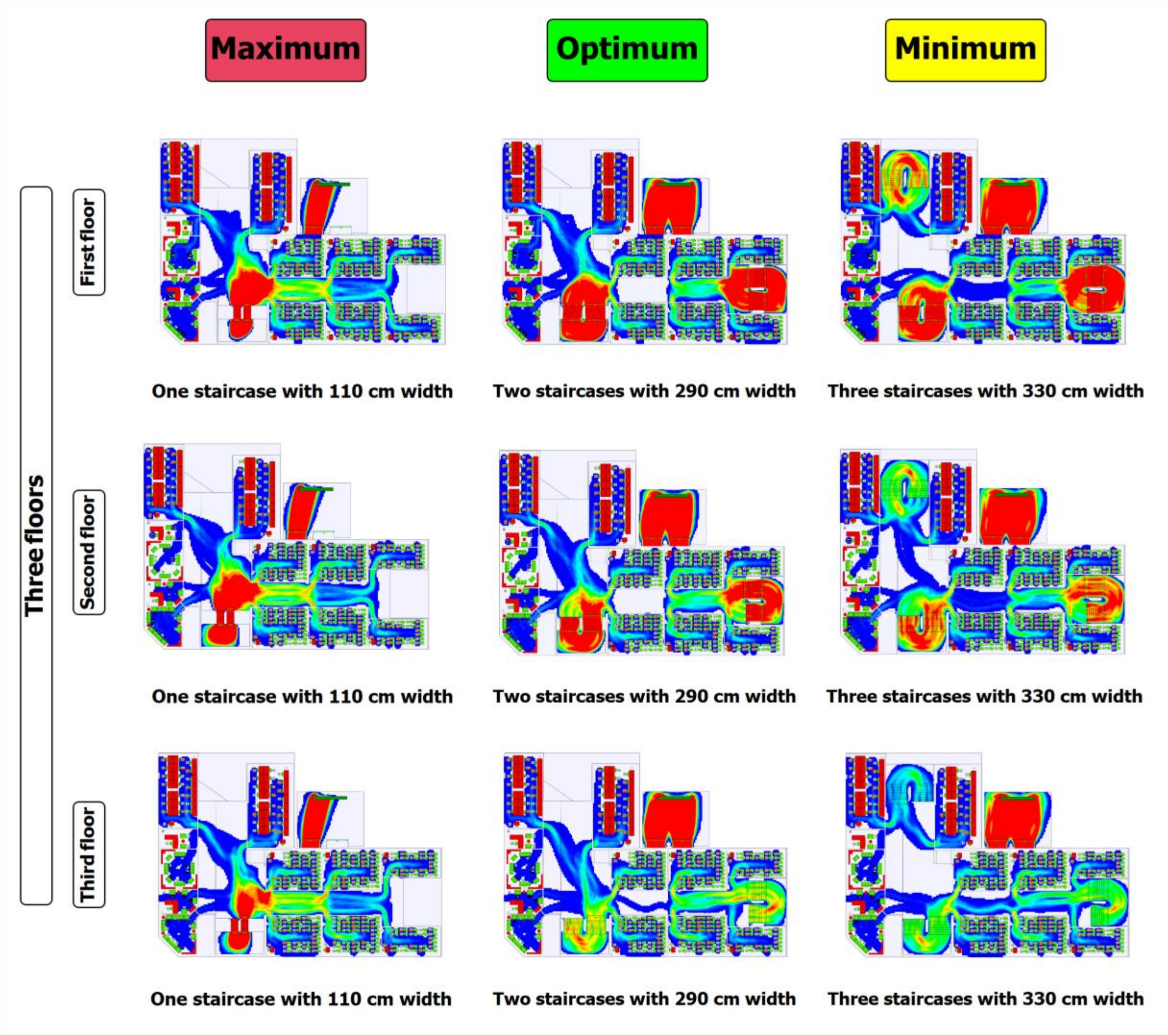
Fig. 10. The maximum density based on maximum, minimum, and the best evacuation times in (a) one floor, (b) two floors, and (c) three floors above the ground.

Fig. 11 shows the agent count presenting the number of agents at each point of the map when evacuating the building for different building scenarios. As can be seen, in the case of only one staircase in the building, the agents have inevitably one choice to exit, and hence, agent junctions in stairs are overcrowded whereas increasing the number of staircases can divide the agents into different staircases for exit that also reduce the evacuation time from the building.



(a)

(b)



(c)

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Fig. 11. The agent count based on maximum, minimum, and the best evacuation times in (a) one floor, (b) two floors, and (c) three floors above the ground.

Fig. 12 shows the time vision map of the agent on the top floor. It indicates windows and floors of the corridors near the stairs and exit doors are the most visited visual points by the agents, and hence, can be used for installing warning signposts to show the direction for exit in an emergency. This was also confirmed by other research works that common areas in buildings such as stairways and sensitive bottlenecks are the most crowded places during the evacuation, which can be more important than the number of doors and their width (Xiao et al., 2022). A similar finding was also reported by advanced technologies such as AR and VR (Lorusso et al., 2022).

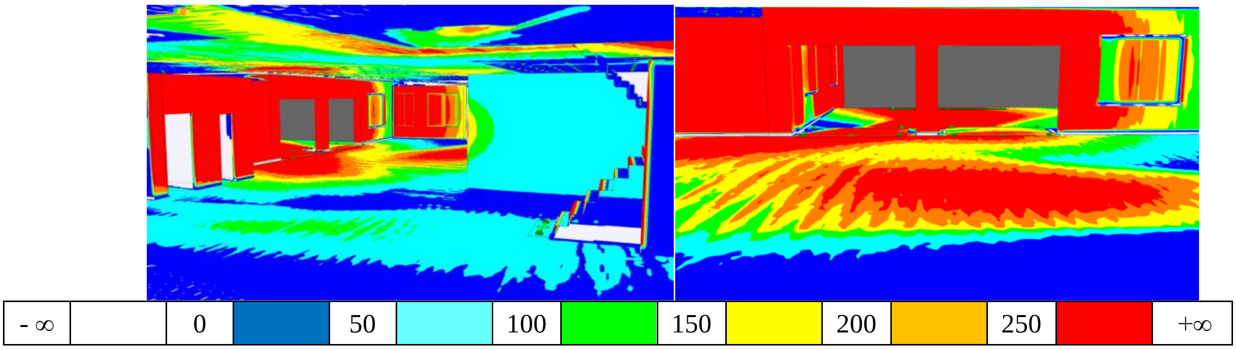

Fig. 12. Vision time in the top floor of visual contacts as per evacuators' points of view.

The main pillars in this study analysed the evacuation time from architectural and civil engineering aspects. However, the use of a coherent social network is considered amongst various research works to analyse building evacuation during an emergency, in which the greater cohesion of people's social network leads to the evacuation cascade during a crisis (Makinoshima et al., 2022). Such an approach can also be viewed from the perspective of system engineering and computational social sciences with a more precise approach. Therefore, individual and social structures can also act as a basic lever.

Another study related to an underground station shows that evacuation time enhancement by up to 27% can be achieved (Guo and Zhang et al., 2022) while the improvement in this study is over 50%. Other research works also show that changing the physical structure of buildings and redesigning them can have better results than installing electrical and mechanical systems (Adjei et al., 2022; Barten et al., 2022; Renne and Mayorga, 2022).

There are some limitations to simulation modeling in this study. Basically, it must be acknowledged that the real world cannot be simulated exactly and in all its details, and the simulated model is always an approximation of the real world but given the advantages and possibilities that simulation offers us, this approximation will be negligible.

4. Managerial insights and crisis management

Both DT and AWBS are demonstrated in Figs. 13 and 14, respectively. In the DT scheme as a semi-smart model, two indexes are defined below.

$$N_{1i} = \frac{\text{population in building}}{SSW} \tag{2}$$

$$N_{2i} = \frac{\text{population in building}}{NSS} \tag{3}$$

where SSW is Stair Service Width and NSS is the Number of Stair Services, respectively. While the N_{i1} is computed based on three 110 cm (min), 190 (as the best value), and 330 (max). The best N_{i1} for 190 SSW is equal to 1.6 and based on Fig. 13, in the first step, if N_{i1} is not between 1.6-2.8, it should be redesigned because of the considerable distance with the best condition. In the next step, if N_{i1}-1.6 is equal to zero, it means the best situation has occurred. Besides, if N_{i1}-1.6 is not equal to zero, it is acceptable with more than 50% based on engineering judgments. A similar way is planned for N_{i2} as another index that should be assessed in the DT algorithm. Finally, if both N_{i1} and N_{i2} locate in the best condition, the highest situation is faced.

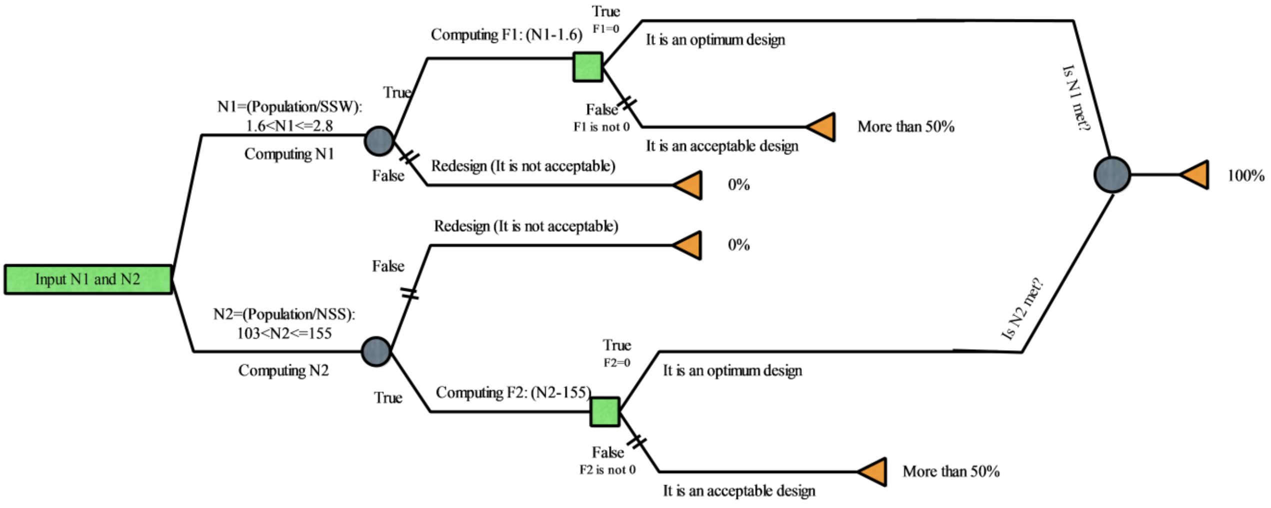

Fig. 13. The schematic plan of DT as a controlling system of the evacuation process in this study

As can be seen in Fig. 14, the effective features for increasing safety levels during the evacuation process are divided into two different groups. The safety system is finished to start the structure and it is ended when the subsections of it are started. The first group is detailed to stair service number and stair service width and whereas, the declared categorised systems are more important in comparison to other ones. Likewise, both the categorisations have Finish to Start structure in their relations. This indicates checking of stair service width and number will be ended when the other one is started. Because, based on Table 4, both parameters have the most significant effect on the evacuation process, and they should be proceeding at the same time. Meanwhile, from an economic point of view, to improve the evacuation situation, changing the width of the stairs is more economical than the number of services, and this can be considered by the managers in the process of re-engineering the building.

In the next level, door width and a number have lower importance in comparison to stair service specifications. Both factors of door width and its number are important in turn, but the main bottleneck of rapid evacuation occurred in the service of the stairs, and this requires a review of the designs. However, it should be noted that in the design control process, checking these two factors (width and number of doors) should be done at the same time and started together. However, the economic priority is to widen the doors.

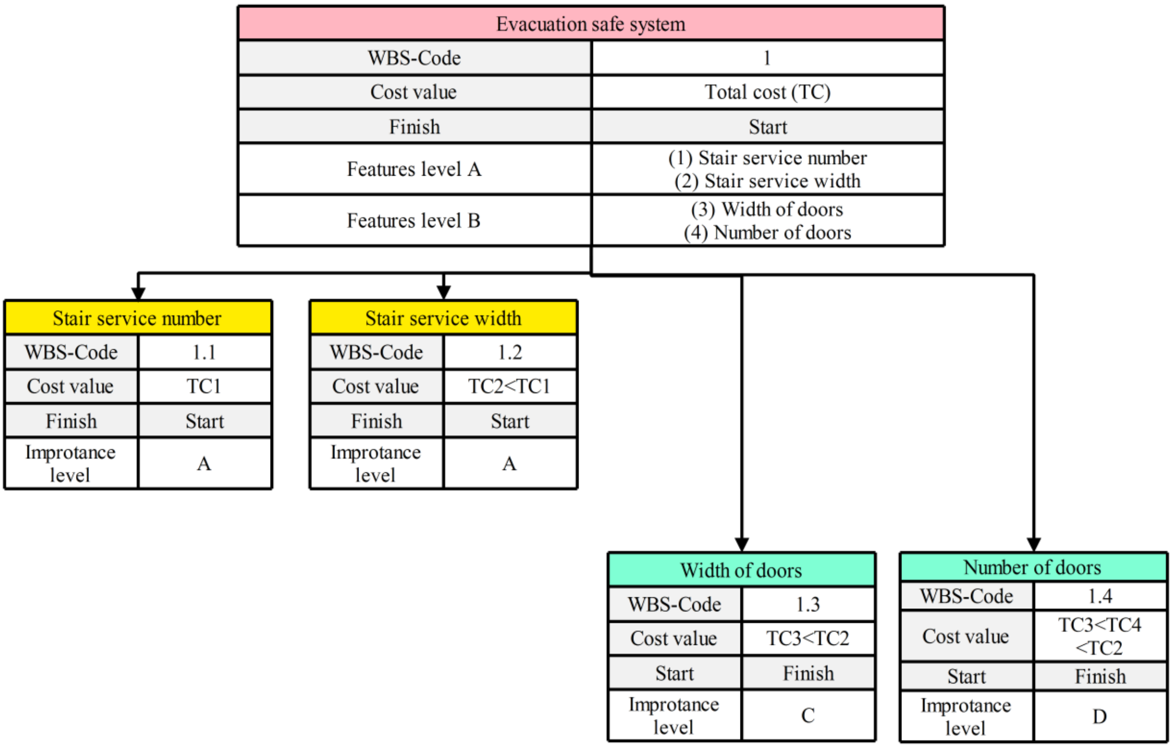

Fig. 14. The plan of AWBS concept in this study.

5. Conclusions

This study presented a framework for the enhancement of the emergency evacuation and management of educational buildings based on the combination of visual modeling software and MassMotion simulation software. The physical 3D model of a building at the Sajjad University of Technology was modelled and transferred to simulation software, then by examining different scenarios, the most significant and effective parameter in the evacuation was identified and the most efficient values for this parameter were obtained from the sensitivity analysis. The results illustrated that in the small changes in staircase width, evacuation time fluctuates strongly. The staircase width was the main feature mainly affecting the evacuation time compared to other parameters. it was found, ne staircase is unacceptable in educational buildings and the selection should be done between two or three staircase scenarios. Three staircases on each floor have less evacuation time in comparison to two staircases. However, two staircases on each floor can fulfil the required safety for the evacuation process in this study. The evacuation time performance of two and three staircases in the same summation of staircases is similar, while three staircases can be recommended for creating more confidence. However, it should be noted that the results presented in this study are related to a building up to three floors that may not necessarily be applied to buildings with more floors. Furthermore, the scope of the study is limited to those parameters mentioned in the research but other potential constraints that may affect the best design of the stairs, such as building codes, regulations, and safety standards should be analysed in future research to see their impacts on the building performance.

The present research suggests machine learning computation can be used as a soft sensor due to the prediction of high-load zones in the evacuation process which is provided based on the combination of Artificial Intelligence and simulation practices. Likewise, fast decision-making system can be integrated with metaheuristic algorithms for enhancing the safe operation of buildings in the case of emergency.

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