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RESEARCH ARTICLE

Creating A Model for Evacuation Simulation of Earthquakes in Multi-Storey Buildings using 3D GIS and Agent-Based Model (ABM)

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Abstract Evacuation simulations in multi-storey building using 3D GIS and ABM require further study. Existing models lack comprehensive input on various building attributes. This research aims to develop a model for simulating earthquake evacuations in multi-storey buildings. The building and its occupants (agents) are modeled in detail, with building dimensions and designs obtained through measurements and field surveys. A field observation was conducted to determine agent's distribution. Agents placed in the building model are given certain behaviors once evacuation begins. The research focuses on a multi-storey building at Universitas Gadjah Mada (UGM). The model can assess the effectiveness of current evacuation facilities. Computer simulation results show that 266 agents require 140.8 seconds to evacuate, with no bottleneck observed at any location. A guest agent, assumed to lack knowledge of the building's emergency information, is observed to exit last. In contrast, the fastest evacuation is achieved by agents familiar with the building, represented by a group of lecturers/staff. Model validation, through comparison with a drill simulation, shows a time difference of 0.45 seconds. Findings indicate that, under current scenarios, the building's evacuation facilities have adequate capacity.

1. Introduction

Java, an island in Indonesia, lies above the Benioff subduction zone between the Indo-Australian and Eurasian tectonic plates, leading to frequent major earthquakes (Saputra et al., 2018). On May 26th, 2006, at 23:54 UTC, a moderate earthquake with a moment magnitude of 6.3 struck the southern region of Yogyakarta, Java (Diambama et al., 2019; Ninatin et al., 2020), resulting in over 5,700 casualties and extensive damage to the area (Diambama et al., 2019).

Evacuation planning is crucial for minimizing the loss of life during earthquakes (He, 2021; No et al., 2020). Digital evacuation simulations offer a practical method to assess a building's evacuation performance (Wu et al., 2024), unlike drill simulation which requires a lot of human resources, costs, and time. The advancement of 3D GIS technology facilitates evacuation simulations (Rahman & Maulud, 2019) by providing a three-dimensional representation of spatial data, incorporating object height or geographical coordinates. This approach enables detailed modeling of complex environments, including multi-storey buildings, allowing for a realistic analysis of evacuation routes and scenarios (Hajji et al., 2021). While conventional GIS usually focuses on a large-scale area, smaller areas such as indoor environments can also be mapped using GIS technology (Tang & Ren, 2012). The 3D GIS incorporates both geometry and indoor attributes of certain buildings (Teo & Cho, 2016).

An agent-based model (ABM) is widely used in various fields, including earthquake research and disaster management. ABM is defined as a model that captures interaction between agents and their environment (Turgut & Bozdag, 2023). ABM needs to define the spatial environment or space where agents move and interact (Medina et al., 2016). It is a simulation technique that models complex systems by representing individual agents and their interactions (Rathinam, 2022). ABM can be applied to large-scale simulations at the micro level (X. Liu & Lim, 2016). In earthquake research, ABM has been used to simulate and analyze evacuation scenarios (Bernardini, 2015; Cimellaro et al., 2017; He, 2021). These simulations take into account human behavior and social factors such as age, gender, and spatial awareness, to create realistic evacuation dynamics (He, 2021). ABM also models post-earthquakes and tsunami evacuations, providing insights into information exchange and decision-making during emergency (Aranha et al., 2017).

Research on evacuation simulations in multi-storey buildings, particularly utilizing 3D GIS and agent-based modeling (ABM), remains limited. Most studies lack detailed floor layouts, often using simplified models that fail to capture the complex interior details essential for realistic simulations. For instance, Castro & Ford (2021) estimated building height and a uniform floor height of 4 meters to create 3D models, omitting detailed interior elements. Similarly, Pagou et al.

(2023) generated "agents" for building components, such as floors, rooms, indoor paths, and exits, using shapefile data, yet lacked specific interior object details. Z. Liu et al. (2016) utilized the 3-story building's floor plan, focusing solely on its empty space. Details on the building were not highlighted in the research by Ding & Weng (2016), which compared evacuation strategies in multi-storey buildings using hypothetical building models with the same layout on each floor. Additionally, R. Liu et al. (2016) incorporated class layouts with furniture to evaluate alternative evacuation scenarios, though detailed building specifics were not emphasized. To address these gaps, this research aims to develop a model for simulating earthquake evacuation in a multi-storey building after a high-intensity earthquake, integrating agent-based modeling and 3D GIS.

2. Methods

This research used a scenario with an MMI of V, a considered moderate earthquake causing indoor items to shake, creating rattling noises, and being felt widely both indoors and outdoors. An MMI of V earthquake can cause moderate shaking and potential damage to buildings and infrastructure (Pandita et al., 2023). The choice of MMI V was selected to simulate realistic evacuation scenarios in multi-storey buildings, as it significantly impacts occupant behavior and evacuation patterns (Bernardini et al., 2019; Gwynne et al., 2019). This study used an MMI V scenario to simulate occupant's reactions in multi-storey buildings under moderate seismic shaking (Nguyen et al., 2015), focusing on evacuation speed, path selection, and crowd dynamics. Key steps included a detailed interior scale, a literature review on agent characteristics, evacuation modeling, model evaluation, and model validation. The flowchart of the work methodology is illustrated in Figure 1.

2.1. *Study Location*

This study was conducted in the Postgraduate School Building (SPS building) at Universitas Gadjah Mada, Yogyakarta, Indonesia, a structure with 5 floors and 1 basement. The basement serves as a parking area, while the 1st and 2nd floors are primarily occupied by office employees. The 3rd and 4th floors are used mainly for classrooms and offices. Although the building has an elevator, it was not used during earthquake simulations. The building has three staircases: one each on the left and right corners and a wider staircase in the center of the building. The 1st and 2nd floors lack of corridors, and only the 1st floor has an exit. The 2nd to 5th floors has no exit, therefore requiring evacuation through the emergency stairs. The basement includes an exit located on the same floor.

The SPS building was selected as the study area for its unique arch structure, which significantly influences evacuation dynamics during seismic events, particularly given its irregular layout. This complexity creates a realistic environment for testing evacuation models, closely simulating the challenges faced by evacuees. A dynamic indoor evacuation model demonstrates how obstacles from damaged components can hinder agent movement, requiring adaptive evacuation strategies (Chu et al., 2022). Additionally, the diverse population within the SPS building, with varying ages and educational backgrounds, provides a unique opportunity to study evacuation behaviors in earthquake-prone regions. This diversity enables a thorough evaluation of multi-storey evacuation strategies, as different agent characteristics significantly influence evacuation dynamics. The complexity of evacuation behavior in diverse groups requires simulations that consider varying physical capabilities and decision-making processes during emergencies (Hassanpour et al., 2022).

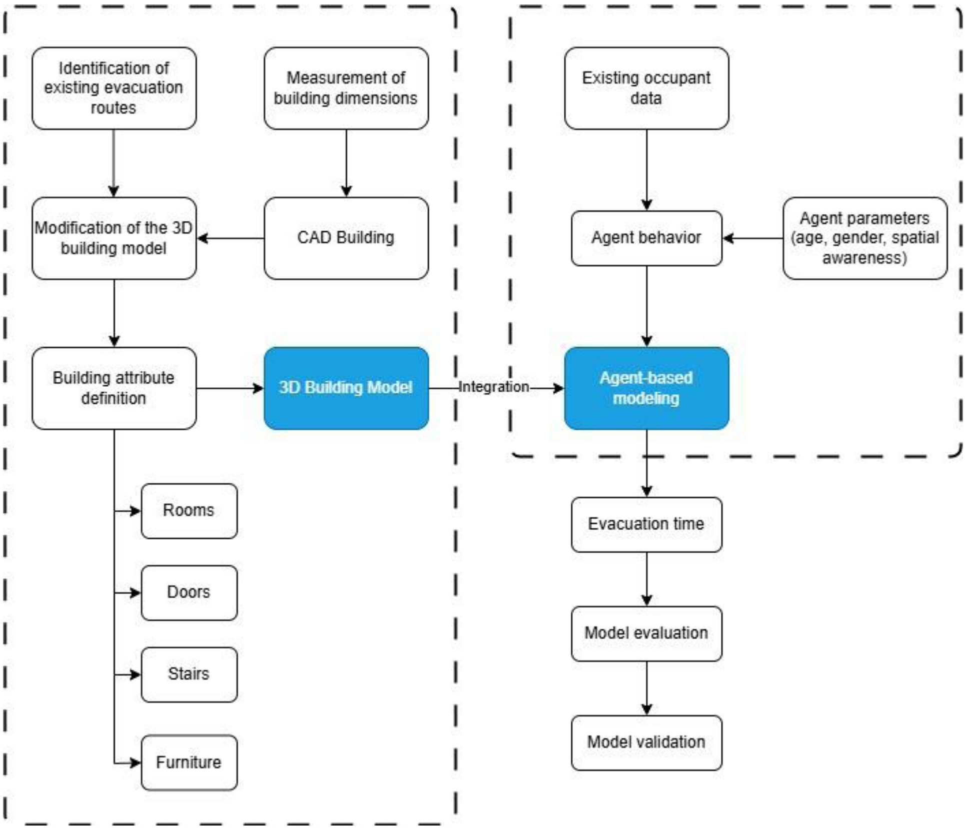

Figure 1. Flowchart of the work

2.2. *Building Model*

Based on observation, key building elements affecting evacuation in a multi-storey building include emergency stairs, doors, and obstacles such as furniture, which consists of tables, chairs, cupboards, and toilets. The building model was visualized at the indoor level, with building attribute data serving as a source of indoor spatial information (Guo et al., 2023). Indoor space has different attributes from exterior components, formed by non-overlapping 3D spatial objects such as rooms, corridors, and stairs (Kim & Li, 2019).

Building dimensions were obtained through field measurement using a laser distance meter and a building blueprint to calculate angles. This method was considered as the most practical for evacuation modeling, even though other methods such as terrestrial laser scanners and close-range photogrammetry also available (Singhal et al., 2023; Spearpoint et al., 2024). Measurement data included room length and width, door width, floor height, width, and length of stairs. Furniture was not measured but depicted based on photographs, as shown in Figure 2.

The multi-storey building was illustrated at a specific scale using Revit 2015 software. Revit was chosen easier for its comprehensive features, allowing the creation of 3D models and building information (Hendriatiningsih et al., 2019). Autodesk Revit offers advantages in BIM over AutoCAD by enabling 3D modeling for detailed design, error checking, and automatic updates, thus improving efficiency and accuracy in building projects (Chandra, 2022). The building elements described in Revit include walls, doors, windows, floors, rooms, and furniture. The CAD format produced by Revit was compatible with Pathfinder software, used for advanced modeling.

Revit building design was used in Pathfinder as additional geometry and visualization, as Pathfinder lacks tools to build complex models. Rooms, stairs, and doors were extracted without gaps to ensure agents could pass through the spaces. Building models did not account for vibration differences across floors during an earthquake, and furniture was statically modeled with no visible earthquake vibration.

2.3. *Agent Characteristic*

An agent represents an occupant of the building, with attributes including walking speed and knowledge of the building layouts. Walking speed is determined by age and gender (Z. Liu et al., 2016). The knowledge of agents was divided into agents who were familiar with the evacuation route and agents who were unfamiliar with it.

According to Takabatake et al. (2017), a human's walking speed primarily varies with age, with individuals under 65 years old reaching a maximum speed of 1.19 m/s, while those over 65 years old typically walk at 0.96 m/s. Furthermore, there are three types of agents based on reaction time and walking speed: lead agent, ordinary agent, and panic agent (Chen, 2020). This research modified the agent types as follows: a lead agent represented by lecturers or staff, who were assumed to be very familiar with the evacuation route; an ordinary agent represented by students, who were quick to adapt in recognizing the evacuation route; and a panic agent, represented by the guest, who has no experience in the building. The agent characteristics are shown in Table 1.

Figure 2. Floor plan and room photo

Table 1. Type and characteristics of agent

Agent type	**Walking speed (m/s)**					**Reaction time (s)**
	Gender	Female		Male		
	Age	< 65	> 65	< 65	> 65	
Lecturer/Staff (*lead agent*)		1,45	0,93	1,48	1,06	0-10
Student (*ordinary agent*)						10-50
Guest (*panic agent*)						40-70

Source: (Chen, 2020; Z. Liu et al., 2016; Takabatake et al., 2017)

2.4. *Evacuation Modeling*

The building model represents the static layer, while agent movement represents the dynamism. According to Jumadi et al. (2016), processing both the static and dynamic layers together results in the integration of GIS and ABM. A 3D GIS model integrates three-dimensional spatial data to realistically represent geographic features and phenomena, enabling the visualization and analysis of spatial relationships and patterns. This is particularly useful for disaster management (Jumadi et al., 2016). ABM, on the other hand, is a computational method that simulates the interactions of autonomous agents within an environment. Agents can represent individuals, organizations, or entities that exhibit behaviors based on certain rules. ABM is particularly effective for modeling complex systems where interactions lead to emergent behaviors, making it suitable for social processes and environmental simulations. When combined, 3D GIS and ABM enhance the modeling of spatial processes by allowing agents to interact within a realistic three-dimensional environment (Anantsuksomsri & Tontisirin, 2022).

Based on the observations of building occupancy during working hours, a total of 266 agents were placed in the building. Agent distribution on each floor is shown in Table 2. In the Pathfinder, agents were programmed to find the nearest exit from their original position. Agents crossed the exit door by avoiding obstacles such as walls and furniture, as well as other agents. Those near the obstacle tend to move slower than agents in the obstacle-free area.

2.5. *Model validation*

Model validation was necessary to ensure the integration of 3D GIS and ABM. The model was validated by comparing the field survey data with real walking simulation. Participants were positioned at the top of the stairs and then walked down the stairs to the bottom. The validation involved calculating the evacuation time on a single floor in the study area, which contained one landing. The characteristics of the agent were implemented on the main stairs, with walking speed and gender roles factored into the simulation. Some students of different genders and ages were simulated walking down the main stairs, and their travel time was measured using a timer. This research validation compared the travel time of actual participants with the simulated travel time.

3. Result and Discussion

1.1. Building Model

The building model consists of two types: the model in Revit, as shown in Figure 3, and the model in Pathfinder. The results of measurements and photographs were depicted in Revit until the entire building was modeled. Once transferred to Pathfinder, the model could not be edited, so the design, including furniture, should be completed in Revit beforehand. Revit offers the advantage of easier and more detailed building modeling. It is particularly effective for modeling curved buildings with non-angular angles and rotating stairs, as it accurately represents angles and distance. In addition, Revit excels in visualization and facilitates data transfer to other software, such as Pathfinder (Marzouk & Al Daoor, 2018).

Table 2. Agent distribution

Floor	**Student** (<65)		**Lecturer/Staff (<65)**		**Lecturer/Staff (>65)**		**Guest** (<65)		**Guest** (>65)	
	M	F	M	F	M	F	M	F	M	F
Basement	-	-	5	-	1	-	-	-	-	-
Level 1	2	-	16	12	-	-	1	3	-	1
Level 2	3	4	7	8	-	-	-	-	-	-
Level 3	26	14	10	4	1	-	-	3	-	-
Level 4	19	16	11	-	-	-	-	-	-	-
Level 5	41	41	6	5	-	-	-	6	-	-
Total	91	75	57	29	-	-	1	13	-	-
	266									

M: Male; F: Female

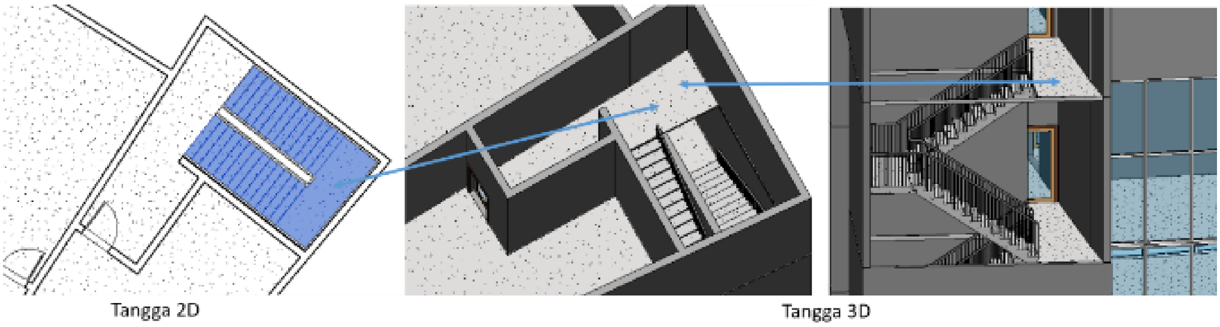

Figure 3. Stair model in Revit

Figure 4. Furniture room extraction

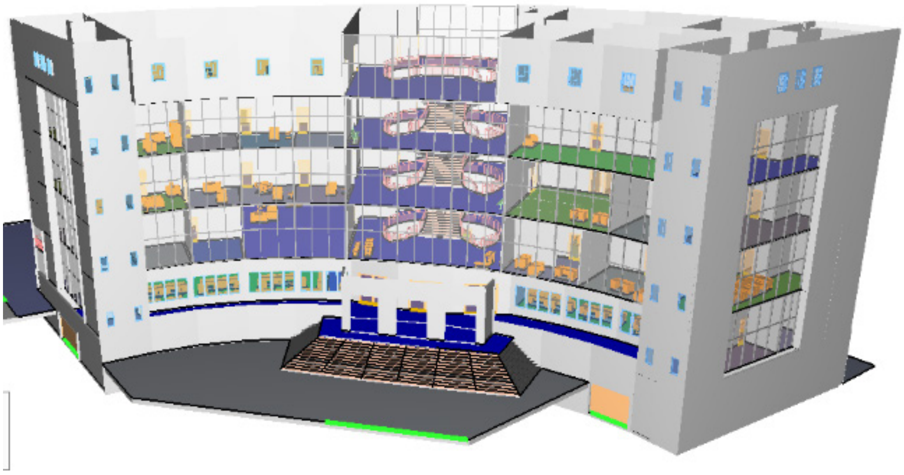

Figure 5. 3D building model

The results of extraction in Pathfinder from the models produced by Revit included rooms, doors, and stairs. Furniture in a room was extracted as a hole-form or empty space that could not be passed by the agent, as shown in Figure 4. These holes were marked in grey color under the furniture.

There are two types of doors: the exit door and the door that connects between two rooms. Both have different functions and definitions in Pathfinder. The exit doors can only have a room on one side (Pathfinder, 2021). The building model has 7 exits, 3 of which are on the 1st floor and the remaining four in the basement.

The shape and number of risers were modeled according to the actual design. Two stairs on the right and left sides of the building were created by calculating the number of treads and the height of the stairs. The middle stair, due to its complicated shape, was extracted from the Revit stair model. One of Pathfinder's weaknesses was the limited stair model, which can only present the same size stair from top to bottom. However, this limitation does not affect the modeling result, it only forms the visual representation.

The Pathfinder building model only requires room, door, and stair elements that are interconnected geometrically. The rest of the designs carried by Revit are useful for visualization (Marzouk & Al Daoor, 2018). The overall building modeling results are shown in Figure 5. In Pathfinder, the geometry model uses a triangulated mesh, which is defined as a 2-dimensional triangulation surface (Pathfinder, 2021). Agents' movement occurs within this irregular navigation mesh.

1.2. Evacuation model

Based on the agent's movement in the building model, the total evacuation time and location of the bottleneck were obtained, similar to the results of the study conducted by Marzouk & Al Daoor (2018). Each agent is programmed to head towards the exit while avoiding other obstacles and other agents (Z. Liu et al., 2016). The evacuation model provides not only evacuation time and agent density but also presents 2D and 3D visualization of the entire evacuation process (Ronchi et al., 2016). The evacuation of 266 agents took 140.8 seconds or 2.35 minutes, with agents' distribution as shown in Table 2. Most agents (34%) use the north exit, followed by 28% using the west exit. The remaining agents exit through the east and south exits. The percentage of the fewest exits is in the basement, as there are only 6 agents on this floor. The majority of agents start on the west side of the building, so the west and north exits in the center of the building are used by most agents. The width of the door does not influence the agent's exit choice (Z. Liu et al., 2016), rather, it depends on the proximity to the emergency stairs.

Based on the agent density, it was observed that the presence of three stairs prevented any bottleneck. On the 5th floor, which had the highest number of agents (80), no bottleneck occurred because the room had two wide doors that could be accessed and located opposite each other. However, closing one of the doors may cause a bottleneck due to the high density, as simulated in Figure 6 (right). It shows a difference in agent density at the 50th second. The bottleneck varies depending on the agent's position (Kobayashi et al., 2014). The evacuation time from a room with one exit is significantly longer, as well, taking 164.6 seconds (2.74 minutes). The number of exits plays a crucial role in affecting the continuity of the agent. Similarly, the width of the exits, as noted in the study of Kobayashi et al. (2014) resulted in evacuation time differences. Rooms with more exits result in better evacuation performance (R. Liu et al., 2016).

Figure 7 shows the situation of the three stairs at the 70th second. It appears that the most frequently used stair is the middle stair which is also the widest stair in the building with a maximum width of 3.8 meters. This stair can accommodate at least 4 people simultaneously on the same tread. In contrast, the stairs on the right and left side of the building can only accommodate 2 people per tread. This set-up demonstrates that the designs of both stairs and exits greatly influence the evacuation process (Kobayashi et al., 2014; Manley et al., 2016). Similar findings are reported by Ronchi et al. (2016), identifying density, delay, walking speed, and distance to exits as key factors influencing the evacuation process. Likewise, Leonita et al., (2017) observed that group walking behavior, particularly when individuals walk side-by-side on stairs, can create queues and hinder the movement of other employees behind them. The research also exposed that all employees tend to walk in groups while holding onto the stair railings.

Among the different types and characteristics, the female guest agent has the longest evacuation time. This is due to programmed longer and the influence of gender aspects, the position of the agent affects the total evacuation time. The initial position of the longest agent is on the top floor. The shortest agent to exit the building is a male lecturer/staff agent whose initial position is on the basement floor used as a car park. On average, female lecturers/staff have the fastest evacuation time, while male guest agents experience the longest time. Table 3 provides evacuation time for each type of agent. These results are valuable for identifying vulnerable individuals during the evacuation process, similar to research conducted by Manley et al. (2016). Special attention should be given to guest agents by optimizing evacuation facilities to ensure accessibility for individuals unfamiliar with the layout.

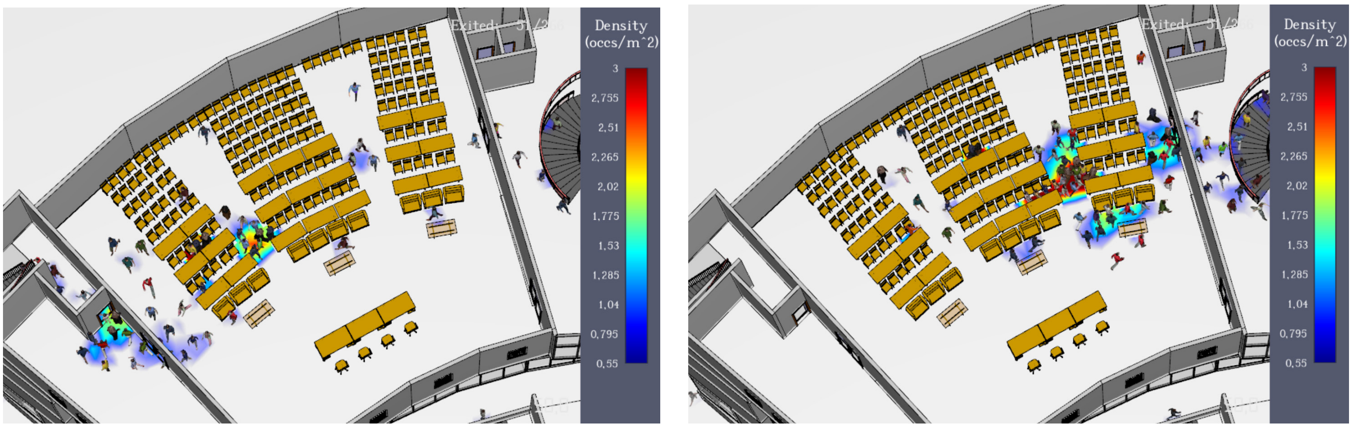

Figure 6. The density difference between 2 exits (left) and 1 exit (right) in the same room

Figure 7. Comparison of 3 stairs at the 70th second. West stair (left), middle stair, east stair (right)

Table 3. Evacuation time based on type & agent character

Agent type	Total	Min (s)	Max (s)	Average (s)
Lecturer/staff (male)	55	5,9	85,4	45,7
Lecturer/staff (female)	29	19,3	73,2	43,8
Lecturer/staff (>65) (male)	2	15,9	102,8	59,3
Student (male)	91	49,2	137,3	93,6
Student (female)	75	47	139,1	94,9
Guest (male)	1	69,2	69,2	69,2
Guest (female)	12	71,4	140,5	103,5
Guest (female) (>65)	1	74,7	74,7	74,7
All type	**266**	**5,9**	**140,5**	**78,7**

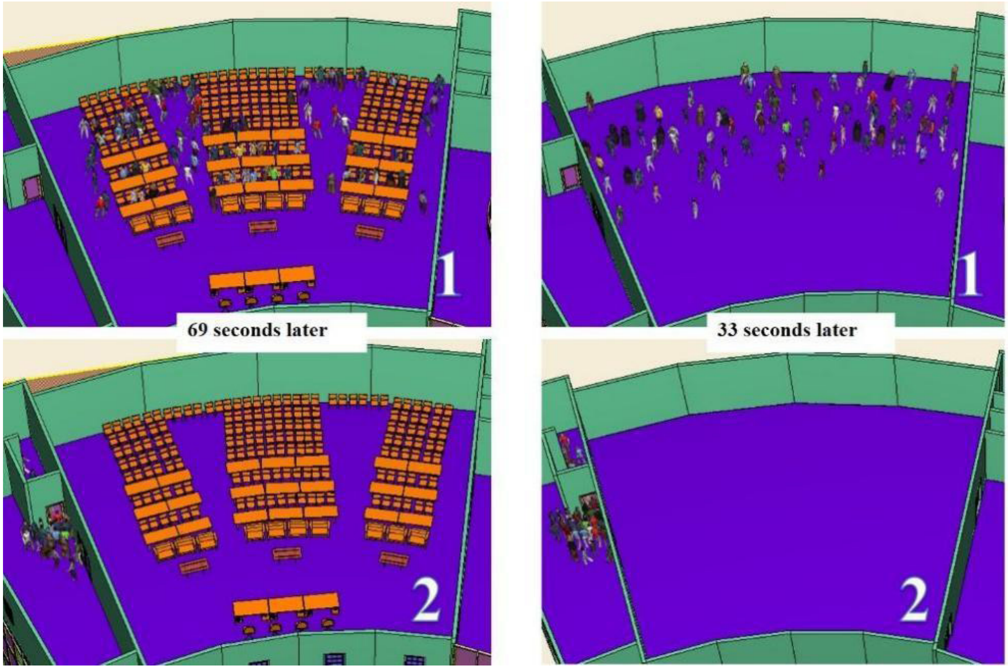

Figure 8. Evacuation comparison in a room with and without furniture

Furniture affects the time of evacuation. Figure 8 compares the evacuation model on the 5th floor (auditorium) with and without furniture. The presence of the furniture creates more obstacles for agents moving towards the exit, resulting in a 36-second increase in evacuation time when furniture is included. This study demonstrates that detailed evacuation modeling in a detailed building model can produce outcomes closely resembling real-world scenarios. Structurally, a new design approach for multi-storey buildings can achieve the same resistance against seismic movements with reduced concrete and reinforcement (Mesutoğlu & Tok, 2021). This method supports the development of earthquake-resistant buildings, thereby enhancing evacuation safety.

This research is limited to modifying agent behavior, though modeling evacuation with varied population characteristics includes complex categories (Jumadi et al., 2016). Similar to the study by Cimellaro et al. (2017), agents in this model always recognize the nearest exit and move without hesitation. However, in real scenarios, some individuals guide others unfamiliar with the layout and direct them to the most suitable exit. This limitation affects the accuracy of the model in simulating actual agent behavior. According to Pax & Pavón (2017), the agent behavior in this study is classified as low-level behavior. This categorization is based on perceptions and basic behaviors when interacting with the environment. When the agent's destination has been determined, the agent can move and avoid obstacles such as walls and other agents. Such behavior falls under the steering behavior category, which is supported by Pathfinder software.

1.3. Model validation

Model validation was conducted through real walking simulations involving student agents within the building. Output models are compared with observations in the building (Lee & Malkawi, 2014; Bandyopadhyay & Singh, 2016; Manley et al., 2016). The validation focused on the main stairs, with agents starting from the top of the upper stairs and moving to the end of the lower stairs. The travel times in the computer simulation and actual measurements were then compared. No repetitions were performed in the model to ensure results accuracy. However, the real walking simulation provided additional references for walking speed accuracy in the model. For female student agents, the model's average descent time was 8.8 seconds, while in real simulations, it was 9.3 seconds, showing a 0.5-second difference. Similarly, for male student agents, the model was 0.4 seconds slower than actual travel times. Those results indicate that the model closely represents real-world situations, both in terms of building's structure and the agent behavior model.

This study effectively highlights the advantages of using 3D GIS technology integrated with agent-based modeling for indoor evacuation simulation. This research has considered the existence of furniture; meanwhile, the building model used did not include barriers in the internal space such as furniture (Tang & Ren, 2012; Tashakkori et al., 2015; Ding & Weng, 2016; Z. Liu et al., 2016). While similar studies by Kobayashi et al. (2014) and Pax & Pavón (2017) included furniture, they did not emphasize its functional impact on evacuation processes. This study confirms that detailed building models, combined with measured agent behavior for obstacle avoidance, can lead to more effective evacuation and produce a more accurate time estimation. Evacuation simulations through computer simulations have proven to be a more cost-effective, time-efficient, and resource-saving method compared to real-life simulations as simulated by Z. Liu et al., (2016); Ronchi et al., (2016); Pax & Pavón (2017); and Marzouk & Al Daoor (2018).

4. Conclusion

The evacuation simulation can be effectively conducted through the integration of agent-based modeling and 3D GIS. On the indoor scale, the 3D GIS can model a building in detail, including rooms, stairs, and furniture, allowing for a comprehensive analysis of the evacuation process. Potential bottlenecks can be obtained through visual representation. The evacuation time in a detailed building model (including furniture) is recorded longer than the less detailed building model. Agents who are assumed to be unfamiliar with the condition of the building, such as guest agents, reach exit the last. In contrast, those who are familiar with the building situation, most represented by a lecturer/employee agent are able to reach the exit most quickly. The 3D result shows that there is no bottleneck. Model validation through real simulation comparison shows a time difference of 0.45 seconds, which means that the model is sufficient to represent the real conditions.

Further research should model more varied agent behavior such as crawling or agents assisting others. High-level behavior can be further studied to model agents capable of making decisions. In addition, modeling the 3D dynamics of buildings is also necessary, such as temporarily simulating building damage to estimate its effects on agents.

Guest agents, assumed to be unfamiliar with the building, must be provided with easily accessible information regarding evacuation facilities, such as evacuation directions. In addition, the management of the evacuation routes must be improved. Some evacuation doors at the research location were found to be locked, preventing access at all times. The location of emergency stairs is also sometimes used as a storeroom, which instead hinders evacuation.

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