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A hybrid hierarchical agent-based simulation approach for buildings indoor layout evaluation based on the post-earthquake evacuation

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ABSTRACT

In the aftermath of severe earthquakes, building occupants evacuation behaviour is a vital indicator of the performance of an indoor building design. However, earthquake evacuation has been systematically neglected in the current building design practice. Arguably, one of the primary reasons for this is that post-earthquake evacuation behaviour is complex and distinct from all other types of evacuation behaviours such as fire. Thus, a comprehensive approach to considering the integration of human evacuation behaviour and a building's indoor layout design, mainly focused on non-structural damage, has been consistently neglected in the literature. In this paper, a hierarchical hybrid Agent-Based Model (ABM) framework integrated with a Cellular Automata (CA) and a 2D Building Information Model (BIM) damage visualisation to consider an approximation of non-structural damage has been developed. The proposed ABM incorporates learning mechanisms and human psychological aspects influencing evacuees' utility during the navigation process. The proposed approach was verified by comparing the results to previous real-life post-earthquake evacuation data and a "model to model" comparison of results from the existing relevant studies. The model prototype was successfully tested to simulate the pedestrian evacuation process from one floor of the new engineering building at The University of Auckland, New Zealand. The proposed simulation approach has been carried out for two different internal layout design alternatives where five population sizes are evacuated through different scenarios. The outputs from this study can be used to improve the design's compatibility of the building's indoor layout with the occupants' post-earthquake evacuation behaviour.

1. Introduction and overview

Human behaviour is an undeniable parameter in building design, where today, the simulation of human behaviour is becoming a crucial necessity in the design of key infrastructures such as airports, hospitals, and public transportation hubs. Predicting human behaviour is an inherently complicated problem due to the psychological aspects of humans, which contain a high amount of uncertainty. Knowing the human preferences to move toward a path or in a building becomes even more vital when considering emergency evacuations after critical events such as earthquakes. In the aftermath of severe earthquakes, how building occupants behave and safely evacuate is a key indicator of the performance of an indoor building design. However, this has been systematically neglected in the current building design practice [1].

There are numerical studies regarding evacuation simulation, but very few of them focused on post-earthquake due to its complexity both in human behaviour and dynamic environmental aspects. Integrating a learning-based navigation model with the incorporation of non-structural damage and the agent-based model can lead to a comprehensive simulation approach to model an intelligent human decision-making process and a dynamic damaged environment in post-earthquake evacuation scenarios.

This paper aims to incorporate human post-earthquake evacuation behaviour into the building's indoor layout design by developing a suitable simulation approach. In order to reach this goal, initially, we investigated how occupants behave in an earthquake event. Then we

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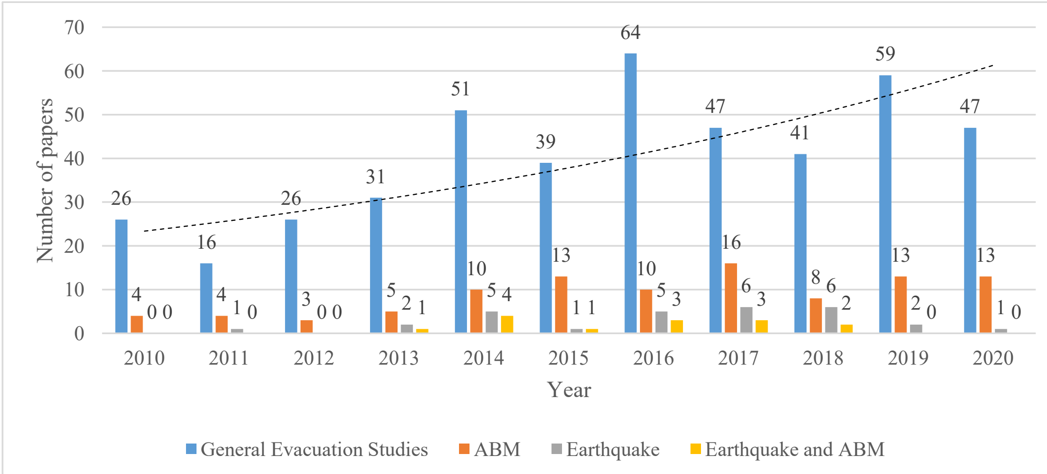


Fig. 1. Number of peer-reviewed papers about evacuation simulation models per year from 2010 to 2020.

developed a novel learning-based agent-based model to address these behaviours and incorporate them into a simulation model. Finally, we tested the proposed simulation model in a real floor plan by mimicking an earthquake and applying randomised non-structural damage into the indoor building environment in a unified interface. Considering a dynamic environment in an earthquake with non-structural damage, physical and psychological aspects of humans, social and individual earthquake-specific behaviours, human interaction with the damaged environment, and smart navigation approach using the reinforcement learning, all in one comprehensive approach, is novel in the relevant state of the art so far.

All the simulation codes and interfaces were specifically developed within the NetLogo 6.0.4 software tool [2], which is a free multi-agent programmable modelling environment. While at the proof-of-concept level, the proposed approach has the potential to assist architects and designers in the future in evaluating a building's indoor layout-based design on occupants' post-earthquake evacuation behaviour.

2. Literature review

2.1. Pedestrian dynamics and simulation classifications

A systematic review has been performed within the existing literature to find out the number of studies working on the evacuation simulation models. To compare the subjects and the focus of studies, we conducted three search strategies of search-strings. First, we used "evacua*" and ("human behavio*" or "occupant behavio*" or "evacuee behavio" or "pedestrian behavio*") and "simulat*" to cover the whole area. Secondly, we filtered the search by focusing on "agent-based" models and finally, we added "earthquake". Fig. 1 shows the number of journal papers between 2010 and 2020, in which the trend line confirms that the number of papers has been increasing in recent years.

However, the result shows that the number of studies that focused on earthquake evacuation is significantly low (the search was conducted on the 20th of March 2021 from Scopus and Engineering Village, and the papers up to the 30th of December 2020 are included). Also, approximately 10 per cent (10 out of 112) of the agent-based studies have conducted a validation or verification test, most of which were qualitative tests. A similar result was stated by Siyam et al. [1] about the lack of standardised validation methodologies for agent-based evacuation models.

In the general classification of pedestrian dynamics simulation based on the models' perspective, there are three main categories: macroscopic, mesoscopic, and microscopic models [3,4]. The models consider more details from the macro-level to the micro. The evacuation models can be considered as a subset of pedestrian dynamics, so the classification is very similar. Evacuation models have two main categories of macroscopic and microscopic, and the third category is the hybrid, which integrates both to use the benefits of previous approaches and avoid the disadvantages [1,5].

Macroscopic models consider the evacuation process as a unified flow (like a fluid), often through optimisation models, while microscopic models focus on each individual and all the interactions. Consequently, macroscopic models cannot explain the details of pedestrian movement; on the other hand, microscopic models usually lead to heavy computational complexity. The hybrid models try to use the advantages and avoid the weak points of both microscopic and macroscopic categories [6].

2.2. Different approaches toward evacuation navigation models

As this paper aims to consider details of humans during the evacuation process, the desired model should be within a microscopic approach. There are three main microscopic approaches, most of which use directly or a combination of them to simulate the pedestrian movements and interactions: Cellular Automata (CA), Social force (SF), and Agent-Based Models (ABM). In the following, we will briefly review each of them and highlight the most relevant studies to evacuation modelling.

2.2.1. Cellular automata

Cellular automata introduced by Neumann considers the system as a set of discrete cells which form a grid environment. The cells' state or quantitative variables in each cell are updated dynamically based on the values of the adjacent cells at the previous time-step [7].

One of the latest studies used a cellular environment to model probabilistic dynamic structural damage to analyse the evacuation process during an earthquake. The study tried to apply the network-based pedestrian dynamics model to simulate a three-story office building in an earthquake event [8]. The study avoided the computational complexity by using a simple approach to combine building damage assessment and evacuation process; however, it could not consider any details, especially in the matter of human behaviour.

Wang et al. [9] used a CA approach to calculate the optimum number of guiders on each floor based on exit capacities during an emergency evacuation. Also, Gao et al. [8] used a modified CA to present simplified evacuation guidance during evacuation based on two coefficients of exit weight coefficient and individual acceptance. Both studies could mention just one or two factors, such as capacity in their models, and considering human behaviour is almost impossible due to the nature of

Table 1
An overview of some open-source pedestrian simulation tools.

Model	Language	Evacuation type	Visualisation	Navigation engine	Smart exploration	Extra features
FDS + Evac	Fortran	General and fire-specific	2D (3D by third-party tools)	Social force model	N/A	Smoke and heat transport from fires
JuPedSim	C++	General and fire-specific	2D/3D	Force-based model	N/A	Smoke spread
MomenTUMv2	Java	General	2D/3D	A force-based model	Search for unknown locations, plan adaptation	Operational and strategic layers
Meneg	C++	General	2D/3D	Behaviour Finite State Machine (BFSM)	Plan computation and adaptation	Bespoke functionality to some extent; algorithms can be compared
Vadere	Java	General	2D	Optimal steps model, the gradient navigation model, and the social force model	N/A	The optional graphical user interface facilitates model comparisons

the cellular approach. Furthermore, the earthquake detail, including the environmental damage assessment and availability of paths, were absent in the latter.

2.2.2. Social force

The social force model is a continuous space system (not discrete) that all the movements are determined by physical forces such as desired force, cohesion force among pedestrians, and avoidance force from obstacles alongside psychological forces such as herding and panic effects [10]. The SF model can consider people's internal drives, especially in emergency and panic situations; therefore, it is widely used in evacuation models after Helbing and Molnár [11] first proposed this approach in their article [12].

The main drawback of this approach is that contrary to CA, it needs heavy computations, especially when a model intends to include some behavioural details. Thus, some studies tried to improve or optimise the SF model by focusing on one or more particular variables. For example, Li et al. [13] used a modified SF to simulate and analyse congestion risk on stairs. Zhao et al. [14] used SF in a three-dimensional environment considering both lateral and vertical swaying forces after Krausz and Bauckhage [15] effort on lateral swaying. To obtain more realistic movement trajectories, Li et al. [16] enhanced the social force model by taking the conflict avoidance of pedestrians into account. One of the primary drawbacks of SFM is that it is difficult to decipher the pedestrians' intentions, which are obscured by the mathematical calculations and parameters [17]. Apparently, studies that used SF have to narrow the subject and focus on limited details of behaviour.

2.2.3. Agent-based model

The agent-based model in the evacuation context considers each individual as an autonomous agent with specific characteristics and behavioural attributes which has a goal and rationally take actions in the environment to reach their goal [18]. The ABM is capable of considering individual and social behaviour besides the dynamic interaction with the physical environment [19]; therefore, it turns to a popular method in evacuation simulation.

Hassanpour and Rassafi [4] focused on the psychological aspects of agents by integrating the affordance concept with ABM for a simulation of evacuation from an underground metro platform. Using an agent-based framework, another study focused on older adults during evacuation and their fall risk [20].

There are few studies that consider earthquake evacuation scenarios. Liu et al. [21] conducted an ABM simulation to integrate human behaviour and structural response in an earthquake by combining a dynamic finite-element, probabilistic damage assessment, and agent-based modelling. This is a valuable study in this context; however, questions can be raised about the ABM component as it used a general and simple agent-based evacuation simulation. In contrast, human behaviour in an earthquake is a complex phenomenon and totally different from other types of evacuations such as fire, flooding, or terrorist attack evacuation that each has its own behavioural characteristics.

Some researchers have integrated two or more approaches above and used hybrid models to take advantage of different approaches and minimise their limitations [1]. For example, a study used a combination of cellular automata and social force interactions to simulate the evacuation process and evacuation time analysis in a building [22]. Lubaś et al. stated that an agent-based model could utilise a non-homogeneous cellular automaton as base support in complex systems. They applied their ABM-CA hybrid approach to consider more variables in an evacuation process, such as different perceptions and the information spread [23].

2.3. Different pedestrian dynamic simulation tools

This section will introduce five of the well-known open-source tools in the pedestrian movement context to briefly compare their capabilities to capture the evacuation process.

2.3.1. Vadere [24]

Vadere is one of the popular open-source pedestrian tools developed in the Computer Science and Mathematics department at the Munich University of Applied Sciences. It uses three Java-based approaches as the navigation engine, namely the optimal steps model, the gradient navigation model, and the social force model. Despite different navigation models that can be utilised in the software, Vadere provides a simple, user-friendly interface for the modellers to use the tool and conduct a comparative analysis of different approaches. The software does not include any specific feature regarding emergency evacuation; however, it provides multiple test cases for evacuation scenarios for the model validation and verification.

2.3.2. JuPedSim [25]

JuPedSim, developed by Armel Ulrich at the Forschungszentrum Julich research centre, is simulation software, which uses a new force-based model to simulate pedestrian dynamics focusing on scenario-based evacuation process. The framework is able to take the 3D environment as an input for geometry, visualise the trajectories, and finally, analyse the simulation by plotting the evacuation densities, velocities and flows.

2.3.3. Menge [26]

Menge is another open-source tool that provides different pedestrian movement approaches to be utilised and compared in its simulation framework. Sean Curtis developed Menge at the University of North Carolina. It uses a Behavioural Finite-State Machine approach (BFSM), an agent-based model as the core of agents' behaviour simulation engine.

2.3.4. MomenTUMv2 [27]

Considering human psychological aspects and agents' preferences in choosing different locations during movement is a factor neglected in most simulation tools. MomenTUMv2 is a pedestrian simulator developed at Technische Universität München focuses on this behavioural issue by combining the interest function model and choices models.

2.3.5. Fire dynamic simulation [28]

Fire dynamic simulation tool (known as FDS + Evac), developed by the National Institute of Standards and Technology (NIST), presents a framework to simulate pedestrian evacuation focusing on fire evacuation. It provides specific features of fire scenarios to capture the effects of smoke and heat on human movement speed and the evacuation quality. The core approach for human movement in this tool is the social force model.

Table 1 summarises the frameworks mentioned above in the crowd dynamics. This review of prior frameworks highlights three major challenges in this field that have previously been highlighted in the literature: appropriate geospatial framework, physical and psychological dimensions of humans in different situations, and dynamic smart human-environment interactions [29,1]. It highlights the lack of a comprehensive approach to capture all these challenges adequately in one package. Also, earthquake-specific considerations and human-based design evaluation are two missed features within simulation tools.

2.4. Integration of ABM evacuation and layout geometry

Coupling agent-based modelling and building information modelling can lead to behaviour-based design optimisation, especially in an emergency. A few studies focused on this issue, which all tried to incorporate human behaviour in building structural details. For example, a study used a simple integration of BIM and ABM to find the effects of facility layout on the evacuation process by calculating evacuation time through different facility layout scenarios [30].

Among different evacuation types, fire evacuation was the most popular in regard to ABM-BIM integration. Sun and Turkan [31] developed a BIM-based simulation by implementing dynamic fire simulation to investigate the efficiency of human evacuation. Another study developed a framework for the calculation of some risk indices in a fire emergence to evaluate the quality of the evacuation process regarding safety. The framework put effort into coupling BIM with ABM fire simulation based on industry foundation classes (IFC) [32]. In spite of these studies, we still have a gap in consideration of earthquake-specific evacuation behaviours in simulation modelling.

Another gap is using the simulation model for enhancing design performance. The evacuation simulation framework prototype was developed by integrating BIM with a simple ABM for an academic building floor plan [33]. In an earthquake context, Liu et al. [21] imported the non-structural damage analysis calculated in a software package into a 2D BIM by defining attributes to the environmental cells and visualised the damages by colours in NetLogo. This study is an excellent example of ABM-2D layout integration, but earthquake-specific behaviours and considerations are still missing.

2.5. Post-earthquake evacuation

Reviewing the literature confirms that although there are significant studies in regard to the evacuation and emergency crowd simulation, there is still a substantial gap in specifically considering the earthquake details and the post-earthquake evacuation simulation in the evacuation process. However, a few studies have focused on post-earthquake evacuation, such as the paper by Jun [34] who coupled the network-based evacuation processes and probabilistic damage assessment [34]. Although this study is a reasonable effort in regard to integrating earthquake physical damage and evacuation simulation, the details of both parts are absent due to several simplifications. Liu et al. [21] presented a valuable work by integrating ABM with probabilistic non-structural damage and injury modelling in order to consider the dynamic effects of building damage on the evacuation process in an earthquake. This study included many details such as social interactions and injury modelling; however, the ABM part of the approach is not very contrastive with other general evacuation behaviours. In contrast, the post-earthquake evacuation behaviour needs more specific considerations to be included.

Table 2
List of post-earthquake behaviours mentioned in the literature (Immersive Virtual Reality-Serious Games = IVRSG, Video Footage analysis = VF, and Hypothetical Surveys = HS).

	The behaviours	Reference
During the shaking	No idea what to do	[51]-IVRSG; [52]-HS
	Continue what was doing before	[52]-HS; [53]-VF
	Drop, cover, and hold*	[51]-IVRSG; [54]-IVRSG; [52]-HS; [55]-VF
	Protect other people	[51]-IVRSG; [52]-HS
	Protect property	[52]-HS
	Immediately leaving the building*	[51]-IVRSG; [53]-VF; [56]-HS; [55]-VF
Pre-evacuation behaviour	Information seeking (it can be exchanging the information-social attachment)*	[57]-HS; [56]-HS; [55]-VF
	Turn-off utilities	[54]-IVRSG; [52]-HS
	Go to a specific area or space in the building (to find someone or something)*	[52]-HS; [55]-VF
	Collecting personal belongings	[54]-IVRSG; [56]-HS; [55]-VF
	Continue or finish the task being done before	[52]-HS; [53]-VF;
	Check on other people (help others) *	[54]- IVRSG; [53]-VF; [56]-HS
	Use devices to contact others or get information (mobile or laptop)	[52]-HS; [51]-IVRSG; [56]-HS; [55]-VF
	Just wait for help or wait and notice instructions*	[51]-IVRSG; [53]-VF
	Immediately leaving the building*	[54]- IVRSG; [52]-HS; [56]-HS
Evacuation	Go to an assembly point*	[54]- IVRSG; [58]-VF; [55]-VF
	Grouping with other people-Herding*	[59]-VF; [58]-VF; [55]-VF

* Refers to the behaviours which are considered in this study. Based on the goal of the study, we assume that the severity of the earthquake drives people to evacuate the building. Accordingly, only the behaviours which are related to the evacuation process will be considered.

In order to have an accurate pedestrian simulation for post-earthquake evacuation, we need to carefully look into the related literature and find what is unique in the event of an earthquake in indoor environments. The key characteristics of an earthquake event and post-earthquake evacuation process can be listed as follows:

Extremely hard to predict: it means that we are dealing with an utterly uncertain phenomenon that can cause stochastic damages at any time without any alert [35].

Random structural and non-structural building damage: the earthquake can cause dynamic changes to the environment, which affects the evacuation process and makes the problem more complicated [36].

Earthquake-specific behaviours: it is not just about evacuating in an earthquake situation but also about reducing fatalities and injuries. Appropriate human behaviour during the earthquake event and the associated post-earthquake evacuation behaviour is vital in decreasing the casualties [37,35]. Studies have shown that building non-structural damage is the main cause of injuries in an earthquake event [38].

Scarce dataset: as the earthquake event is inherently a unique phenomenon, real data about earthquake evacuation behaviours are very poor [39].

Before starting the simulation model, we investigated different behaviours mentioned in the relevant literature for the post-earthquake evacuation. Table 2 lists different behaviours during and after an earthquake, based on the previous studies which analysed a few

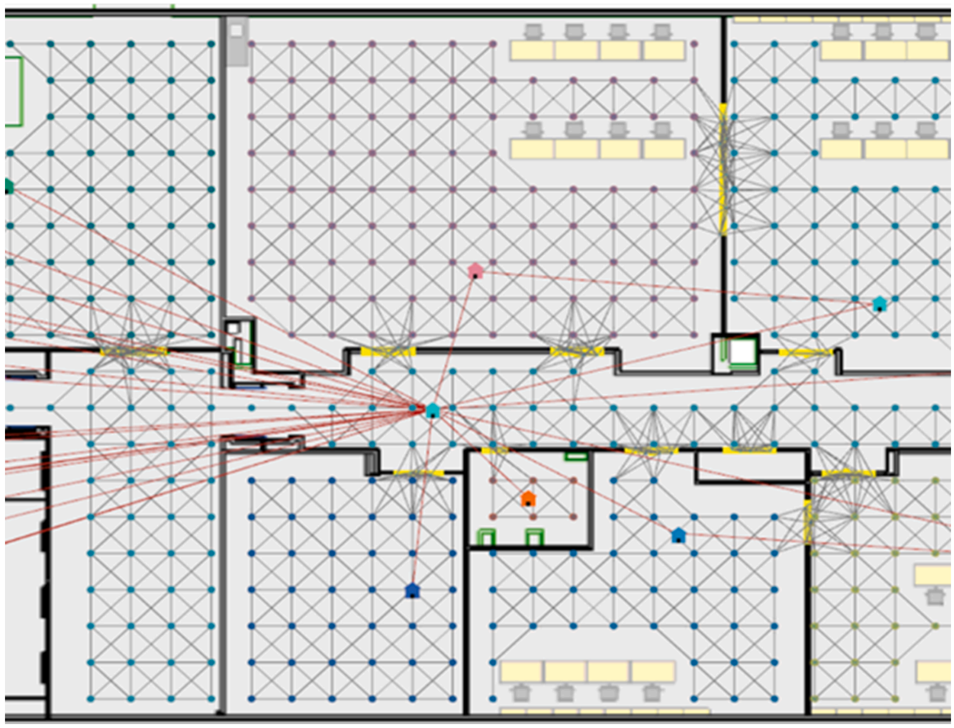


Fig. 2. Node network to represent the environment.

available datasets in earthquake emergencies. All the mentioned behaviours are derived from analysing Video Footage data (VF), Hypothetical Surveys (HS), or Immersive Virtual Reality-Serious Games studies (IVR-SG).

3. Modelling approach

In this section, the framework of the simulation model for the post-earthquake evacuation is explained. To have a comprehensive approach, we consider most of the challenges that exist in the relevant literature. There are three main modelling dimensions to be considered in the proposed approach to reach the study goal for evacuation simulation: the environment simulation, the agent simulation, and the navigation procedure (interactions).

3.1. Environment simulation

In this study, we used a hybrid framework that integrated cellular and graph-based models to simulate the details of the environment. Each node represents an architectural area or space in the plan, while each cell represents the details of the physical environment (obstruction). Considering an evacuation process in the real world, people initially make a decision about their main action (for example, whether to go out of the building or help others). In this study, this major decision, one of the starred behaviours in Table 2, is considered as the goal. Rooms and nodes in the environment represent different spaces that can facilitate agents to reach their goal; so, the agents will choose a node as a target, leading to fulfilling their goal. According to their goal, the target node may change dynamically (for example, when the agents are searching to join their family members or friends, their target node may change based on their partner's position). Their target node might be the same place they are already in, so they do not need to move.

After choosing their final destination, they will unintentionally map their path. In other words, people will be choosing their next nodes during the evacuation process in their heads. For example, someone may think to exit from the room first, then pass the corridor to find the stairs and exit.

Furthermore, in order to reach a certain intended area, the agent should avoid obstacles and hazards. Finally, at the lowest level, they will choose their next step at each time step to reach the selected area. The last layer will be represented by choosing desired cells.

The graph approach is one of the most beneficial methods in modelling spatial architecture layout in which the areas are categorised into two types: main areas (such as rooms or corridors) and spaces (the spaces inside the main area), according to Guo and Li [40]. As shown in Fig. 2 (screenshot from the modelled environment of the case study in NetLogo), there is a mesh of nodes and links that represent walkway spaces all over the architectural layout. For example, a node can be an empty space between furniture or an internal door between rooms. The nodes are connected to their neighbour nodes with links (grey links in Fig. 2). A link between two nodes means that there is no blockage between them, and agents can walk directly from one end of the link to the other. The length of these links is the distance between two nodes, which can be adjusted by the user (adjusting mesh granularity). The finer the mesh, the more accuracy in environment representation, the more complexity of calculations, and stronger computer processor needed consequently. The modeller can also generate nodes manually as well, in the case he wants to customise the environment details.

As you can see in Fig. 2, there are some bigger nodes in Fig. 2 with the shape of a house, which represent larger areas (such as rooms or corridors). We call them rooms in order to differentiate them from the nodes. Each node belongs to a room. Based on the developed codes, the rooms will be recognised automatically by the spaces surrounded by walls or internal doors (yellow areas in Fig. 2). However, the shape and position of the rooms in Fig. 2 are just for the purpose of visualisation of the rooms and their connections. In fact, the rooms are a set of nodes within different closed spaces of the environment. As you might have noticed in Fig. 2, nodes have certain colours same as their room.

The key point is the definition of the links between rooms (red links in Fig. 2) which is different from the links between nodes. The red links only represent the connections between rooms, and their lengths do not have any specific meaning. A red link between two rooms means that at least one of the nodes from each room are connected together with a grey link. So, the distance between two rooms will be calculated by the

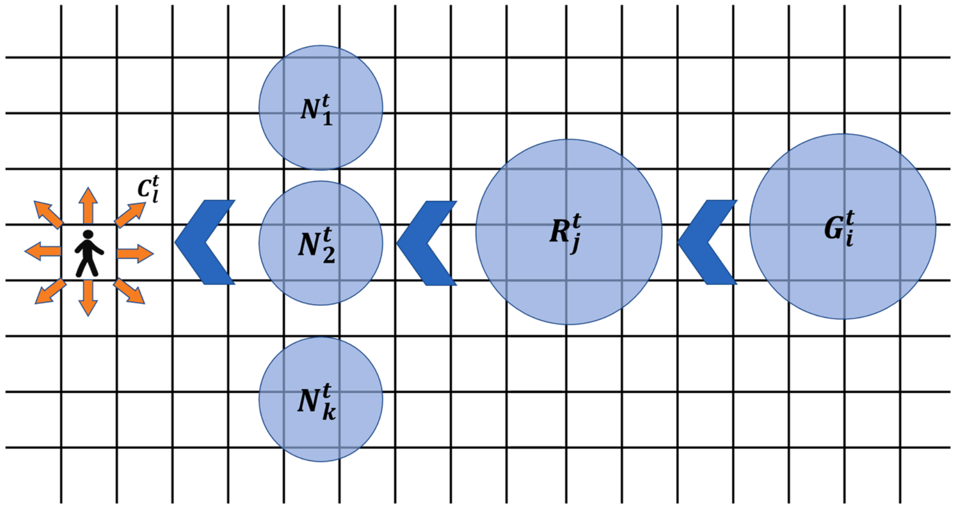


Fig. 3. Hierarchical selection of goal, room, node, and cell.

shortest path formed by the sum of grey links lengths, not the length of red links. However, the links between rooms have a critical role in finding the path in the hierarchical decision-making process. In other words, the existence of rooms facilitates more realistic navigation of agents in the hierarchical approach that we will discuss more in the navigation process section.

3.2. Agents' simulation

We may have a high population heterogeneity in the real-life situation where people may have different gender, ages, physical/mental conditions, education, and culture. However, we have to select some of these attributes regarding their relevance to the evacuation context. The proposed simulation approach has considered three aspects of an agent: physical attributes, mental attributes, and social interaction.

3.2.1. Physical attributes

3.2.1.1. Body. According to previous studies such as Hurley et al. [41], people instinctively avoid physical contact with others during their group movement. Considering a private zone or a "body ellipse" for each agent can be a proper solution to capture this fact based on Crooks et al. [42]. This study assumed a 0.5 * 0.5 body ellipse, which includes physical body size and the personal zone for each agent. This area is identical to the size of each cell in the ABM software. So, agents occupy a complete cell if they stand in the middle of the cell. Also, at each time step, two agents cannot stand at the same point (no collision); however, as the agents' movement is not cellular, each cell may contain more than one agent at each time step (i.e., the agents may occupy a part of a cell). Another key factor regarding physical body condition is the speed of agents in an evacuation situation. The speed is distributed by normal distribution among agents with a mean of 1.2 m/s and a standard deviation of 0.15 based on previous studies regarding pedestrian movement speed [43]. However, the agents' practical speed may change according to their fear level or injury condition. The movement speed of agents can be affected by the congestion and blockage, so the assigned speed is the maximum speed that the agent can move with, and it can be called the *potential speed*.

3.2.1.2. Injuries. Some agents may be injured during the evacuation, which means that either they cannot evacuate without help or their speed is lower than the normal situation. There are three states of injuries: 0: no injury or minor injury which does not affect the movement speed, 1: need others to help for moving, and the speed of movement will be reduced, and 2: which means severe injuries or death that cannot move even with the help of others.

3.2.2. Mental attributes

3.2.2.1. Knowledge status. This attribute represents the amount of familiarity of an agent with the environment. Each agent has a unique amount of knowledge about the details of the building plan, which is represented by nodes and edges. So, the knowledge of each agent is an array containing the utilities of nodes and links between them. The point is that each agent is updating his knowledge dynamically during the evacuation process. Even a person with full knowledge of the building plan may update his knowledge because of changes that may be due to building non-structural damage. Furthermore, agents can update their information by talking to other agents. So, the spreading of knowledge has been considered in this study. More explanations about the knowledge status of agents will be discussed when talking about the navigation and learning process later.

3.2.2.2. Fear effects. Each agent has a fear level, an integer number between 0 and 2, and directly affects the agent's movement speed and navigation process (choosing target nodes). A fear level of 0 means that the agent has no fear, and 2 means he or she is terrified of hazards. The fear amount depends on the agent's characteristics and the situation he or she is located at each time step (in the matter of how close to non-structural damages). The person with a fear level of 2 will not engage the "drop, cover, and hold" and start evacuation immediately, which cause increase the probability of being injured or dead.

3.2.3. Social behaviour

3.2.3.1. Herding effects. It has been shown that people are willing to follow the crowd in an evacuation process [10,44]. This occurs when the agents' goals are identical. So, in this study, agents will choose the edges which have been chosen by other agents ahead. However, if they have different goals (such as joining their family), there will not be any herding effect.

3.2.3.2. Family members and friends. In the real-world evacuation, people are not always alone. In this study, some agents (randomly) are considered as family or friends who make groups and move together. At the beginning of the evacuation process, family members and friends will search for their partners before starting the evacuation. So, the goal of these agents is to reunite first and then they will change their goals to

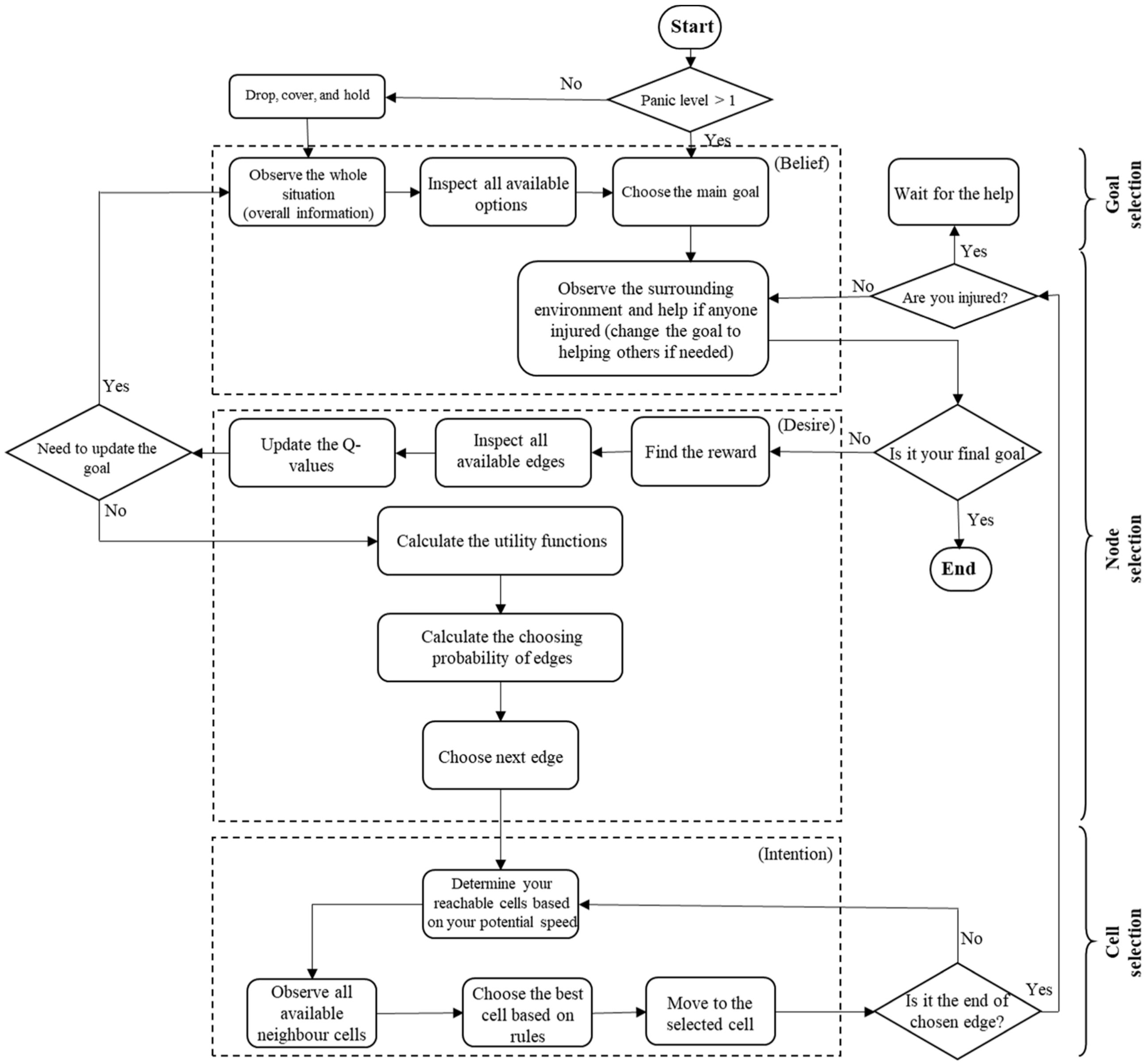


Fig. 4. An overview of the hierarchical navigation process.

exiting the building.

3.2.3.3. Helping injured people. It is assumed that if an agent or a group see an injured agent who needs help, they will help them. One or some of the agents will be the helper in a group, but the whole group movement speed will decrease when helping an injured agent. This reasonable assumption is based on some previous studies [45,46]. As we mentioned, we have three levels of injuries that only in level 1, the agents will help the injured person. In the model, helping others means the agents will stay close to each other and move together at a slower speed.

3.3. Navigation process

Two phases can be considered in an earthquake event regarding the evacuation process: during the shaking and after the shaking. Also, there are two main behaviours during the shaking phase of an earthquake: "drop, cover, and hold" and "immediate evacuation" (based on Song and Su [47]). Dependent on the fear level, the agents either start the egress immediately after feeling the earthquake or after the end of shaking. The main engine of the navigation process is the same for both groups; however, the speed and the details of choices through the navigation will be different in people with high fear levels.

3.3.1. The hierarchical framework of the system architecture

The core concept of the proposed model is derived from the belief-desire–intention (BDI), which is a well-known approach to simulate human behaviour. People, first, will inspect their surrounding environment and define their goal set. Then they define their plan set to reach their desired goal, and finally, they will undertake an action according to the plan.

The agents in this study perform a hierarchical decision-making process by solving a utility-based choice model at each time step to choose among their available options. Fig. 3 shows the hierarchical framework of the environment. First, the agents will choose their target node or goal among the goal set available at the time t (G_i^t {i = number of goals}). The goals can be going toward the exit area, helping others, or searching for their partner or friends. Next, they will choose the room among the available room-set (R_j^t{j = number of rooms}), which facilitates reaching their goal better among the available nodes. The rooms represent different main spaces or rooms in the environment. Then, they choose the best nodes (N_k^t {k = number of nodes}), which represent a part of an area within their sight. Finally, they will choose the appropriate cell toward the selected node at time *t* to trigger the movement action (C_l^t {l = number of cells}).

The cell selection layer is conducted by two predefined rules that describe how the agents choose their next step toward the target node. These rules are strict and simple, which depend on the availability and damage level of the cells and the distance from the target node. Depending on their speed, agents can traverse some of their neighbouring cells (in the radius equal to the agents' speed) at each time step. The first rule is that the cell must be available. The available cells are the ones, which represent the walkways and are not wholly occupied. The second rule is that the best cell is the closest cell to the target node with minimum impacts of damages imposed by the surrounding non-structural elements. So, after choosing the next node, agents turn to face one of the available cells with minimum damage and distance to the target node. Finally, the moving is executed by walking forward toward the selected cell. Fig. 4 shows an overall flowchart of the proposed approach where the BDI framework has been integrated with learning-based hierarchical agent-based navigation.

3.3.2. Learning process

This study intends to model a smart agent who acts rationally; however, his logic may be blurred by the amount of fear in the situation, but the agent will never act completely foolish. In most simple buildings, the agents are familiar with the layout of the building. However, in complicated layouts, usually, some visitors may not have enough information about the building layout's details. Furthermore, after the damages caused by the earthquake, there might be major changes in the layout, and some paths may be blocked. Therefore, there should be a reasonable navigation model for the agents.

Reinforcement learning has been used regarding the navigation model in this study. The basis of the learning part relies on Markov Decision Processes (MDPs), in which utility functions are used instead of predefined rewards. In other words, we are dealing with utility-based agents who are trying to maximise their utilities by choosing the best path toward their goals. On the other hand, their utility function will be updated based on the distance from the goal and the amount of perceived hazard.

At each particular time (t), the agent is in a specific status of the environment St (St ∊ S). After choosing an action (At) according to his knowledge (previous utilities of the edges) and moving toward the chosen direction, he will gain an amount of reward from the environment and update his knowledge. At the same time, he will put himself in a new status, St + 1.

The q-values will be defined for each edge. At each time step, the agents choose among the available edges from their current node to the other nodes. The decision is made based on the q-values of the edges. The q-values will be updated by the previous knowledge and the rewards of the node located at the other end of the edges. The node's reward will also be updated for each agent based on the node situation (distance from the goal) and the hazard that exists in neighbour cells.

An equation based on the Bellman equation is used to update the q-values (based on [29]:

$$Qmax_k = \max\{Q - valuesofthechosennodeN_k\}$$
$$Qvalue_i^t = (1-\alpha)Qvalue_i^{t-1} + \alpha(reward_k + \gamma Qmax_k) \tag{1}$$

$Qvalue_i^t$ is the q-value of the edge i at the time t; $reward_k$ is the reward of the chosen node (N_j), which is a value for the node according to their position and situation in the environment toward the goal of agents; α and γ are the learning rate and discount factor, with both having a value between 0 and 1. The weight of fresh knowledge (new learning) vs old information is represented by the learning rate (α). If α = 0, the q-values will not be updated and will remain constant, while α = 1 indicates that the new q-value will be updated solely depending on the chosen node's reward and its situation. γ, the discount factor, will add the weight of the future options to the q-value of the edge.

We may directly use the q-values of the links to select the best route; however, to consider people's tastes and characteristics, utility functions have been utilised. The utility functions give weights to the q-values, and the agents perceived hazards toward the link (Eq. (2)). In fact, q-values represent the dynamic knowledge of agents in the layout. Technically, links have an array whose members are the q-values for each agent. So, for the agents familiar with the layout, q-values of edges are known (the array members already have values). So, they choose the edges with the highest q-values that is the shortest path toward the target nodes. However, for the visitors who do not have information about the layout, q-values are unknown (0 for all edges). They will select the edge based on their observation and the damages they see ahead toward the edges. If visitors have no clue from their observation or do not see any other agents to be followed, they select the next nodes randomly. However, all agents, irrespective of information levels, will update their knowledge during the navigation.

$$U_i^t = \propto_n Q_i^t + \beta_n H_i^t \tag{2}$$

where

U_i^t: The utility of the alternative (edge) i at the time t for the agent n
Q_i^t: q-value of the alternative i at the time t for the agent n
H_i^t: The hazard amount that agent n observes toward the node at the alternative i at the time t (perceived hazard toward nodes)

$\propto_n$ and β_n: The weights of q-value and amount of hazard for the agent n, respectively. These weights depend on the characteristics and the risk-acceptance of the agents. In the case study, these variables only depend on the fear level of the agents, where high fear levels lead to higher weights to the hazard that exists through the edge. As $\alpha + \beta = 1$, people will choose the alternatives according to their distance from the goal and the amount of hazard (damage-level) that existed in each edge. Finally, as we assumed a linear utility function multiple options, the probability of choosing an alternative was calculated by the multinomial logit equation:

$$P_i^t = \frac{exp\left(\propto_n Q_i^t + \beta_n H_i^t\right)}{\sum_{j=1}^{j} exp\left(\propto_n Q_{nj}^t + \beta_n H_{nj}^t\right)} \tag{3}$$

where P_i^t is the probability of alternative i evaluated at the time t for the agent n (J is the total number of alternatives).

Following the flowchart depicted in Fig. 4, we illustrate how the proposed model works by imagining a real-life evacuation scenario. Let us imagine a person in a small office within a middle-size room in a large building with a complex architectural layout where suddenly an earthquake occurs. We assume the person does not panic and engages the drop, cover, and hold during the shaking phase. After the shaking, the person observes the situation and decides to go out as soon as possible (the goal is getting out). This is the first layer of the hierarchical navigation model that is goal selection. As mentioned, each node represents a certain area in the layout. It means the nodes representing the main exit areas from the layout will be this person's target nodes (goal). To reach the target node, first, he must get out from the small office to the middle-size room, then go to the corridor, finally exit from the exit areas. In fact, the person inspects the available paths from his current room to the target nodes. If the person is familiar with the layout (has full information about the plan's details), he will choose the next room based on the shortest path to the exit node. If the person does not have any information, he just chooses the next room based on his observations (e.g., from the office to the main room or from the room to the corridor). After choosing the next room, he will choose the shortest path to reach the selected room. It means he selects the nearest node of the next selected room. Selecting nodes is the second layer in the hierarchical

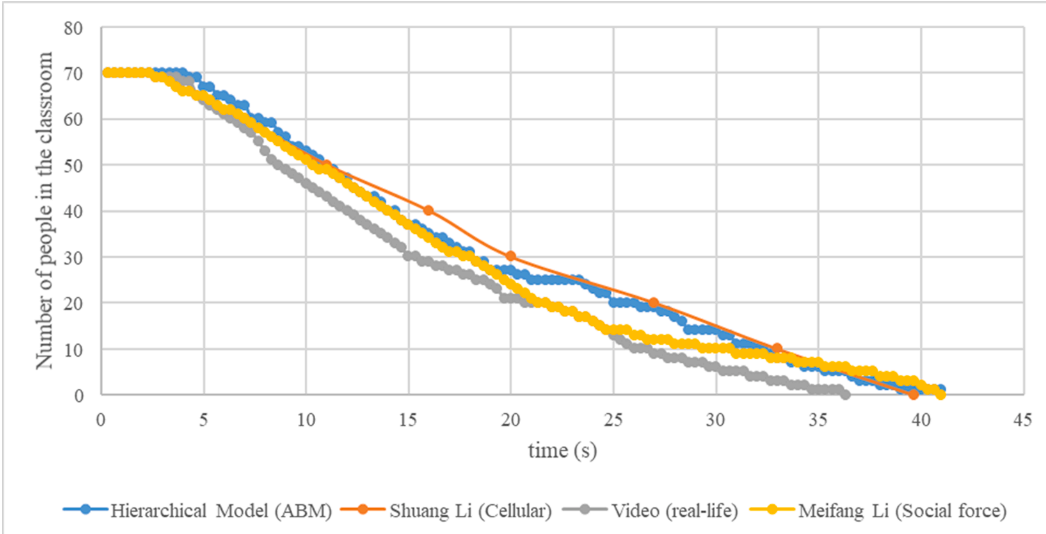


Fig. 5. Comparison of evacuation process from the same environment through evacuation time.

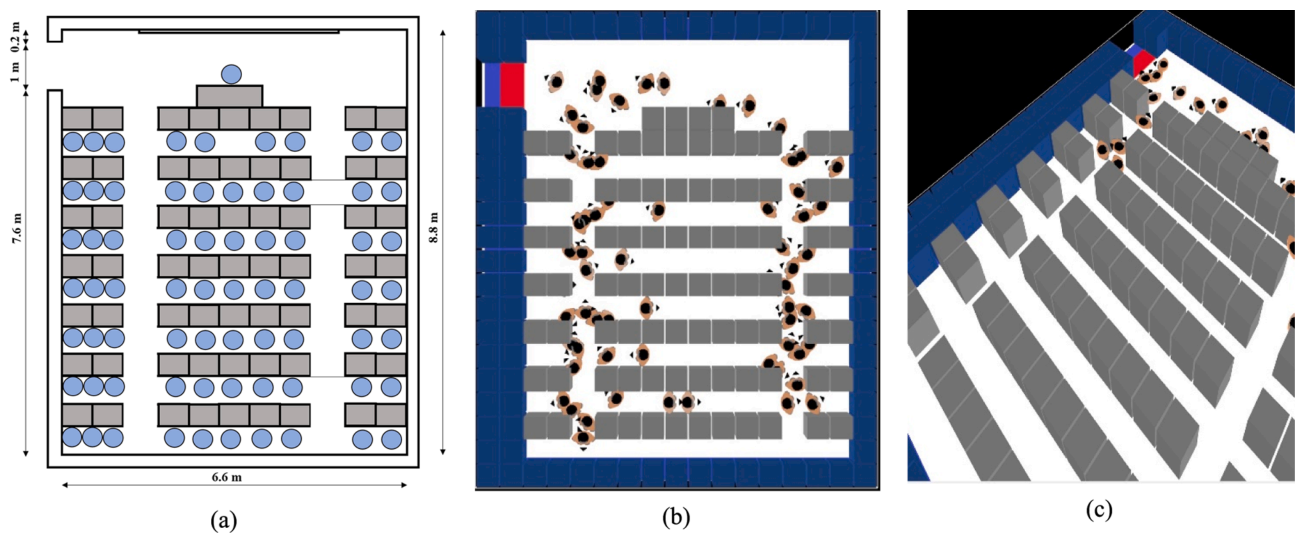


Fig. 6. (a) The classroom dimensions with the initial positions of students. (b) a screenshot of NetLogo after 5 s, (c) a 3D screenshot of NetLogo after 30 s.

process and will determine the direction of his moving. Finally, in the last layer of the hierarchical navigation process, he walks toward the direction by choosing the best cell where he will interact with the damaged areas of the layout. So, the hierarchical approach within a cellular-graph environment facilitates the consideration of both agents' taste (by utility functions) and their memory (by learning process) in the decision-making process.

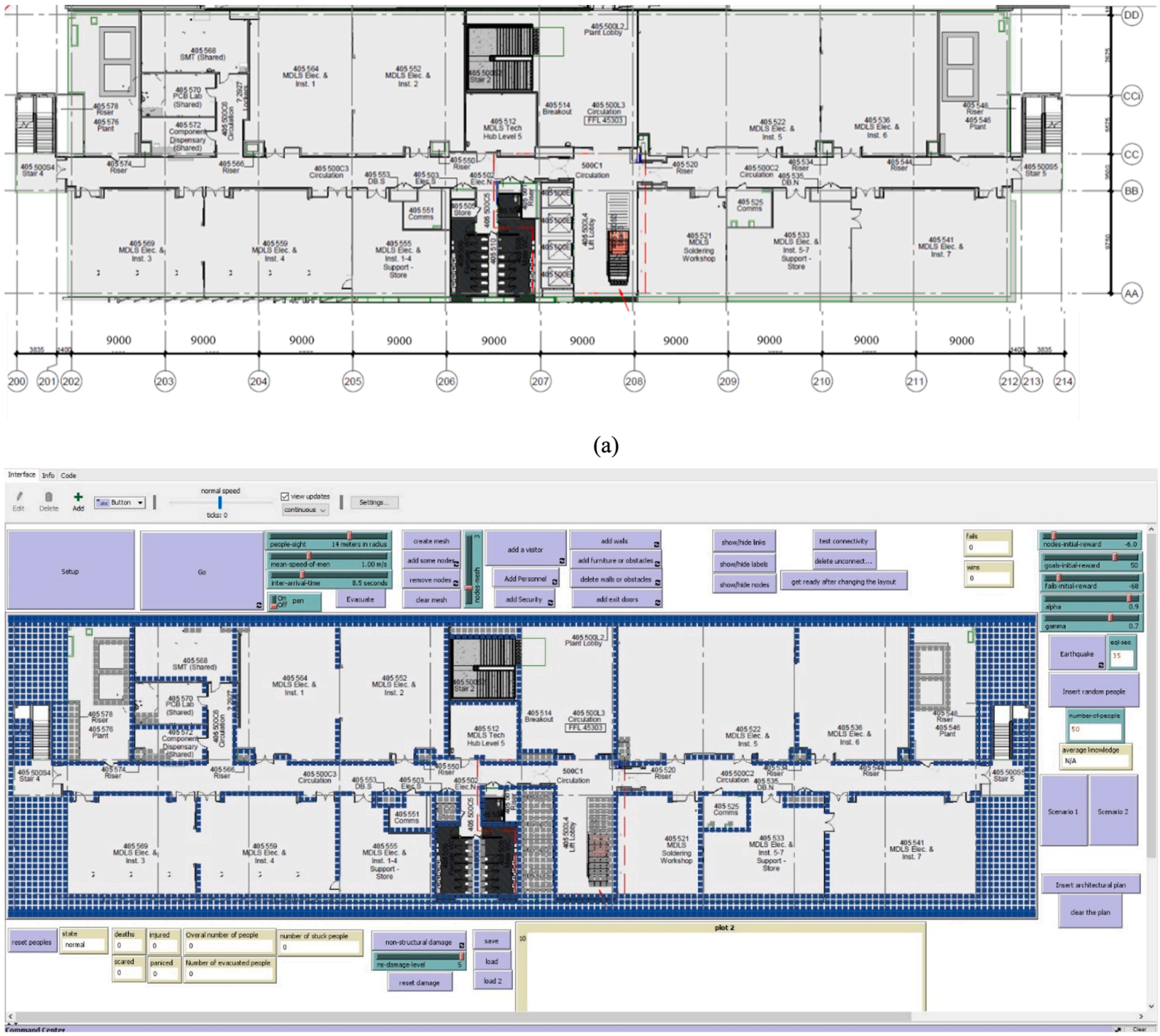
4. Implementation and verification of the proposed approach

Before modelling the building, the simulation model is coded in NetLogo and verified by comparing the results of the model with previous studies. After that, the proposed approach was tested by simulating one floor of an academic building, and the results were analysed.

4.1. Validation and verification of navigation process

As some of the previous studies (such as Hassanpour et al. [29] and Siyam et al. [1]) confirm, the validation of the ABM simulation has always been a challenge. It will be more challenging when the model is dealing with an emergency such as earthquakes. Also, videos with sufficient and informative data from earthquakes evacuation are scarce [48]. One of the recommended methods for verifying simulation models is the model to model comparison [49]. We conducted an analysis comparing the evacuation results from different studies on the same video. The video recorded the 2013 Ya'an earthquake evacuation from Mingshan high school in China. This video has been previously used in some research to verify simulation models where 70 people, including 69 students and 1 teacher, evacuate the classroom.

Fig. 6 shows the layout dimensions derived from previous studies and the screenshots of the simulated classroom within the ABM software. The line graph (Fig. 5) compares the recorded evacuation results between different approaches, including the proposed hierarchical agent-based used in this study (blue curve). The grey curve is the data derived from the video analysis. The red and yellow curves belong to the cellular [48] and the social force model [50], respectively. Besides some qualitative tests (such as reasonable navigation around the corner and among the obstacles without penetrating the boundaries), the comparisons of curves confirm that the hierarchical ABM model acceptably simulates the evacuation process.



(a)

(b)

Fig. 7. The 5th floor of the Engineering building plan at the University of Auckland, (b) The NetLogo interface of the simulated model.

4.2. Case study

The purpose of this section is to illustrate the application of the proposed approach in post-earthquake evacuation. Therefore, we need to determine a case study to illustrate the potential details we can have in the simulation. Accordingly, the 5th floor of the engineering building of the University of Auckland has been chosen to perform the simulation approach in different scenarios.

Assumptions and some considerations for the case study are as follows:

(1) All the dimensions and spatial architecture layout spaces simulated based on the real-life plans (Fig. 7). For the nodes mesh, the distance between two successive nodes is assumed 1.5 m.
(2) Nearly all the spaces of the floor plan (Fig. 7) are Multi-Disciplinary Learning Spaces (MDLS). So, the randomness of the non-structural damage is identical for different rooms except for the middle corridor.
(3) Three non-structural elements have been considered to mimic the non-structural damage consideration: internal partition walls, fragile shelves, and suspended ceilings. We assumed that all the 0. walls are partitions with fragile shelves, which randomly will take damage. Also, it is assumed that the suspended ceiling tiles are equally distributed throughout the whole building, which may take damage as well. Table 3 shows the details of desired non-structural elements with their damage states. In future studies, a probabilistic non-structural damage assessment can be conducted.
(4) The movement speed of the agents is random-normally distributed among the agents with the mean value of 1.2 m/s and the standard deviation of 0.15 based on literature [43]. So, each agent has a specific speed.
(5) The agents are categorised into three groups, including visitors, normal personnel, and security personnel. The agents are scattered in the plan randomly. The visitors and personnel try to evacuate after shaking while security personnel try to help others and evacuate last. Regarding the familiarity with the architectural plan, security agents have the highest knowledge level, and the visitors have the minimum.

Table 3
Non-structural components with their damage states and fragility parameters (Based on the data from FEMA P-58 Fragility Specification for Performance Assessment Calculation Tool (PACT), 2018).

Component name	Code in FEMA P-58	Component Description	Damage state Description
Suspended ceiling	C3032.001a-d	Suspended Lay-in Acoustic Tile Ceiling, Support: Vertical hanging wires only. Includes lighting fixtures in suspended ceiling	DS1: 5 % of ceiling grid and tile damage
			DS2: 30% of ceiling grid and tile damage DS3: 50% of ceiling grid and tile damage.
Wall partition	C1011.011	Wall Partition, Type: Gypsum with metal studs, Full Height, Fixed Below, Fixed Above	DS1: Screw pop-out, cracking of wallboard warping or cracking of tape, slight crushing of wall panel at corners. DS2: Moderate cracking or crushing of gypsum wallboards (typically in corners). Moderate corner gap openings, bending of boundary studs. DS3: Buckling of studs and tearing of tracks, tearing or bending of the top track, tearing at corners with transverse walls, large gap openings, walls displaced.
Fragile objects on shelves	E2022.013	Unsecured fragile objects on shelves, the low friction surface	DS1: Object falls off shelf or shelf overturns, and object breaks or object breaks within the cabinet.

Table 4
The components used for coding in NetLogo and their attributes.

Room	Nodes	Cells	Agents
nodes: A set of all nodes within the room area **Connections:** A set of the links between the room and other rooms with at least one node in common **Utility:** An array whose members show overall rewards of the room for each agent calculated by utility functions. (different for each agent)	**Reward:** An array whose members represent a utility of the node based on the goal and amount of danger exists in neighbour cells for each agent **Neighbour nodes:** other nodes in the neighbourhood of the node that is connected to the node (no obstacle between them) **Availability:** A Boolean variable representing whether the node contains at least one neighbour node at the time-step	**Meaning:** A nominal variable representing the functionality of the cell (e.g., wall, walkway) **Impact level:** A numerical variable representing the level of damage during the evacuation (0: None, 1: Slight, 2: Moderate, 3: Extensive, 4: Complete block/collapse (not usable) **Availability:** A Boolean variable (0: meaning = walkway and not fully occupied; 1: none of the above conditions)	**Gender:** Boolean Male/female **Speed:** Movement speed, different for each agent based on the physical condition **Manner:** Boolean Normal/Emergency **Type:** A nominal variable representing the career of agents (Visitor, employee, security personnel) Family member/friends **Knowledge:** Represent how much the agent knows about the rooms and their connections in the environment **Goal:** A node which the agent aims to reach **Next-node:** The node which the agent target at each time step **Fear level:** A numerical amount representing the amount of fear the agent has at each time step (0: no fear, 1: scared, 2: panicked) **Injury level:** A numerical amount representing the level of injury (0: no injury, 1: slight injury, 2: severe injury/death)

(6) Agents have the ability to inspect the environment to find their path toward their goal by observing the spaces during the navigation. It means that they do not have to be at a specific node to update the q-values but can update q-values by observations. They may get the information of a specific room or space just by looking inside (being at the area entrance), not essentially entering the area.
(7) There are some joint agents who can represent partners, family members or friends. In the evacuation process, they move together; if they are apart, they will try to find each other before exiting.
(8) At each time step, if agents see other agents with the same goal, they will make a group. The grouping in this model means the agents move together (same direction) after joining. An agent with the highest knowledge will be the leader in a group, and others will follow him.
(9) If an agent or a group see injured agents, they will help the agents and evacuate together. In this condition, the group speed will be lower, according to the injured agent. They do not do anything with the dead agents.
(10) The amount of α and β in Eq. (2) depends on the fear level (F) of the agents as follows: if F = 0 then $\alpha = 0.5, \beta = 0.5$; if F = 1: $\alpha = 0.4, \beta = 0.6$; if F = 2 then $\alpha = 0.3, \beta = 0.7$.

4.2.1. Non-structural damage and injuries

The seismic damage assessment of a building is an extensive subject that needs a dedicated study to include details. Therefore, due to the scope of this paper, we mimic and simplify the building non-structural damage to show the potential of the proposed approach in considering the fatal and non-fatal injuries as well as agents' interaction with the dynamic damaged environment. Further research will focus on indoor

Table 5
Impact state (obstruction) definition of different spaces in building layout after non-structural damage (based on [60]).

Impact	Performance Level	Damage condition in general architectural Systems	Egress condition	Injury state
None	Fully-Operational	No damage or Negligible damage at the cell	Not Impaired, normal egress	No injury
Slight	Operational	Light to moderate damage-One of the elements reaches DS1 at the cell	No major obstructions	Light-Agents do not need help, but their speed will be negatively affected
Moderate	Life Safe	Moderate to severe damage-One of the elements reaches DS2, or two elements reach DS1 at the same cell	Partial obstructions	Moderate-Agents can move with the help
Extensive	Near Collapse	Severe damage -One of the elements reaches DS3, or two elements reach DS2, or three elements reaches DS1 at the same cell	Egress may be obstructed	Sever-Agents cannot move, must be carried by others
Complete	Collapse	Destruction of components-Two elements reach DS3, or three elements reaches DS2 at the same cell	Completely obstructed	Dead

building damage using structural-based probabilistic methods. As it was not the direct purpose of this study, the physical details of the earthquake (such as earthquake intensity and the spectral acceleration estimation, accurate assessment of fragility functions) were simply mimicked in the current study and will be addressed in the future research.

Table 4 summarises all the components and their attributes coded in the NetLogo software. The amount of damage imposed to non-structural elements in an earthquake can be graded by different damage states. With detailed information of the elements, we can calculate the occurrence probability of damage states by fragility functions in future studies. We assumed that three damage states (DS1, DS2, and DS3) might be randomly imposed on the non-structural elements. Also, as mentioned before that suspended ceiling tiles are equally distributed throughout the whole building. A combination of damages can occur during an earthquake, which can affect the element's performance and the injuries and egress speed. Table 5 shows the different impact levels of non-structural damage states on the evacuation process. Fig. 8 shows the screenshots of the ABM software where depicts the evacuation process after non-structural damage and the interaction of agents with the damaged environment.

4.2.2. Simulation results and discussion

We implemented the proposed approach to simulate the evacuation process from the 5th floor of the new engineering building at The University of Auckland, New Zealand, through different simplified design scenarios. The earthquake intensity is assumed constant for each earthquake scenario, and the duration of the earthquake is assumed to be 35 s. Different population scenarios are randomly scattered in the desired plan. Table 6 shows details of scenarios, and Fig. 9 shows the evacuation trajectories for 100 people from the two design scenarios.

Based on the randomised people's characteristics and positions, some may start the evacuation process immediately after feeling the shaking, while others will engage "drop, cover, and hold. Accordingly, the people who start the evacuation process during the shaking phase face a higher probability of being injured. However, the focus of this study was not on the number of injuries or deaths because of the constant earthquake intensity and duration assumption and random estimation of the non-structural damage in the simulation runs.

We conducted five runs for each scenario (50 runs in total) where both Average Evacuation Time (AET) and Total Evacuation Time (TET) have been calculated in the simulation. The AET shows the average time needed for people to exit from the exit areas of the plan, while TET is the time needed for all agents to be evacuated. In some simulation runs,

Table 6
Details of different scenarios in the simulation.

Scenario	Population	Design scenarios
1	100	D1: Two side exits (left and right)
2		D2: One middle exit
3	200	D1: Two side exits (left and right)
4		D2: One middle exit
5	300	D1: Two side exits (left and right)
6		D2: One middle exit
7	400	D1: Two side exits (left and right)
8		D2: One middle exit
9	500	D1: Two side exits (left and right)
10		D2: One middle exit

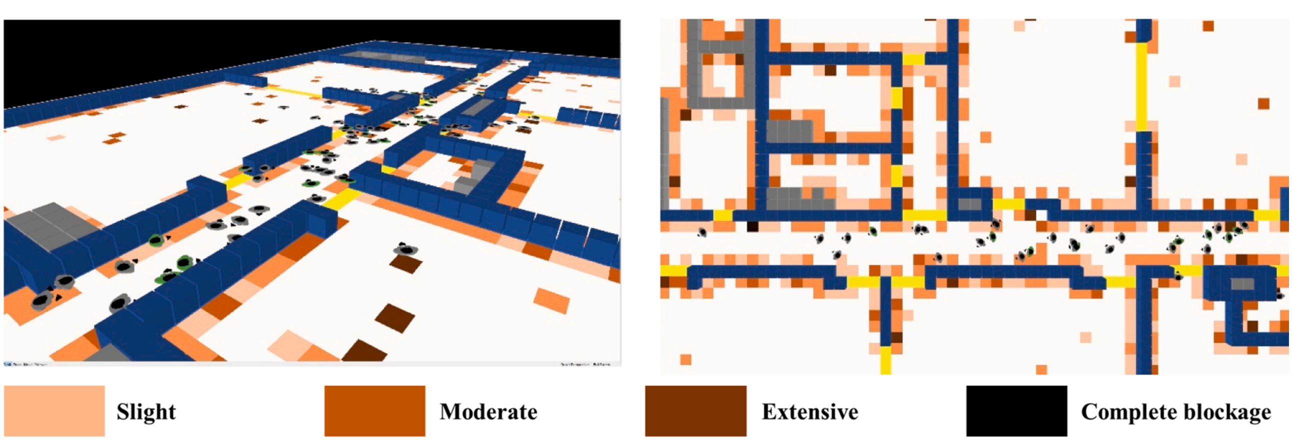


Fig. 8. Post-earthquake evacuation simulation; agents' interaction with the different impact levels of damaged environment.

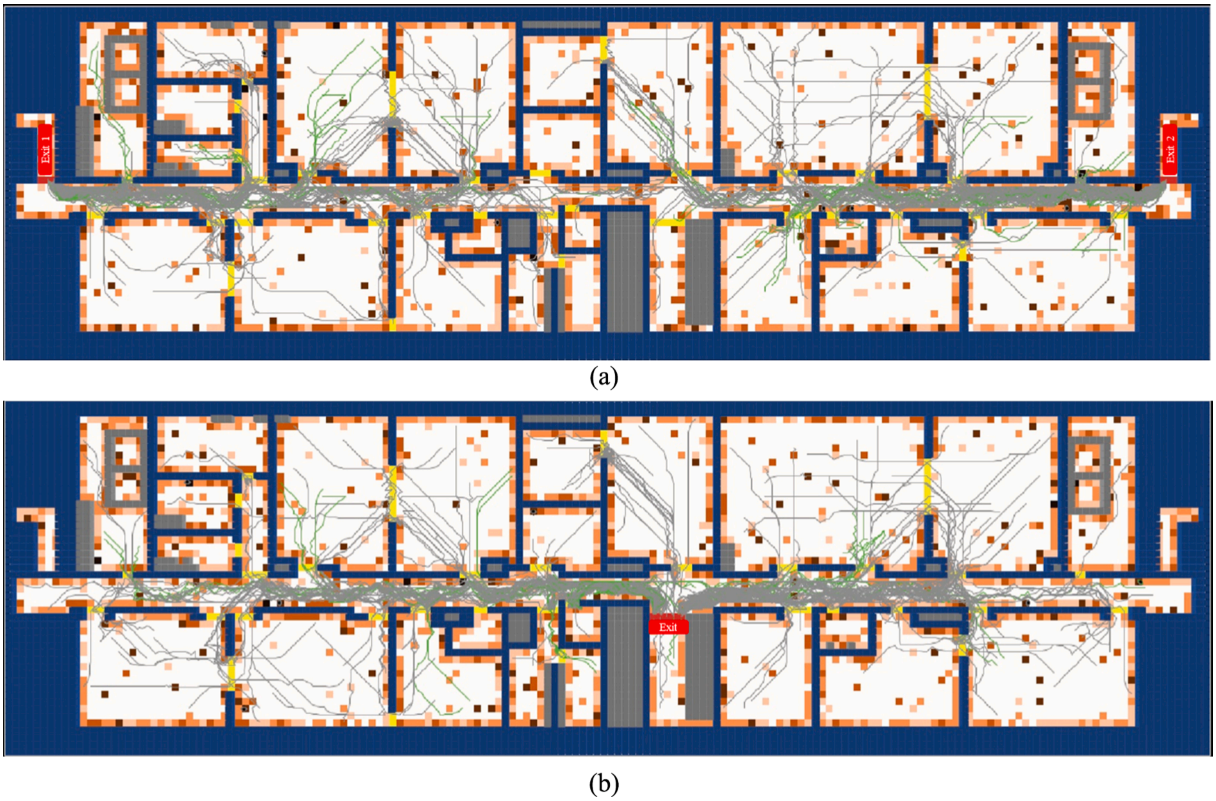


Fig. 9. The evacuation trajectories of the simulated plan (a) First design scenario. two exit doors in the left and right side of the plan; (b) second design scenario. one wider exit door in the middle of the plan.

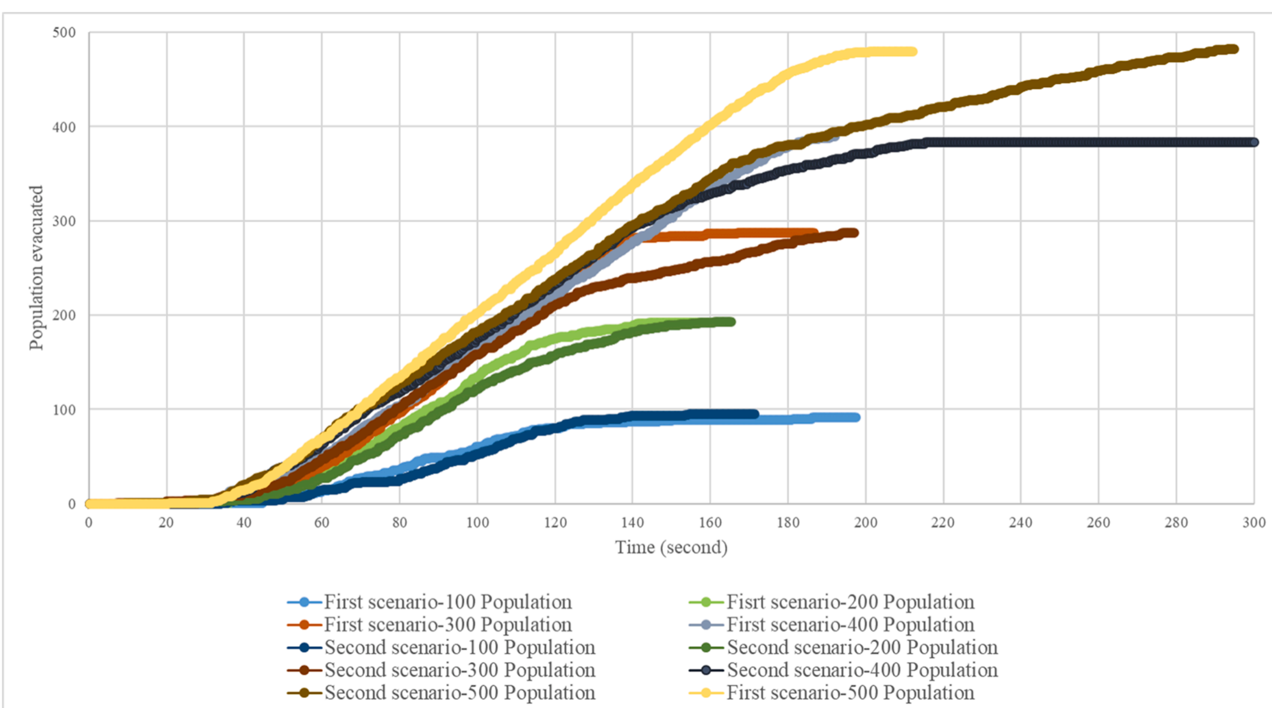


Fig. 10. Comparison of evacuation through time for different design scenarios and population.

people could not evacuate from the plan due to the non-structural damage and exit blockage.

The initial interpretation from the evacuation results through different scenarios (shown in Fig. 10) is that there is not a significant difference between the performance of the design scenarios for the small population size. However, in large population sizes, the slope of the middle part of the evacuation curve for the first scenario runs (two exits on each side of the plan) are steeper than the second scenario (one exit in

Table 7
The Between-Subjects Effects derived from a two-way ANOVA test for average and total evacuation time.

		Average evacuation time (AET)			Total evacuation time (TET)		
Source	df	Mean Square	F	Sig.	Mean Square	F	Sig.
Corrected Model	9	1116.217	66.350	0.000	8140.115	6.840	0.000
Intercept	1	511763.894	30420.312	0.000	2362964.083	1985.455	0.000
Scenario	1	104.472	6.210	0.017	2130.739	1.790	0.188
Population	4	2435.424	144.767	0.000	16286.061	13.684	0.000
Scenario * Population	4	49.945	2.969	0.031	1496.514	1.257	0.303
Error	40	16.823			1190.137		
Total	50						
Corrected Total	49						
		a. R Squared = 0.937 (Adjusted R Squared = 0.923)			a. R Squared = 0.606 (Adjusted R Squared = 0.518)		

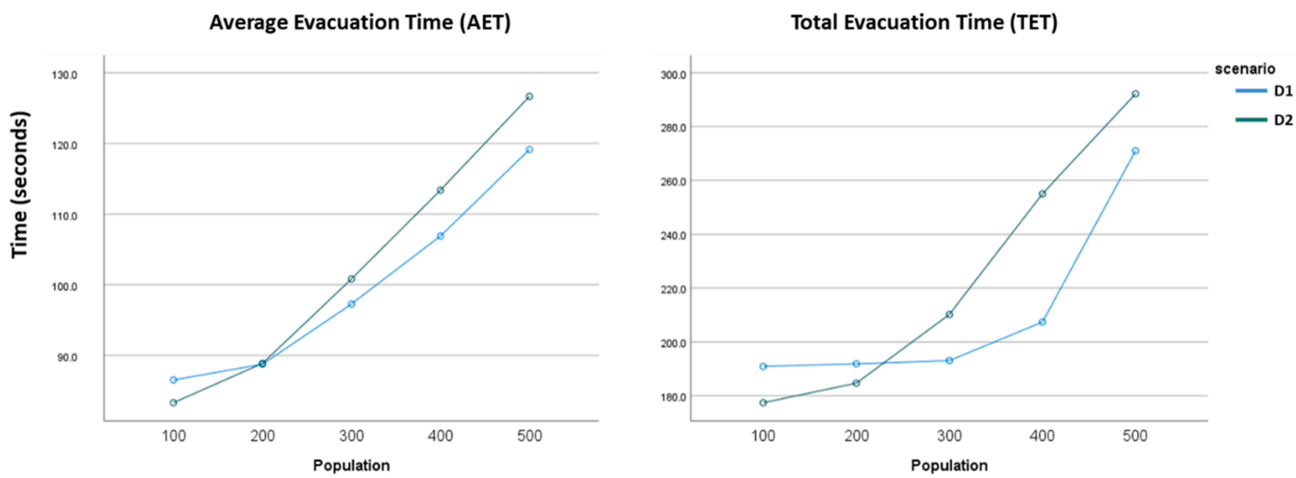


Fig. 11. The average and total evacuation time for different population sizes and two design scenarios.

the middle of the plan).

The two-way ANOVA has been conducted separately for average and total evacuation time for different population and design scenarios. The IBM SPSS statistics 27 has been used for the statistical analysis. The results showed that there are significant differences in AET between population sizes and design scenarios (Table 7). So, we can interpret that both population and design scenarios are affecting the AET, while the inter-group Tukey test for population showed that the mean value for AET is not changing significantly between 100 and 200 people. The congestion can be the reason for this result. It implies that in a small population (under 200 people), there would not be any considerable congestion during people movement.

The TET is not changing significantly in the two design scenarios. Also, the interaction effect of design and population is not significant in TET. The inter-group analysis for TET does not show a significant difference for mean TET for the runs with a population size smaller than 300. The line graph on the right side of Fig. 11 is almost horizontal accordingly. Also, the graph shows that the TET for D2 is lower in the population of 100 and 200. However, it increases dramatically for larger population sizes.

Generally, the inter-group analysis and evacuation curves (Fig. 11) confirm that the D2 leads to lower AET and TET compared with D1 when the population size is small. The shorter access distance to the middle of the corridor may have caused this result. However, the first design scenario is recommended for large population sizes (more than 300 people). The congestion near the only middle exit area and the limited capacity of the main corridor can be the reason for this.

Another vital point is that as the earthquake randomly causes damage to the plan, in some runs of simulation, regardless of population size, some people are stuck inside the plan. It means that the exit areas were blocked, and people had no choice but to wait for external help to clear the obstacles for them to continue the evacuation process. since there was just one middle exit option in D2, the number of runs ended with people stuck, was dramatically higher than D1 where people could use the other exit if one were blocked. So, regarding safety, even for small population sizes, although the D2 scenario leads to a faster evacuation process, it may cause a higher risk of casualties.

5. Conclusion

This paper utilised advanced computer technologies in a novel simulation approach to evaluate the building indoor design performance based on human evacuation behaviour. A new agent-based simulation approach has been developed to incorporate post-earthquake evacuation behaviour with building internal layout design.

Earthquake-specific behaviours and considerations including fear level for humans, drop, cover, and hold, knowledge state about the dynamic changes of the environment, smart navigation through the damaged environment, the social group making (joining family members, herding), panic behaviour (rushing to exit during the shaking phase), and transferring of information between agents have been considered in ABM model which cannot be found altogether in previous studies. As a limitation in the current study, it should be noted that the physical details of the earthquake (such as earthquake intensity and the spectral acceleration estimation, accurate assessment of fragility functions) were mimicked. However, it was not the direct purpose of this paper and will be addressed in future research of the authors.

The non-structural damage was approximated in the desired plan according to logical assumptions. The proposed approach was successfully verified through a model-to-model comparison of the results from a real-life earthquake evacuation video recorded in the 2013 Ya'an-China earthquake where students evacuated from Mingshan high school.

A floor of an education building was simulated as a case study to test the proposed approach through different scenarios. Five categories of population size were tested to evacuate from two different internal layout design plans. The results showed that although the second design scenario provided better performance for small population sizes, the risk of being stuck was higher than the first design layout. Also, the evacuation time was much higher for large population sizes in the second architectural layout alternative. The implementation of the proposed approach illustrated the potential benefits of the developed prototype, which can be used for design alternatives evaluation. It was shown that the hybrid cellular-graph approach is helpful when different spaces and their connections in the layout are crucial, which is exactly the agent-based modelling requirement. Furthermore, applying discrete utility-based choice modelling and reinforcement learning in the navigation model is smoothly applicable in a node-based environment.

The accurate non-structural damage calculation and considering details of furniture and other obstacles are the study's limitations. For future studies, a probabilistic non-structural damage assessment and relevant databases can be coupled with the proposed approach to have a more realistic post-earthquake physical consequence. The authors believe that the proposed model, if coupled with other BIM tools, will become a functional tool for designers to evaluate the architectural design of buildings.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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