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BIM based framework for building evacuation using Bluetooth Low Energy and crowd simulation

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ABSTRACT

Crowd evacuation is an area that has been studied by numerous researchers over the last years. Many models have been developed to simulate the evacuation. However, most of the developed models involved emergency routing of building occupants using hypothetical assumptions of their positions without integrating their actual locations into the models. Thus, in order to increase efficiency and accuracy of evacuation models, evacuees' real locations can be identified and then integrated into the model. In this research, Building Information Modelling (BIM), agent based simulation and Bluetooth Low Energy technology are integrated together to create an evacuation framework capable of indicating locations of building occupants and identifying the optimum evacuation path based on these locations. Point cloud data of a building is collected from 3D laser scanner, then converted to 3D BIM model, which is then imported into an agent based crowd simulation software. Also, an indoor positioning module is developed, which is composed of an indoor positioning system (IPS) developed by the authors. Through the IPS, evacuees' locations are calculated, whereas Bluetooth emitters –beacons- held by evacuees emit signals that are detected by group of gateways mounted in the building detect. The locations are then sent to the crowd simulation software, then through integrating the modules, optimum evacuation route is identified, which is then converted to directions through a dynamic signage module. A case study is presented to illustrate the proposed framework. The results of the case study show that the developed indoor positioning system has an accuracy of 1.88 m with a maximum error range of 3.934 m. Moreover, the results indicate that the implemented indoor positioning system is capable of correctly detecting the evacuees in the rooms they are actually in with an accuracy of 93%. Finally, the simulation shows that the full evacuation of the floor under study took 2 min and 48 s.

1. Introduction

Emergency evacuation has been an action of great importance to the society throughout history, to ensure the safety and security of people. Rapid evacuation can be needed as a result of various incidents; such as: fires, terrorist attacks, earthquakes, or chemical gas leaks. Over the past years, the topic of emergency management and evacuation planning has been the focus of several academic researchers due to its extreme importance. This importance is derived from the dreadful impact that can be reached if a poorly managed

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evacuation process occurs. In other words, many human lives can be lost or threatened if an evacuation incident occurred and the building occupants did not manage to egress the building rapidly and in a planned manner. From that point, the idea of this research emerged. Emergency evacuation refers to the process of letting the people out of a dangerous area; either as a result of the presence of a natural catastrophe as an earthquake, or a man-made disaster as a terroristic attack. According to U.S. Fire Administration, 3400 deaths occurred due to building fires in 2017. Also, in 2017 alone there had been 14,670 injuries, and a loss of $23 billion in property. These numbers were caused by a total of 1,319,500 fires [1]. Not only is emergency evacuation needed in case of building fires, but also, in case of natural disasters as earthquakes. According to US Geological Survey [2], in 2015 only, nearly 9624 people died worldwide as a result of earthquakes. The aforementioned statistics clearly show that emergency incidents cause huge numbers of injuries and fatalities, creating an undeniable urge to plan the emergency evacuation process. Lack of adaptive and efficient evacuation plans is one of the main reasons behind the devastating number of deaths and injuries during emergencies. In light of this, great attention shall be paid to the evacuation planning domain for the reduction of this amount of deaths and injuries. And with the emergence of technological advancements, safe, realistic, adaptive and efficient evacuation processes can be guaranteed.

The main purpose of this research is to maximize the safety of building occupants through the development of accurate, adaptive and efficient evacuation plans, and then the conversion of the generated evacuation routes into directions to be followed by evacuees. In order to develop an efficient and adaptive evacuation plan, location of evacuees at the time of emergency has to be taken into consideration. Also, to guarantee that the developed evacuation plan is accurate and representative of reality, human attributes (as velocity, body radius) and interactions shall be taken into account during the development of the plan. Also, building details shall be considered in the process pf evacuation plan development. In order to prove the hypothesis of the proposed research, the aforementioned framework was implemented on a case study floor at one of the buildings at the Faculty of Engineering, Cairo University.

2. Literature review

2.1. Agent based modelling

An Agent Based Model (ABM) is a dynamic model comprised of a group of heterogeneous objects named agents. Agents refer to the autonomic components that together form the complex system being modelled or simulated. They are usually in a continuous process of interactions with other agents and with the surrounding environment. The modes of agents' interactions are specified according to set of predefined rules in a computer-based environment. Many fields have made use of Agent Based Models such as; geography, sociology, military, safety management, finance and healthcare [3].

There are several platforms used for the implementation of agent based models. Table 1 illustrates four of the platforms through which agent based models can be developed. The table highlights the modelling language and level of programming skills required for each tool. It also presents whether there is a built in capability for developing movies or animations within each tool or not. Finally, it presents examples of publications that made use of each tool.

On the other hand, there is a number of computational tools that are oriented towards evacuation modelling specifically such as; EVACNET4, WAYOUT, Simulex and MassMotion [11]. For the purpose of this research, MassMotion [12] is utilized as the agent based simulation software. MassMotion offers several features that are perfectly aligned with the requirements of this research. Whereas it highly supports the interoperability between different computer programs. This feature is greatly needed in the development of this research since the research is comprised of several modules. Moreover, MassMotion offers 3D visualization of the simulation runs, making it easier for users, particularly safety managers, to visualize evacuation process and identify potential bottlenecks. It is worth noting that, MassMotion is modelled using a modelling method called behavioral model, which means that agents take actions and make decisions till reaching building exit, which is their goal [11].

When considering the emergency management domain, it can be observed that the body of knowledge have been enriched by the work of several scholars which made use of agent based simulation in such domain. For example, Bao and Huo [13] developed an ABM for simulating staircases evacuation. This model took into consideration both translational and rotational movements of agents as well as the geometrical details of the staircase. The authors utilized mathematical formulation in order to model agents' rotational behavior. This was achieved through the development of mathematical models for agents' attractive and repulsive behaviors between one another, as well as the repulsive behavior between agents and the surrounding environment. This model was not only suitable for staircase evacuations, but also, for the evacuation of regular rooms. The model was validated using numerical examples and it was concluded that the model was able to simulate realistic evacuation dynamics in a precise manner.

In addition to this, Delcea et al. [14] utilized agent based simulation in studying the impact of evacuation doors' distribution on evacuation time of classrooms and lecture halls. Two doors were distributed in eighteen different configurations for a classroom and a lecture hall. Three configurations showed symmetrical distribution of the two doors over the classroom and the lecture hall, while fifteen configurations showed an asymmetrical configuration of the doors. The model considered the variability of agents' velocities,

Table 1
Agent based modelling platforms.

Plateform	Modeling Language	Required Programming Skill	Animation Ability	Publications
SWARM	Object-C, Java	Strong	No	[4]
Repast	Java, Python, Microsoft.Net	Strong	Yes	[5,6]
MASON	Java	Strong	Yes	[7]
NetLogo	Proprietary scripting language	Basic	Yes	[8–10]

size of evacuation doors and presence of obstacles. Results of the simulation showed that, in most cases, the symmetrical positioning of doors provided less evacuation times than asymmetrical positioning.

Additionally, D'Orazio et al. [15] developed an intelligent ABM for simulating evacuation as a result of earthquakes. The purpose of the model was to illustrate the interaction between evacuees and each other and with the surrounding environment during earthquake evacuation. The authors collected data about people's behaviors in evacuation incidents from videos showing real earthquake evacuation incidents, then from this data, a comprehensive behavioral analysis was performed, and results of the analysis were later incorporated into the model. Also, Kim and Heo [16] developed an ABM in order to simulate an evacuation process caused by release of radioactive materials. The model relied upon the inclusion of four different elements (multi-agent based model) and their interactions together. Those four elements are; evacuees, hazardous material, safety shelters and transportation vehicles. This research was complemented by a case study for the conceptual demonstration of the multi-agent based model.

Not only were evacuations as a result of natural catastrophes and radioactive materials' leakage simulated via agent based modelling, but also evacuations caused by building fires. Whereas, Marzouk and Hassan [17] developed an agent based evacuation framework for simulating the evacuation process in museums in case of fire incidents. Due to the variable nature of museum visitors, several aspects were considered in the framework, as age, physical features, gender, and visitors' awareness of the surroundings. A case study was performed to assess the degree of practicality of the framework. Regarding integrating Agent Based Modelling with other technologies, Marzouk and Mohamed [18] utilized agent based simulation and multi criteria decision making in order to assess the safety performance of buildings from a fire safety perspective. The framework integrated 3D BIM modelling with agent based simulation and decision support tools to develop a quantitative assessment approach for the evaluation of building evacuation performance. Several criteria for assessment were considered as the evacuation time and percentage of evacuated occupants per floor. A case study was conducted to present and validate the framework.

In addition to this, Beyaz et al. [19] integrated Building Information Modelling with agent based simulation for the inclusion of building details and occupant data into an evacuation model. 2D Cad drawings were used for inputting building's spatial data into the model. Whereas, they were imported into a 3D modelling software for the generation of 3D BIM model. Afterwards, the 3D model was imported into Unity software which was utilized as a simulation platform, on which the ABM approach was created. A case study was performed involving the simulation of a fire evacuation incident on one of buildings in Istanbul Technical University. The authors concluded that, integration between BIM and ABM is an effective approach for modelling evacuation processes, guaranteeing a three dimensional visualization of the process. This is beneficial for decision makers to evaluate evacuation performance of buildings and to take any needed corrective actions to improve evacuation performance.

It can be observed that the extensive literature incorporating ABM in emergency management domain reflects the perks of its utilization in such area. For this reason, Agent Based Modelling was utilized in this research. Whereas, through it, human characteristics (as pre-movement times, speed, body attributes) were incorporated into the developed framework.

2.2. Indoor positioning

The incorporation of evacuees' actual locations during an emergency is extremely essential for the development of a realistic and efficient evacuation framework. In order to identify people's locations, an indoor positioning system (IPS) was needed to be developed and later incorporated into the developed framework. This is due to the fact that this research addresses indoor environments and particularly high educational buildings. An indoor positioning system (IPS) refers to a system that is capable of locating people or assets in the indoor environments [20]. The need to utilize a specifically indoor positioning system emerged from the fact that satellite based technologies such as GPS usually fail in offering precise location data of people or objects inside buildings. This occurs due to interferences and signal attenuation caused by barriers such as slabs and walls [21]. Whereas, their accuracy become extremely low in non-line of sight cases [22]. There are numerous technologies that can be used for the development of a precise IPS. An extensive analysis of the present indoor localization technologies is performed in order to choose the most appropriate one for the intended application. The following paragraphs shed the light over three of the most common technologies and illustrate which of them is the most appropriate for the intended application.

One of the most well-known indoor positioning technologies is Wi-Fi. Wi-Fi is a simple synonym for Wireless Local Area Network (WLAN). Using Wi-Fi in indoor positioning and navigation systems necessarily requires maintaining a list of available wireless routers in the location in which the system operates. A main strength to the Wi-Fi is its availability, whereas, approximately most of the devices and buildings available nowadays are equipped with WLAN connectivity. It is worth noting that Wi-Fi based positioning that utilizes RSS method involves an extremely high variance in precision, whereas accuracy may vary from 3 to up to 30 m [23]. This is not acceptable in the context of defining the positions of people in indoor locations.

Another prominent technology in the indoor navigation area is image based technology or camera-based positioning, which involves the use of optical information from camera with the computer vision and image processing technologies. It is considered a quick and reliant indoor positioning technology [24]. Cell phone cameras, Omni-directional cameras, and three-dimensional cameras can all be used; however, their output varies based on how much information can be extracted from their images. Computer vision positioning technology can only detect positions in the Line of Sight (LOS), making it difficult to solve blockages caused by walls and obstacles. As a result, such systems' coverage is limited [25]. Line of sight coverage is a fundamental obstacle for the intended application since the application's purpose is to suit any emergency incident, so in case the emergency incident was fire, any technology relying upon the LOS will not be appropriate since LOS is not guaranteed due to presence of smoke.

Last but not least, Amongst the well-established technologies that serves various applications is Bluetooth Low Energy (BLE), which is part of Bluetooth 4.0 standard developed by Bluetooth Special Interest Group (SIG) [26]. What differs BLE from classic Bluetooth is its ability to consume much lower energy, making it suitable for applications that do not need the transfer of huge amounts of data

[27]. Recently, BLE is widely used as an indoor positioning technology as it has variety of benefits [28]; firstly its implementation is relatively low in cost, whereas, Bluetooth chips are less costly than many other chips as Wi-Fi for example. Also, its power consumption is very low, for example; it uses fifth of the power that Wi-Fi does because it needs less transmitting power and has an automatic power control mechanism.

In the light of the analysis of different indoor technologies presented above, it is concluded that BLE is the most suitable technology for the intended application, whereas it stands out among all other indoor localization technologies. BLE technology due to its capability to overcame the disadvantages of other mentioned technologies. Whereas, BLE surmounts the difficulty of line of sight coverage present in image based technologies allowing Bluetooth to fully operate in conditions like fire where LOS is not available. Additionally, BLE consumes much fewer power than Wi-Fi, resulting in low operation cost [29]. This is an extremely crucial point of strength that is essential for a continuously operating indoor positioning system. And last but not least, Bluetooth also provides an appropriate position accuracy ranging from 0.9 to 2 m [30]. The intended accuracy to be reached in this application was 5 m.

The reason for choosing such value is due to the fact that, indoor localization in the context of this research is needed to localize building occupants, then based on the calculated locations, the most appropriate evacuation route(s) will be generated. In light of this, if the accuracy of the positioning system implemented exceeded 5 m, a person may be located at a totally different room from what the actual evacuee position is, resulting in the generation of a non-appropriate evacuation route.

Some researchers have made use of indoor positioning technologies in developing emergency models and/or frameworks, along with BIM. Whereas Rueppel and Stuebbe [31] developed an evacuation model to be utilized by saviors for reaching hazardous areas rapidly and efficiently. The authors integrated BIM with indoor localization technologies for the development of the model. Three indoor localization technologies were utilized namely, Radio Frequency Identification (RFID), Ultra wide band (UWB), and wireless LAN (WLAN). The developed model was capable of identifying firefighters' location in real time, and then developing the shortest navigation path for rapidly reaching the risky areas. The firefighters' locations were identified through mobile devices, and hand-held tags supporting the aforementioned technologies. Also, Deng et al. [32] proposed a BIM enabled evacuation framework, that utilizes computer vision for the localization of occupants in the indoor environments. The framework is capable of generating evacuation route as per the detected locations. The authors utilized machine learning to assess the safety of the produced route. A case study on a building was performed to validate the developed framework and the results proved its practicality and efficiency.

2.3. Research gap

There are number of studies that developed BIM-enabled evacuation systems supported by indoor localization technologies, however, none of the previous research efforts integrated agent based modelling with indoor localization technologies, and BIM for modelling a dynamic evacuation process. In this research, a combination of real data was guaranteed through utilization of several modules altogether. Firstly, the BIM module for feeding actual spatial details of the building into the developed framework. Secondly, the Positioning module which, using BLE technology, incorporates realistic location data into the evacuation framework. And, finally the Agent Based Modelling module which incorporates personal attributes into the model. Such combination of realistic data was not previously implemented by any other research.

3. Proposed framework

The proposed framework enables safety and facility managers to develop evacuation plans that are efficient, dynamic and realistic. Through the utilization of geometry of the building, locations of building occupants, and their physical properties (i.e. pre-movement

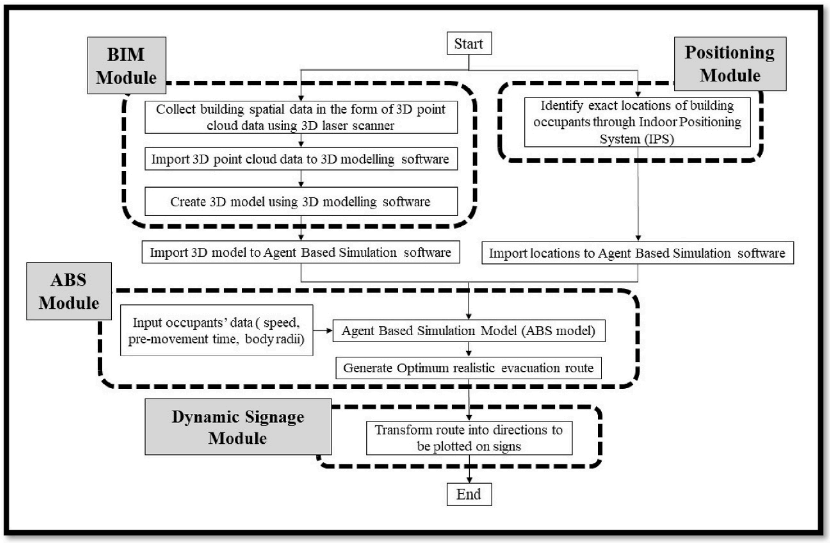


Fig. 1. Proposed framework and its components.

time, body size, speed), the produced evacuation plan is guaranteed to be credible and having a close depiction of reality. The proposed framework mainly consists of four modules; BIM module, Positioning module, Agent based simulation module and Dynamic signage module. Fig. 1 illustrates the proposed framework and flow of data between different components.

The first module is the BIM module; it focuses on the generation of 3D model for the building to be evacuated. Firstly, spatial data of buildings are collected using 3D laser scanner. Then, 3D point cloud data from laser scanner is imported to 3D modelling software, whereas it is transformed into Computer Aided Design (CAD) model. The output of this module is a comprehensive 3D model comprising geometrical data of the building under consideration. The discussed module addresses only existing buildings, so, if the building needed to be modelled is in the pre-construction or construction phase, 3D laser scanner will not be utilized, alternatively, CAD drawings will be imported directly into 3D modelling software to create BIM model.

The second module is the Positioning module which involves the development of an IPS created by the authors. The first step in designing such system is choosing an indoor positioning technology to be implemented. While, the second step is determining the indoor positioning technique or algorithms through which the physical position of the target of interest will be calculated. The choice of an indoor positioning technique requires the choice of both a signal measurement technique and a position calculation algorithm [33]. Through the indoor positioning system developed, locations of people inside building are calculated in the form of xy coordinates with respect to a specific reference system.

The third module is the Crowd simulation module or Agent Based Simulation (ABS) module. This module simulate the evacuation process and generates the optimum route. This module collects the outputs of the two previously mentioned modules. BIM model, produced in the first module, is exported from 3D modelling software as an Industry Foundation Class (IFC) file and imported to ABS software, feeding geometrical data of the building considered into the ABS model.Moreover, locations produced from the second module are imported into ABS software. Integrating the previously mentioned modules with this module guarantees that the ABS model created accounts for real spatial details of the building, exact locations of building occupants at the emergency time and human characteristics leading to a realistic simulation process. Consequently, the optimum route or the evacuation plan generated from simulation is ensured to be realistic, credible and accurate. The generated optimum route is the input of the following module.

The last module is the Dynamic signage module. It assumes that there is a set of virtual dynamic signs aiming at leading evacuees towards exits securely. Signs are assumed to be scattered among area to be evacuated. This module transforms the routes produced in the third module into left, right and forward directions. to be communicated to evacuees so that they can be directed towards building exits safely. In other words, through simulation, virtual agents evacuate the virtual building through the optimum evacuation route generated by agent based simulation module. This route is then transformed into right, left and straight directions to be communicated to real evacuees to follow the generated optimum route. Signs are dynamic; which means that directions plotted on them change with the change in route produced from ABS module as result of simulating different evacuation scenarios. Also, directions plotted on each sign is not static throughout the same evacuation scenario, depending upon route produced from ABS software. For example, a sign can indicate left direction at start of simulation, leading certain group of evacuees to the left, and at the end of simulation, it changes into right direction guiding other group to the right.

3.1. BIM module

The first step in this module is capturing the interior details of the building under consideration using the 3D laser scanner. The 3D laser scanner utilized in this research is Leica BLK 360 [34]. Utilization of 3D laser scanner to document spatial data rather than 2D CAD drawings enhances the accuracy of the generated model, since in many cases, as built drawings are not available leading to the utilization of drawings generated in the building's pre-construction stage. These drawings can be a way far from the actual constructed facility leading to inaccuracies in the produced model. On the other hand, surveying using 3D laser scanners saves a lot of the time and effort consumed in case of manual surveys. 3D Laser scanners collect data only within its field of view. So, in order to create a full and comprehensive representation of the surveyed area and capture all its spatial details, the scanner is put at different positions throughout the area, taking multiple scans from different angles. Then, using 3D point cloud processing software named Leica Cyclone [34], different scans are collected and registered together forming a full digital representation of the surveyed structure. This comprehensive digital representation is then imported into Autodesk Revit, which is the 3D modelling software utilized in this research. Only the fundamental features of the building shown in scans are modelled; such as walls, door openings, columns, slabs and obstacles such as desks or chairs. The created 3D model of the building understudy is the output of this module.

3.2. Positioning module

The first step in development of an indoor positioning system (IPS) is the choice of the indoor positioning technology. The technology used in the proposed framework is Bluetooth Low Energy. The IPS developed in this research utilizes receivers as reference nodes, while transmitters as target nodes. There was a realistic assumption made in this research, whereas it was assumed that the Bluetooth transmitters (called beacons) provided to building occupants will be the same as access cards, such that, if an occupant does not have his beacon, he will not be allowed to enter the building. This guarantees that all the people inside the building will be detected by sensors all the time, and consequently, if any emergency incident occurs, the generated route from the simulation will be the actual optimum route since the model aligns with reality in an extremely close manner.

For the identification of target location, a suitable signal measurement technique shall be chosen, followed by the choice of an appropriate position calculation algorithm. The signal measurement method utilized in this research is the Received Signal Strength (RSS) method. The RSS method is a popular technology due its high availability and reduced cost [27]. Also, its implementation does not require any additional devices [35]. This method is based on the measurement of strength of the signal when being received [36]. Whereas the distance travelled by a signal from a transmitter to a receiver can be estimated through the difference between the strength of the transmitted signal and received one. This is based on the fact that the power or strength of electromagnetic waves transferred from a transmitter to a receiver decreases as the distance between them increases. This inversely proportional relation is modelled using what is called by a path loss model. A path loss model is a signal propagation model that is used to convert the value of the received signal strength into distance based on modelling the signal attenuation through space [37]. The path loss model equation used in this research is as follows [28];

$$RSSI = -\left(10\, n_{cal} \log_{-}(10)\;\; d + A\right) \tag{1}$$

Where; Parameter A defines the absolute energy, represented by dBm, at a distance of 1 m from the transmitter, which is RSSI reading at 1 m from the transmitter. n_{cal} is the signal transmission constant, and it is dependent upon the signal transmission environment. d is the distance from the transmitter node to the receiver node.

The output of the signal measurement phase is distance between reference and target nodes. With regard to the position calculation phase, trilateration technique is utilized in this research as the position calculation algorithm. Using this technique, coordinates of the target node are calculated using distance of the target node from at least three reference nodes, and the coordinates of these reference nodes with respect to a specific referencing system [38,39]. It is worth mentioning that distances between target node and reference nodes are calculated in the signal measurement phase. Fig. 2 depicts the flow and transfer of data through the positioning module in the proposed model. Whereas target nodes transmit Bluetooth signals which are received by reference nodes. The strength of these signals is measured by reference nodes (receivers) and through the utilization of a path loss model, the value of the received signals at every reference node detecting the target node, is converted into distance. Then, the distances between target node and three different reference nodes (at least) are used, along with the coordinates of these reference nodes, to calculate the coordinates of the target node through trilateration equations. It is worth mentioning that all the details concerning the implementation of positioning module in the proposed model; such as the path loss model used, the boards and sensors used as target and reference nodes, etc. are explained thoroughly in case study section hereinafter.

As shown in Fig. 2, the output of this module is the coordinates of the target nodes, which indicates coordinates of building occupants in the proposed model. The coordinates are in the form of x, y coordinates. This location data is imported into MassMotion software using comma separated value (csv) file as the interface for data transfer.

Concerning implemented system components; ESP32 D1 R32 boards are used as receiving gateways (receivers or base stations). Whereas they calculate the RSSI of the signals received and thereby calculates the distances of the transmitters allowing for the localization of the objects meant to be localized. The path loss model equation (Equation (1)) is implemented on the board using Arduino programming language. With regard to transmitters, Bluetooth beacons named iB004-N, and supported by “Ankhmaway” [40] are used in this research. These beacons are given to the individuals who are planned to be localized inside the building. Each Bluetooth beacon has a unique identifier and sends radio frequency signals continuously to any connected base station in order to be localized. For beacons to be detected by the boards, their Bluetooth ID has to be coded into the Arduino code, for the board to detect only the needed beacons and not all the present Bluetooth transmitters (mobile phones or other devices emitting Bluetooth signals). Fig. 3 shows implemented system components.

3.3. Agent based simulation module

The purpose of this module is to model the evacuation process while incorporating realistic data into the developed model to reach a realistic output. Some of the data incorporated into the model are the outputs of the other previously mentioned modules and others are not. The inputs of previously mentioned modules are 3D BIM model and occupants’ location data. Other inputs to the model include agents’ attributes as body radius, velocity and pre-movement time. Pre-movement time refers to the time taken by evacuee to become aware of the incident and respond accordingly [41].

3.4. Dynamic signage module

The purpose of this module is to convert the optimum route generated by the agent based simulation software into directions which are presented on virtual signs. Unlike traditional signage system where building exit signs remain unchanged, the developed signage system is dynamic; which means that the directions generated continuously change with the change of evacuation route produced from

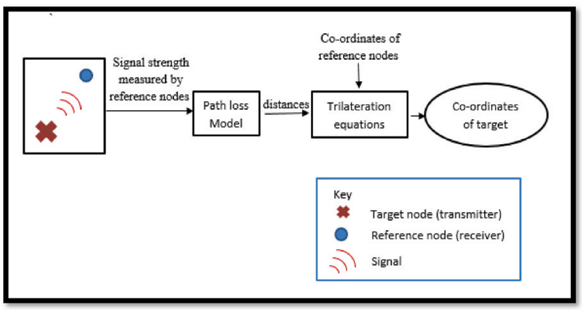


Fig. 2. Data flow through positioning module.

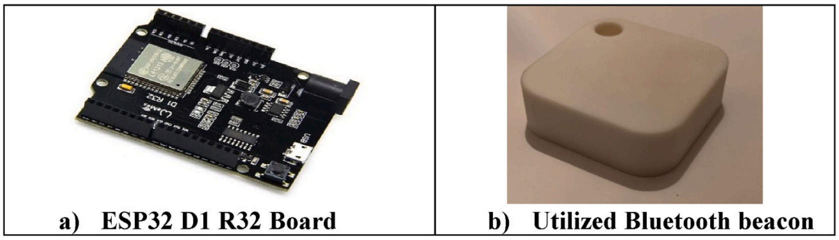


Fig. 3. Implemented system components.

the simulation software.

The optimum route generated through MassMotion is produced in the form of a comma separated values file (csv file) which is the main input of the Dynamic Signage Module. This file contains positions of all agents generated in the simulation at all times from start of simulation till the end at exit portals. Each record in the file indicates the position of a certain agent at a certain point in time. The file consists of a set of data as, agent ID, position of each agent in x, y and z coordinates and the simulation time in seconds. The other inputs of the dynamic signage module are the details concerning signs, whereas dynamic signs are assumed to be scattered among the area to be evacuated throughout all the possible evacuation routes. Details of these signs include; signs' coordinates, IDs and direction perpendicular to the direction of motion of agents towards each sign. This perpendicular direction is needed to generate directions from agents' positions extracted from MassMotion in the manner described thereafter in the next section.

In order to process the agents' positions file, a code is written in python programming language, in order to convert the x, y, z coordinates of agents into directions to be followed during evacuation process. Positions of signs assumed to be scattered throughout area modelled, are entered by the user in terms of x, y and z coordinates. Generally, the directions an agent followed are identified through changes its coordinates over time. Fig. 4 illustrates (on the top right corner) the co-ordinate system of MassMotion Software and the directions of increase of x, y and z axes. It is worth mentioning that, in MassMotion, agents move on the x-z plane. The agents' positions file contains huge amount of data, among which are lots of records and lots of frames that are not needed for the identification of directions followed by agents during simulation.

The records necessary for direction identification are those of the agents when they pass by the positions of signs originally entered by the user, at any point in time. So, the code starts with extracting those records from the original file, then putting them in a separate new csv file in an ascending order from smallest to largest point in time. Then, for each record in the new file, the ID of the sign at which the agent is present, is appended. Not only is the sign ID added to each record, but also, the direction which is perpendicular to the motion of agent towards that sign (which are inputs of the dynamic signage system). This perpendicular direction will then be used in the process of identification of direction to be plotted on the sign in the manner illustrated in the next paragraph.

In order to determine directions each agent followed over simulation time; the code utilizes the filtered data in the new file. Firstly, it checks the first record in the new list, then, it checks the next record having same agent ID, but different sign ID at a later point in time. This means this agent moved from sign 1 (present in the first record) to sign 2 (present in the following record). Then, the code subtracts the agent's position present in the first record from that present in the second record (the succeeding one). The resulting difference is in the form of x, y and z-coordinates (i.e., delta x, delta y, delta z). Then, for the first record, the code checks the perpendicular direction which was appended to the record. If it is the z-direction, then, sign of delta z is what identifies whether this agent turned left, right or moved straight, if the perpendicular direction is the x-direction, then, the sign of delta x is what identifies the direction taken by the agent and so forth. Once the direction is determined, it is appended to the first record, and this new data is added in a separate file.

For each direction generated, an image showing this direction is assigned, taking into consideration the configuration of co-ordinate system and direction of axes implemented in MassMotion. An illustrative example is presented in Fig. 5 explaining how directions are presented in this research. The figure shows a screenshot of a floor from MassMotion, for illustration purposes, signs (1),

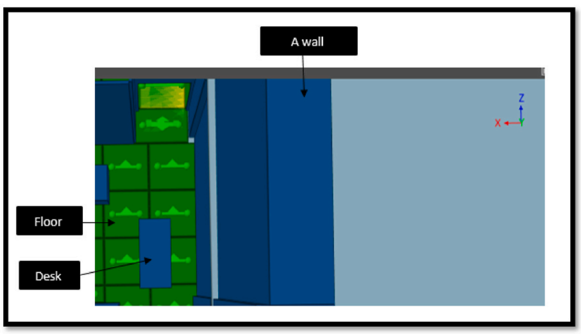


Fig. 4. Part of a MassMotion floor showing co-ordinate system calibration.

(2) and (3) are assumed to be in the positions shown in the figure.

As explained in the previous paragraph, the coordinates of this agent when crossing the first sign is recorded. Similarly, its coordinates when it crosses another sign, at a later point in time are also recorded, then both coordinates are subtracted from each other generating (delta x, delta y, and delta z). According to co-ordinate system of the program, the agent is moving in the direction of decrease of x-axis (i.e. –x direction), and the direction perpendicular to its motion is the z-direction. As a result, the sign of delta z is what indicates it moved to the right, left or straight, whereas, if the delta z was positive, this means that it turned left, and consequently, an image showing a left arrow appears. A negative delta z value shows that the agent turned right, and a right arrow appears. In the same manner, a delta z amounting zero indicates that the agent moved straight and a straight arrow appears.

After directions followed by each agent throughout the simulation time is identified, the appropriate sign plots the appropriate direction at the appropriate time. But, what if, at a certain time, there are group of people taking different directions, i.e., a person entered right, then seconds right after that, another one turned left, then another one turned right. In that case, the sign will show right then left then right again over a couple of seconds. This undoubtedly will confuse the people following that sign and will not be aware of what direction to pursue. In order to overcome this problem, performing further analysis on agents' positions file was a must. This analysis involves dividing simulation time into specified time intervals e.g., dividing a 1-min simulation time into six-time intervals of 10 s each, and then generating a more like an "average" direction for each sign, for each specified time interval. The code analyses the data in the following manner: firstly, it counts the number of agents taking every direction for each specified time span, then, stores number of agents pursuing each direction -in each time interval -in a list, arranged in descending order, from the largest to smallest.

Afterwards, any condition can be applied to that list according to the project under study. In this research, the condition developed is as follows.

– Since the code lists number of agents pursuing each direction and arranges them in descending order, the formula presented hereinafter is applied on such list to calculate a direction ratio.

$$Ratio = \frac{Highest\ number\ of\ agents\ pursuing\ a\ direction}{2nd\ \ highest\ number\ of\ agents\ pursuing\ another\ direction} \tag{2}$$

–if the ratio is more than 5, then the direction pursued by highest number of agents is the direction that will be plotted. Otherwise, both highest and second highest direction will be plotted, with the direction pursed by higher number of agents plotted using a larger arrow. For illustration, Fig. 6 presents how arrows having different directions are displayed using signage module which are the arrows plotted in case ratio is less than 5.0. The red arrows represent main direction, while the blue ones represent the auxiliary direction.

The aforementioned condition is just an example of the conditions that can be applied on aforementioned list. The reason for utilizing this condition in this research, since it was experimented on the case study and it produced good results. However, any other condition can be added to the code according to the user's preference and nature of the building being evacuated.

Following this, as per that condition and the analysis mentioned before, the average direction representing each sign, for each specified period is determined and listed in an output file offering the following information for each sign.

– The time interval upon which average direction is calculated (e.g., every 11 s of the simulation time).
– Average direction identified for every time interval concerning that sign.
– Point in time at which the average direction will be plotted on the sign.

4. Case study

4.1. Case description

This section presents the framework implementation on a case study. The case study is performed on a floor in Civil Engineering

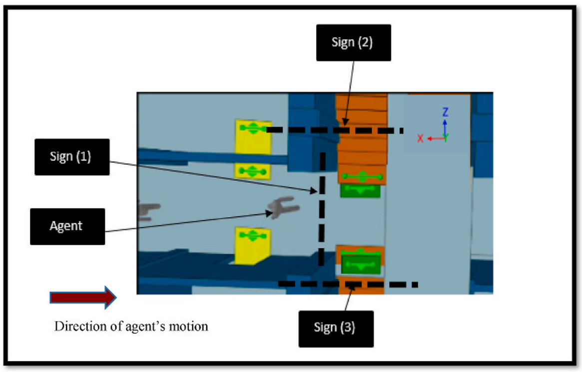


Fig. 5. Driving directions of signs.

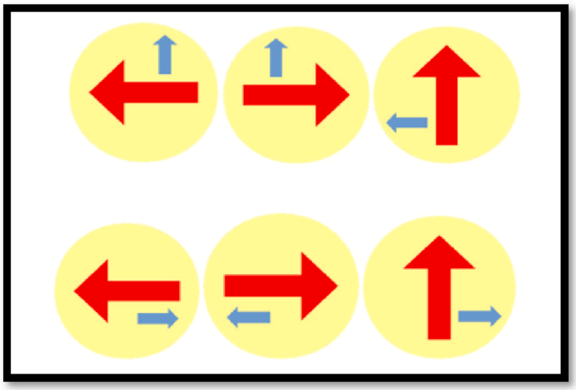


Fig. 6. Arrows showing multiple directions to be plotted on signs.

Building, Faculty of Engineering, Cairo University. The building was constructed in 1928. The case study experiment is performed through distributing a number of Bluetooth beacons all over the chosen floor, where the beacons represent evacuees, and then the deployed system calculates the beacon's positions, generates the optimum route for evacuation based on these positions, and finally displays this route as directions. The developed system is verified through calculating the system's accuracy and checking that it doesn't exceed the required accuracy. Additionally, it is validated by checking the final output, which is the generated directions, and observing whether they are generated in accordance with the input or not. The considered floor consists of 13 rooms; each room is given a code for illustration purposes. Fig. 7 illustrates the room codes, dimensions and accessible areas of the floor.

4.2. Running system modules

Firstly, with regard to BIM module, Leica Cyclone program is used to collect scans, register, and process them into a full consistent digital representation of the floor. Then, registered point cloud data is imported to Autodesk Revit using Leica CloudWorx plug in. Then, a 3D model of the floor is created through drawing objects in alignment with the registered point cloud data. Exit routes of the floor are also modelled on Revit. Fig. 8 shows an image of the 3D model of the floor and exits in Autodesk Revit.

As for the implementation of the positioning module, as a start, the layout of the receiving gateways to be utilized in the experiment is identified. This refers to the identification of the exact locations where the Esp-32 boards (receivers or reference nodes) are going to be put. The generated layout of the gateways has to guarantee that any beacon put in the considered floor has to be read by at least three Esp-32 boards for coordinates to be calculated using the trilateration equations. In this research, the layout developed, mainly enables beacons to be covered by four receiving gateways for a better accuracy during coordinates' calculation. During the layout planning process, cost is optimized such that no redundant gateways are put leading to increasing costs and no added value.

The layout planning process involves the application of two iterative steps: boards' space characterization, and BLE signals' transmission range check. As mentioned previously, path loss model is utilized to convert difference between transmitted and received power to distance between the transmitter and the receiver. This model needs to be calibrated for each room in the concerned floor,

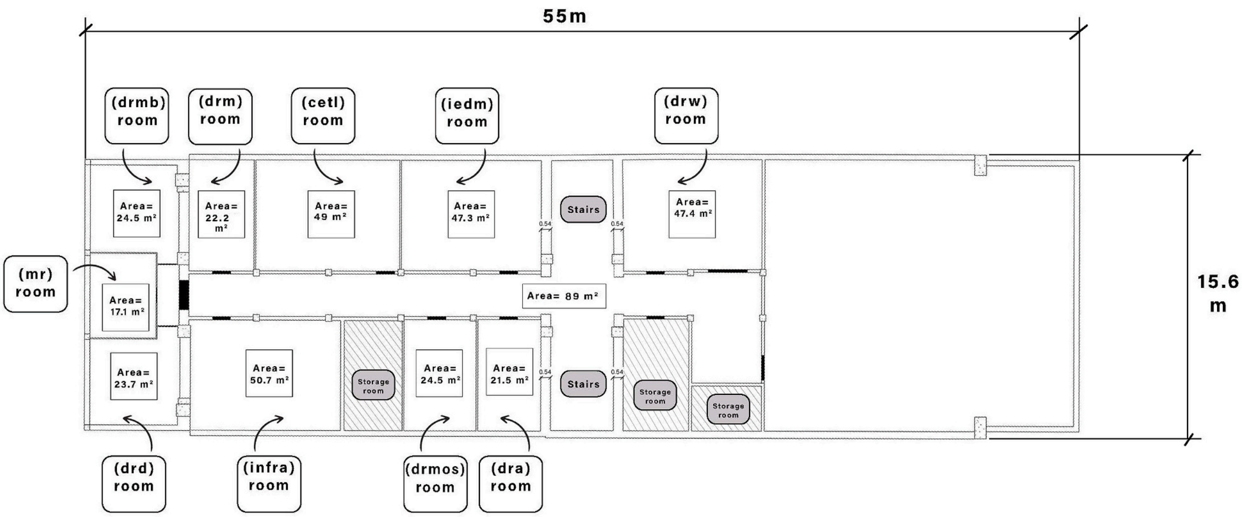


Fig. 7. Floor plan of the case study with rooms' areas.

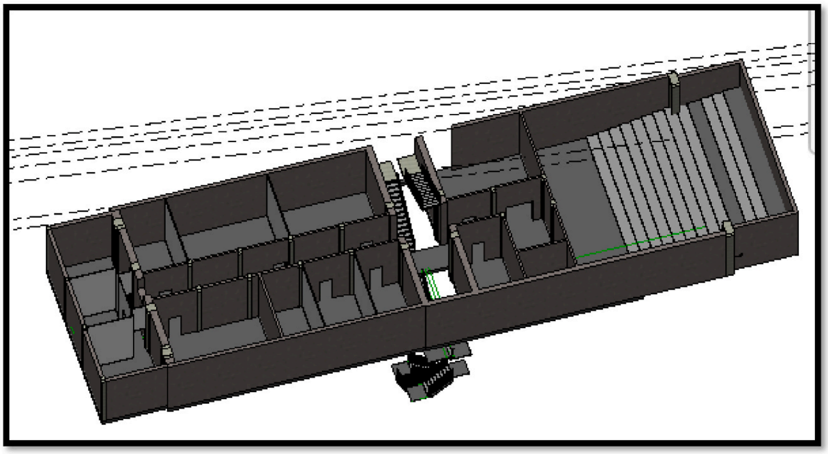


Fig. 8. 3D model of the case study in Autodesk Revit.

due to the fact that transmitted signals are affected by the nature of the environment through which the signals are passing, i.e., signal attenuation through thick walls is higher than the attenuation through thin ones. In other words, the intensity of Bluetooth signals is affected by the type, density and thickness of the obstructions or obstacles they are passing through [42]. So, the process of adjusting space parameters in the propagation model to be relevant to the propagation environment is named Space Characterization process, and it is the first step in the layout planning process.

The second step is Signals' transmission range check, which refers to the process of checking the coverage range of the Esp-32 boards experimentally, i.e., the range beyond which Bluetooth beacons are no longer detected by the board. This process is experimentally done without complete reliance on the range present in the board's or beacon's datasheet, due to the great discrepancies between data written on datasheets and the one identified by experimentation. This is also because of varying signal attenuation levels which change from room to room. These two steps are applied in a repetitive manner; leading to an incremental development of the gateways' layout. In other words, the two steps are undergone along with each other for full development of the layout.

The final gateway layout developed for the floor under consideration is shown in Fig. 9. An ID is assigned to each board on the layout. Thirty – two ESP-32 boards are needed to cover the area under study while achieving the condition that, any beacon placed in the area under study is read by at least three boards.

After the layout of gateways (sensors) have been established, and each sensor has been calibrated, the coordinates of any beacon in any area in the intended floor, can be calculated via trilateration equations which is implemented on a python code. The space characterization parameters for all the 32 boards utilized in the concerned floor is presented in Table 2.

Regarding the implementation of Agent Based Simulation module, it is worth mentioning that, for the simulation to start, there must be entry and exit portals for agents to enter and leave the simulation. Concerning exit portals, they were drawn at the building's exit. There are two exits for the floor under study of the building, one involving descending downstairs and leaving from the main gate of the building (Exit 1). The other one involves ascending upstairs to reach the upper floor (2nd floor), and then descending to the outside of the building through taking a back staircase connecting the 2nd floor to the outside of the building. As a result, two exit portals are drawn, one for each exit. The building exits are clearly shown in Fig. 10.

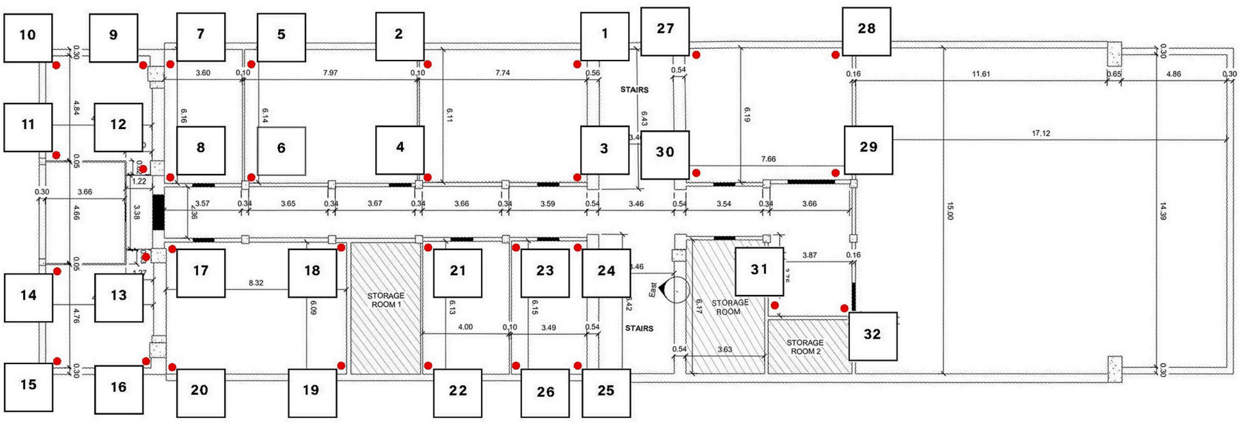


Fig. 9. Final gateway's layout with each Sensor ID.

Table 2
Space characterization parameters for the considered floor.

Sensor ID	A	n	Room code
Sensor 1	−53.667	2.642	iedm
Sensor 2	−53.667	2.642	
Sensor 3	−53.667	2.642	
Sensor 4	−53.667	2.642	
Sensor 5	−58.1333	2.2	cetl
Sensor 6	−53.667	2.5	
Sensor 7	−64.467	1.526	drm
Sensor 8	−64.4	1.879	
Sensor 9	−64.64	2	drmb, drmb
Sensor 10	−64.64	2	
Sensor 11	−64.64	2	
Sensor 12	−64.64	2	
Sensor 13	−56.733	3.184	drd
Sensor 14	−56.733	3.184	
Sensor 15	−56.733	3.184	
Sensor 16	−56.733	3.184	
Sensor 17	−55.667	3.417	infra
Sensor 18	−55.667	3.417	
Sensor 19	−55.667	3.417	
Sensor 20	−55.667	3.417	
Sensor 21	−55.8667	3.089	drmos
Sensor 22	−55.8667	3.089	
Sensor 23	−55.8667	3.089	dra
Sensor 24	−55.8667	3.089	
Sensor 25	−55.8667	3.089	
Sensor 26	−55.8667	3.089	
Sensor 27	−56.1333	2.794	drw
Sensor 28	−56.1333	2.794	
Sensor 29	−56.1333	2.794	
Sensor 30	−56.1333	2.794	
Sensor 31	−53.667	3.3	corr
Sensor 32	−53.666	3.089	

Regarding entry portals, they cannot have a fixed location since locations of agents are neither fixed nor known ahead, alternatively, they are continuously changing based on real people's locations calculated using the positioning module. This means that, for the system to operate as per its intended purpose, any location on the floor under study, shall be accessible so that any location calculated in the positioning module can be imported into the model. To achieve this, it was inevitable to transform the floor under study into set of adjacent portals, right next to each other, in a manner that there is no region, not even a small one, that is not covered by portals.

The size of the portals chosen to cover the floor was 1 m × 1 m, to achieve a balance between the effort required in scene construction and accuracy of the developed system. Fig. 11 shows the model after adding series of entry portals of size 1 m × 1 m each. Since, portals of very small size will be hectic to construct, and portals of very large size will trade off the accuracy of the system. It is to be noted that, there was a unique name given to each portal throughout the whole floor under study. Such unique identification is essential during interfacing between positioning module with ABS module.

Creating agents involves two main aspects: their personal properties or attributes and their locations. As mentioned in Chapter 3, agent properties include body radius and speed which are assigned through MassMotion, which are assumed as following.

- Body radius of agents = 0.25 m

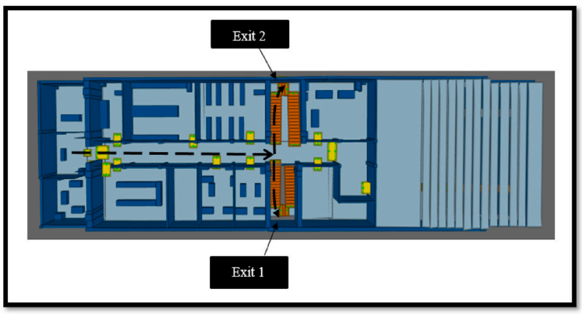


Fig. 10. Model of the 1st floor with building exits.

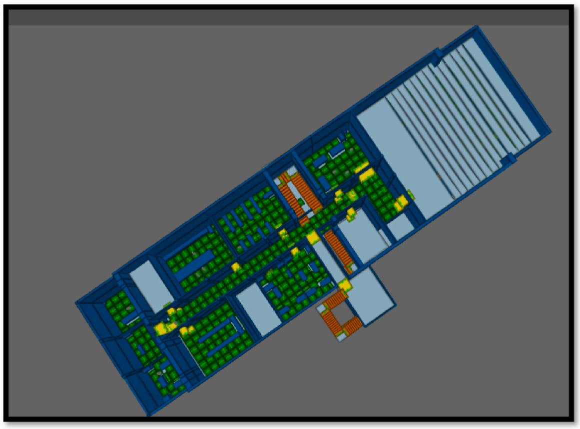


Fig. 11. MassMotion floor model after adding portals.

- Agents' speed distribution is as follows; minimum value = 0.65 m/s, maximum value = 2.05 m/s, mean = 1.65 m/s and standard deviation = 0.25
- Pre-movement time distribution is as follows; minimum value = 16 s, maximum value = 63 s, mean = 35 s, standard deviation = 16

The aforementioned assumptions concerning agents' body radius and speed were based on the preset values utilized on MassMotion based on references mentioned in the MassMotion user guide [12]. While the assumption of pre-movement time distribution was based on British Standards Institution (2004) [43]. The other aspect that is considered during creating agents is their locations. As previously mentioned, location data is calculated in the positioning module, whereas all the beacons' calculated coordinates are stored in the database. In order to import such locations into MassMotion, it was necessary to find out an interface that enables such integration.

Since agents enter the simulation through entry portals, it was inevitable to convert calculated coordinates into portals. Since each portal has a unique name and occupies a specific coordinate range (on both x and y axes), it was so easy to assign the calculated coordinates (of agents or beacons) to the appropriate portals, using a simple python code. This code also, counts the numbers of agents in each portal and puts them in a Microsoft Excel file, which is then imported into MassMotion.

Finally, regarding the implementation of the Dynamic Signage module, several input data is supplied to the module, this input data include.

- Positions of agents during the simulation, which is extracted from MassMotion model right after the agent based simulation ends.
- Positions of signs, which are shown in Table 3, along with the perpendicular direction to the agents' motion towards each sign. The locations of signs are presented in Fig. 12

4.3. System verification

In order to be able to verify the developed System, an experiment is performed, involving covering the area of the tested floor with beacons representing people or evacuees. A total number of 69 beacons were scattered throughout the floor in different locations. Table 4 shows the number of beacons put at each room.

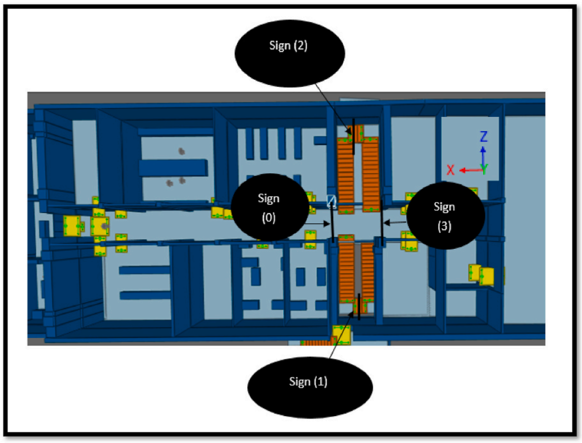
Fig. 13 shows one of the sensors put in one of (cetl) room corners during the experiment. It should be noted that the experiment was conducted during COVID-19 restrictions. So, it was impossible at the time of conducting the experiment to perform it with the aid of humans. Alternatively, beacons were scattered throughout the whole floor without human aid. This is considered a limitation of this case study implementation, since, effect of human body on RSSI was not included.

5. Results and discussion

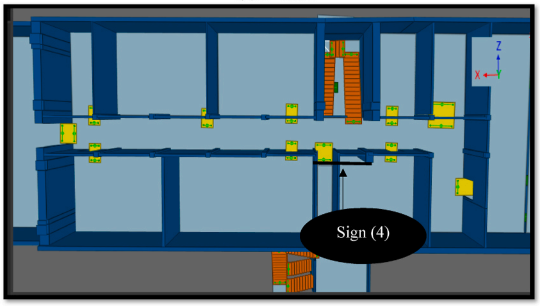
The results in this research was classified into three types; 1) the results from agent based simulation software which is the building evacuation time, 2) the results from the positioning module, which is the calculated coordinates of the 69 beacons scattered all over the

Table 3
Location of signs and perpendicular direction at each sign.

Sign ID	X	Y	Z	Perpendicular direction
0	30.568	0.019034	11.8196	z
3	24.568	0.019034	11.8196	z
2	28.6525	2.27297	17.9872	z
1	27.2657	−2.53	4.69139	z
4	27.3088	4.79186	11.7377	x



(a) 1st floor



(b) 2nd floor

Fig. 12. Location of signs of floors 1 and 2.

Table 4
Number of beacons put at each room.

Room Code	Number of beacons
drw	6
infra	9
iedm	16
cetl	15
drmb	5
drm	3
Mr	3
Drd	4
drmos	4
Dra	4

floor area, 3) the results of the dynamic signage module represented in the directions plotted and the times at which these directions are plotted. Firstly, the building evacuation time resulted from ABS module was 2 min and 48 s.

Concerning results of Positioning module and for its verification, positions calculated by the system are collected. The difference between actual coordinates of the referred beacons and the coordinates are calculated by the IPS. The results of all the 69 beacons show the following.

- The indoor positioning system accuracy = ±1.88 m
- Maximum error range = 3.934 m

Only five readings out of 69 readings show errors in the room in which beacons are present, and a single beacon was not read by the system, probably because of the beacon itself, since all other beacons in the same area were detected successfully by the positioning system developed. This means that around 93% of the beacons present (representing evacuees), were assigned to correct rooms. Fig. 14 shows snapshots from simulation at different times. The snapshots -especially the ones at simulation time of 30 s and 1 min-show that there is a bottleneck at region of diversion between two stairs.

Analyzing simulation results, it is found out that 52.9% of the agents (36 agents) were evacuated through exit 1, while the rest (32 agents) were evacuated through exit 2. This shows that evacuation was nearly evenly distributed throughout both exits, with exit 1

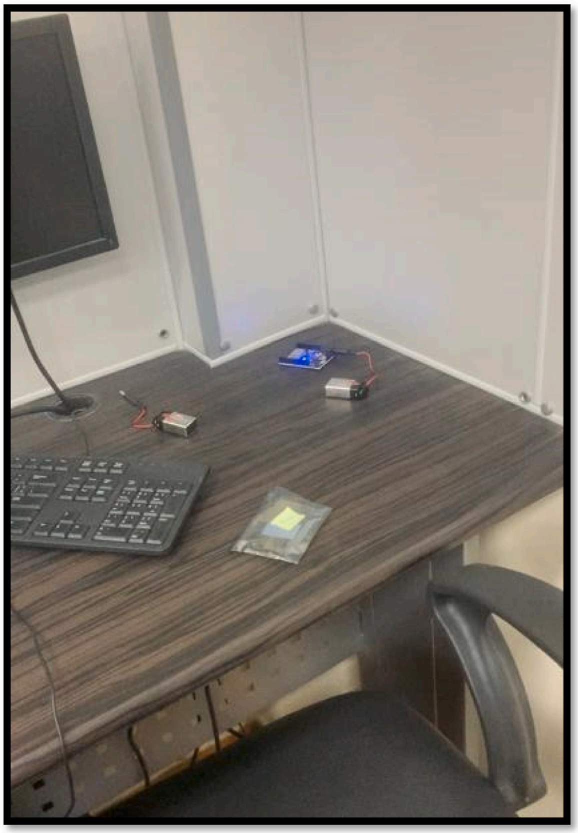


Fig. 13. An Esp-32 board put at one of the corners for (cetl) room.

having slightly higher percentage. As for the results of the Dynamic Signage module, results from the output file generated from the system are shown in Table 5. The table presents the "average" direction generated at each sign and the timing in which this average direction starts to show.

It can be observed that, signs (0), (2) and (4) shows directions at start of simulation and did not change throughout the simulation time. That's because they are static signs. Concerning signs (1) and (3), they are dynamically changing throughout the simulation. It can also be observed that sign (3) did not appear in the table except one time, particularly at 00:00:02. This indicates that this sign plotted only one direction (left direction) from 00:00:02 till end of simulation. Regarding sign (0), it plotted three directions over simulation time; one at 00:00:02, another at 00:00:13 and finally at 00:00:24. The last time a change in direction is observed on sign (0) was at 00:00:24, indicating that this direction (right direction) was plotted on the sign from that point in time till end of simulation.

Last but not least, with respect to the scalability of the developed indoor positioning system, it is noteworthy that the coverage range of the utilized boards (base stations) is around 10 m. However, system transmission range can be increased in case other hardware devices are utilized. Whereas the coverage range of BLE based positioning systems can reach up to 30 m [44,45]. With respect to the dimensional space of the developed positioning system, it is worth mentioning that it can read locations within the two-Dimensional space.

6. Conclusion

This research created a comprehensive evacuation model that combines agent-based simulation, indoor positioning technology, and building information modelling (BIM) in order to determine the optimum path that evacuees should take based on their current locations. The suggested architecture localizes evacuees, pinpoints the ideal path for their secure escape, and then plots directions of the chosen path on virtual signs via a dynamic signage system. To validate the proposed framework, a real-world case study was performed. This research outperforms over previous work in evacuation modelling domain mainly because of the comprehensive integration between the following aspects; employing real world data into evacuation model, represented in geometric and spatial details of building under study which is input through BIM, personal attributes and behaviors of people represented in the utilization of ABM, and real locations of evacuees represented in their location identification through BLE based IPS and inputting them later into the model. Additionally, the optimized route(s) generated from the realistic evacuation model created, is converted into directions and presented on virtual signs through the signage system which is changeable as per any change in the model (change in people's locations, change in density of building inhabitants, etc.).

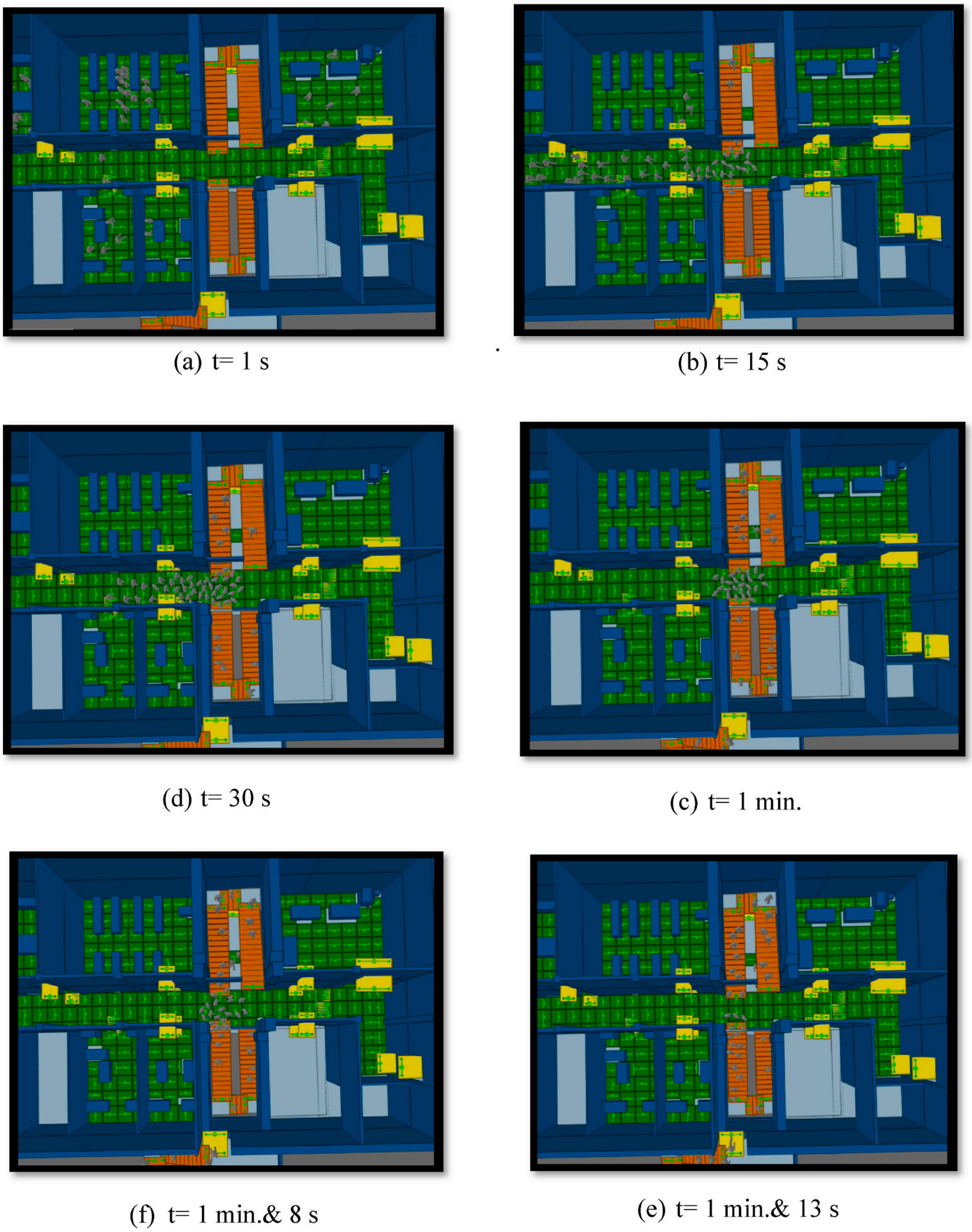
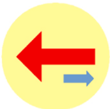
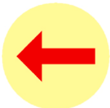
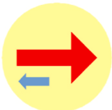
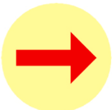


Fig. 14. Snapshots from simulation at different simulation times.

On the other hand, despite the contributions added to the body of knowledge through this research, there were some limitations for it. Firstly, concerning signage system, in case system is practically implemented using actual signs, people may get confused during evacuation since signs address multiple people at the same time. For example, if a sign shows a big arrow pointing right and a small one pointing left, people may not know what this dual direction indicates. This can happen in case evacuees have no proper knowledge of the system and of different signs' indications. However, such limitation can be overcome through presenting an orientation to building users to familiarize them with signage system implemented and what do signs indicate. In addition to that, this study did not consider the effect of the evacuees' blurring vision or respiratory distress caused by the smoke emitted in case the emergency incident is fire. This research can be extended in the future to study effect of smoke on evacuees and incorporate it into the framework. Additionally, the developed framework did not consider the location of source of hazard since it was not oriented towards a specific hazard per se. So, it is recommended, in case they are addressing an emergency incident of gas leak or fire, to consider the location of the source of

Table 5
Results of Dynamic Signage module.

Direction	Sign ID	Time of showing direction
	1	00:00:00
	2	00:00:00
	4	00:00:00
	0	00:00:02
	3	00:00:02
	0	00:00:13
	0	00:00:24

hazard and how can the location of hazard affect the evacuation route. Also, it is suggested that the process of evacuees' guidance of the optimum evacuation route can be enhanced in the future by incorporating a voice guidance system to the developed framework.

Author statement

Pakinam Elsayed: Conceptualization, Methodology, Investigation, Software, Validation, Writing- Original draft preparation. Hassan Mostafa: Conceptualization, Methodology, Supervision, Writing- Reviewing and Editing. Mohamed Marzouk: Conceptualization, Methodology, Supervision, Project administration, Investigation, Validation, Writing- Reviewing and Editing.

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.

Data availability

Data will be made available on request.

Acknowledgment

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