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Developing an evacuation evaluation model for offshore oil and gas platforms using BIM and agent-based model

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ABSTRACT

Accidents on offshore oil and gas platforms (OOGPs) usually cause serious fatalities and financial losses considering the demanding environment where such platforms are located and the complicated topsides structure that the platforms have. Conducting evacuation planning on OOGPs is challenging. Computational tools are considered as a good way to plan evacuation by emergency simulation. However, the complex structure of OOGPs and various evacuation behaviors can weaken the advantages of computational simulation. Therefore, this study develops a simulation model for OOGPs to evaluate different evacuation plans to improve evacuation performance by integrating building information modeling (BIM) technology and agent-based model (ABM). The developed model consists of four parts: evacuation model input, simulation environment modeling, agent definition, and simulation and comparison. Necessary platform information is extracted from BIM and then used to model the simulation environment by integrating matrix model and network model. In addition to essential attributes, environment sensing and dynamic escape path planning functions are developed and assigned to agents in order to improve simulation performance. Total evacuation time for all agents on an offshore platform is used to evaluate the evacuation performance of each simulation. An example OOGP BIM topsides with different emergency scenarios is used to illustrate the developed evacuation evaluation model. The results show that the developed model can accurately simulate evacuation and improve evacuation performance on OOGPs. The developed model is also applicable to other industries such as the architecture, engineering, and construction industry, where there is an increasing demand for evacuation planning and simulation.

1. Introduction

Accidents on offshore oil and gas platforms (OOGPs) usually cause acute fatalities [1] and financial losses as OOGPs have demanding environment and oil and gas production is a difficult and potentially dangerous operation. The demanding environment includes limited accessibility and danger of encountering hurricanes, massive waves, and storms. Drilling and processing oil and gas turn offshore platforms into a high-pressure, inflammable, and dangerous environment with frequent accidents, including a gas leak, fire, explosion, blow out, structural failure, and adverse weather condition [2,3]. According to the historical records, the deadliest offshore platform accident was the Piper Alpha disaster in the North Sea [4], in which 167 people died. In 1982, the accident on Ocean Ranger Oil Rig in North Atlantic Sea capsized and killed 84 people due to a powerful storm with 190 km/h winds and 20 m high waves [5]. Another example is one of the latest accidents happened in 2010 at Deepwater Horizon Oil Spill, which caused an explosion and severe oil leak and 11 people died in Gulf of Mexico [6]. Therefore, effective emergency response planning is important and necessary to improve safety management on offshore platforms.

Evacuation during these emergency circumstances is one of the most significant aspects to be considered when evaluating the safety management of OOGPs. Conducting evacuation planning is a challenging task as OOGPs are built on sea using complex structures and workers cannot simply escape from the OOGPs during an emergency [7]. Compared to buildings, evacuation on offshore platforms faces more limiting conditions as platforms locate on the sea and contain congested working space. In addition, the facilities (functional modules) on offshore platform have higher possibility of catching fire, which makes evacuation on offshore platforms more challenging. Therefore, in order to well simulate such dynamic environment changes, the possibility of catching fire (risk level) of each module is also required. These risk levels for functional modules can be obtained

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by analyzing historical accident database of similar modules from other offshore platforms. Offshore oil and gas platforms usually have Escape, Evacuation, and Rescue (EER) plans and resources to protect personnel in the event of a major accident [8–10]. EER addresses the entire process based on which personnel is removed from a major accident event to an ultimate place of safety. Escape means people move away from a dangerous situation to a safe place; evacuation means people are leaving hazard zones following the planned method; and rescue is the process that people move from a temporary safe place to a place of safety where medical assistance is available [11,12]. 2D escape routes planning and escape drill exercises [10] are important parts of EER programs. However, evacuation plans based on 2D escape routes only provide simple accessible paths without considering potential changes of evacuation environment. In addition, 2D evacuation plan may also cause different understanding of the emergency response. Although the escape drill exercise is a useful approach to evaluate the efficiency of the escape paths and to provide workers with a detailed understanding of emergency response on OOGPs, escape drill usually costs extra time and workforce, and can cause safety issues as OOGPs have limited working space and extreme environment around them.

Computational tools for emergency evacuation simulation and design have advantages over the traditional practices of 2D escape routes and evacuation drill exercises. Unlimited emergency scenarios, evacuation plans, and escape drills can be simulated and evaluated with the help of computational simulation models. Agent-based model (ABM) is one of the common computational models used to simulate the actions and interactions of people under emergency in the simulation. To generate the simulation environment efficiently, building information modeling (BIM), considering the rich geometric and semantic information it provides, has been increasingly popular in the modeling of simulation environment. Therefore, this study develops a model based on BIM and ABM to conduct evacuation simulations in a 3D virtual environment and to evaluate and improve safety management on OOGPs. BIM is used to set up the 3D virtual environment as it contains geometric and semantic information of OOGPs. ABM is used to simulate evacuation behaviors including basic attributes and social behaviors of all agents. The evacuation performance of each new scenario is evaluated by the total escape time.

The rest of this paper is organized as follows. Related works are reviewed in Section 2. Section 3 introduces the developed model. Detailed development of the proposed model is also included in this section. An example with evacuation simulation results is used to illustrate and evaluate the proposed framework in Section 4. Section 5 concludes the paper.

2. Literature review

2.1. Offshore emergency response

Well planned offshore emergency response is critical to OOGPs, and much research effort has been made to achieve a satisfactory emergency response. For example, Musharraf et al. [13] used a virtual environment to assess offshore emergency evacuation behaviors by using Bayesian Network approach. In this study, behavior indicators were measured to evaluate unobservable performance influencing factors like moral, motivation, and attitude which play a major role in shaping the evacuation performance. In addition, human error for critical steps in the escape, evacuation, and rescue (EER) process on offshore installations has been identified and evaluated using the framework proposed by Deacon et al. [14]. Norazahar et al. [15] also proposed a framework to address and discuss the contribution of human and organization aspects to the evacuation operations of the Deepwater Horizon Oil Spill [6], which is the latest offshore accident that has also been studied by Skogdalen et al. [9]. Escape and evacuation sequence from this accident was reviewed based on the testimonies from the survivors. Skogdalen et al. concluded that emergency drill exercises, including the worst-case scenarios to prepare for EER operations during offshore accidents, are important. Current studies pay more attention to learning lessons from offshore accidents and are suggested to improve the EER system such as conducting evacuation drills considering the worst scenarios. However, how to improve offshore evacuation performance in a more preventive and predictive manner, for instance, evacuation simulation using computational tools, is still lacking.

2.2. Evacuation simulation using agent-based model

Agent-based modeling (ABM) is a relatively new modeling paradigm for simulation of real-world systems. In ABM, every individual agent has certain attributes and behaviors controlled by decision rules and is persistently interacting with other agents in an environment to pursue specific goals [16–18]. Considering the advantages of low cost and risk to simulate various emergency scenarios for unlimited times, ABM is commonly used to simulate and evaluate evacuation plans. Previous studies [19–23] have used ABM or integrated ABM with Fire Dynamics Simulator (FDS) to study the human evacuation behaviors under fire emergencies. In addition, to improve the simulation performance, social behaviors in emergencies were investigated in [24–27]. Simulation environment modeling is an important part of ABM-based evacuation model development. Matrix-based model (also referred to as cell decomposition model) and network model (also called roadmap model) are commonly used in the reviewed ABM-based evacuation studies. In a matrix-based model, the simulation environment is divided into grids or nodes with defined attributes, which can easily store and collect environment information during simulation. However, the accuracy of escape path generated using search algorithm such as A* is heavily dependent on grid size, which has a direct impact on the computing time. In the network model, the optimized evacuation path can reflect real escape path better, but the environmental information is challenging to be represented. The two models are demonstrated in Fig. 1.

2.3. Path planning using visibility graph

Visibility graph (VG) is a graph of intervisible vertices among multiple polygons in the Euclidean plane, which is commonly discussed in computational geometry [28] and used for robot motion planning. As mentioned in Section 2.2, network models take advantages over the matrix models when planning the escape path. Therefore, visibility graph is applied in the development of the evacuation model in this paper. Traditional global path planning algorithms using visibility graph usually search for a path after a complete visibility graph is constructed [29–33]. However, it is very time consuming to construct a complete visibility graph, and path optimization efficiency is drastically decreased when edge number of the obstacles increases [34]. Algorithms have been proposed by previous studies to reduce the computational time. For example, Huang and Chung [35] and Zhang et al. [36] improved the efficiency of path planning by ignoring redundant obstacles that have no impact on the optimal path. Nguyet et al. [37] and Ping et al. [38] reduced the number of the visibility edges by simplifying obstacles to a rectangle or combining tiny obstacles. Other studies such as Lv et al. [34] tried to construct visibility graph and search the path simultaneously. All reviewed VG-based path optimization methodologies only considered static path planning. The Euclidean plane, including the obstacles and start position, is assumed to be unchanged during path planning. However, the constructed visibility graph is likely to change during emergencies such as fire accidents and structural failures. The changes can be caused by fire, collapsed facilities blocked, and herding behavior at a certain exit.

2.4. BIM application on emergency response

In the architecture, engineering, and construction (AEC) industry, building information modeling (BIM) has been increasingly used for the

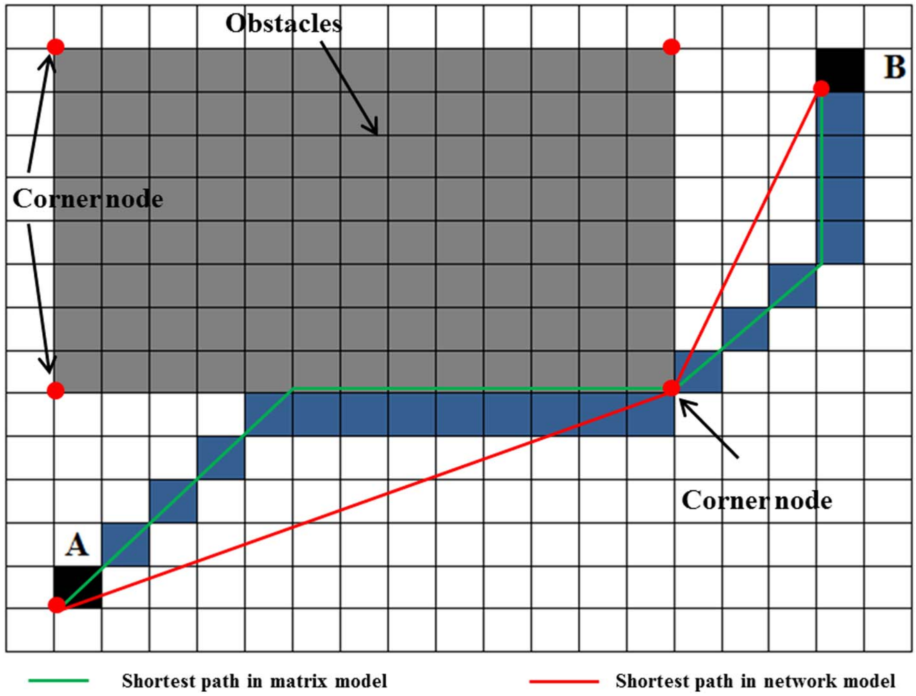

Fig. 1. Difference between matrix and network models.

past decade. BIM can provide a 3D digital representation of building structure (with accurate geometric and semantic information) and be integrated with ABM for efficient emergency simulation. A few studies have applied BIM for emergency simulation in the AEC industry. For example, Wang et al. [39] proposed a BIM-based model to support fire safety management, including evacuation assessment, escape route planning, safety education, and equipment maintenance. Since BIM can provide rich information about buildings, integrating BIM and fire dynamic simulation (FDS) software has also been studied. Wang et al. [40] integrated BIM and FDS software by using a .dwg file, exported from Revit, as the input file for FDS software. Shi and Liu [41] presented a powerful platform, which integrated BIM, 3D GIS, and FDS software, to simulate occupant evacuation in the fire environment. In addition, a new serious gaming approach based on BIM was presented to study the effect of building condition on human behavior during evacuation [42]. Zhang and Issa [43] proposed a BIM-based Immersive Serious Gaming environment to simulate evacuation to solicit behavior decisions made by players. As locating trapped occupants during a fire emergency is also meaningful, Li et al. [44] designed an environment beacon deployment algorithm to support a sequence based localization scheme. BIM has also been applied to the oil and gas industry, for instance, in supporting LNG construction projects by 4D BIM [45] and in supporting OOGP decommissioning by BIM applications [46–49]. However, BIM-based safety management studies on OOGP emergency responses are still lacking. More efforts should be made to take advantage of the BIM technology to facilitate emergency response study on OOGPs.

2.5. Review summary

After reviewing related work on emergency response with various technologies in both the AEC and oil and gas industries, it is believed that the safety management on OOGPs could be improved after conducting following activities:

- Modeling simulation environment by integrating both matrix and network models;
- Developing a dynamic escape route planning module based on visibility graph;
- Setting up evacuation simulation using BIM technology; and
- Simulating evacuation drill exercises.

3. Model development

A BIM-based evacuation model for OOGPs is developed and shown in Fig. 2. The BIM-based evacuation model for OOGPs consists of four main parts: (1) evacuation model input, (2) simulation environment modeling, (3) agent definition, and (4) simulation and comparison. The evacuation model input part (Part 1) is based on BIM models of OOGP topsides, which contains dimensions, locations, and semantic information of all functional modules on topsides, where required information is extracted and simplified. In simulation environment modeling (Part 2), based on the information obtained from Part 1, simulation environment is modeled by integrating matrix and network models. Accidents generator is also defined in Part 2 to set up various scenarios. The agent definition part (Part 3) is based on the modeled simulation environment. Basic attributes, environment sensing function, and dynamic escape path planning are involved in this part. Based on Part 3, multiple agents with defined attributes can be generated. By integrating the multiple agents with the modeled simulation environment, different emergency scenarios, and people's behaviors during emergencies can be simulated and evaluated. The improvement of safety management on OOGPs using the developed model can be verified based on the results of different simulations. The details of these four main parts are introduced and discussed in the following sections.

3.1. Evacuation model input

For the past decade, BIM plays an increasingly important role in the architecture, engineering, and construction (AEC) industry considering the rich geometric and semantic information it contains. The digital representations applied through the lifecycle of building projects enable an early involvement of the AEC industry. Even though BIM has been applied to support design, construction, operation, and demolition of buildings [50–54], BIM applications to the oil and gas industry, especially for offshore platforms, are still limited. Industry Foundation Classes (IFC) is currently the main neutral file format for data exchange

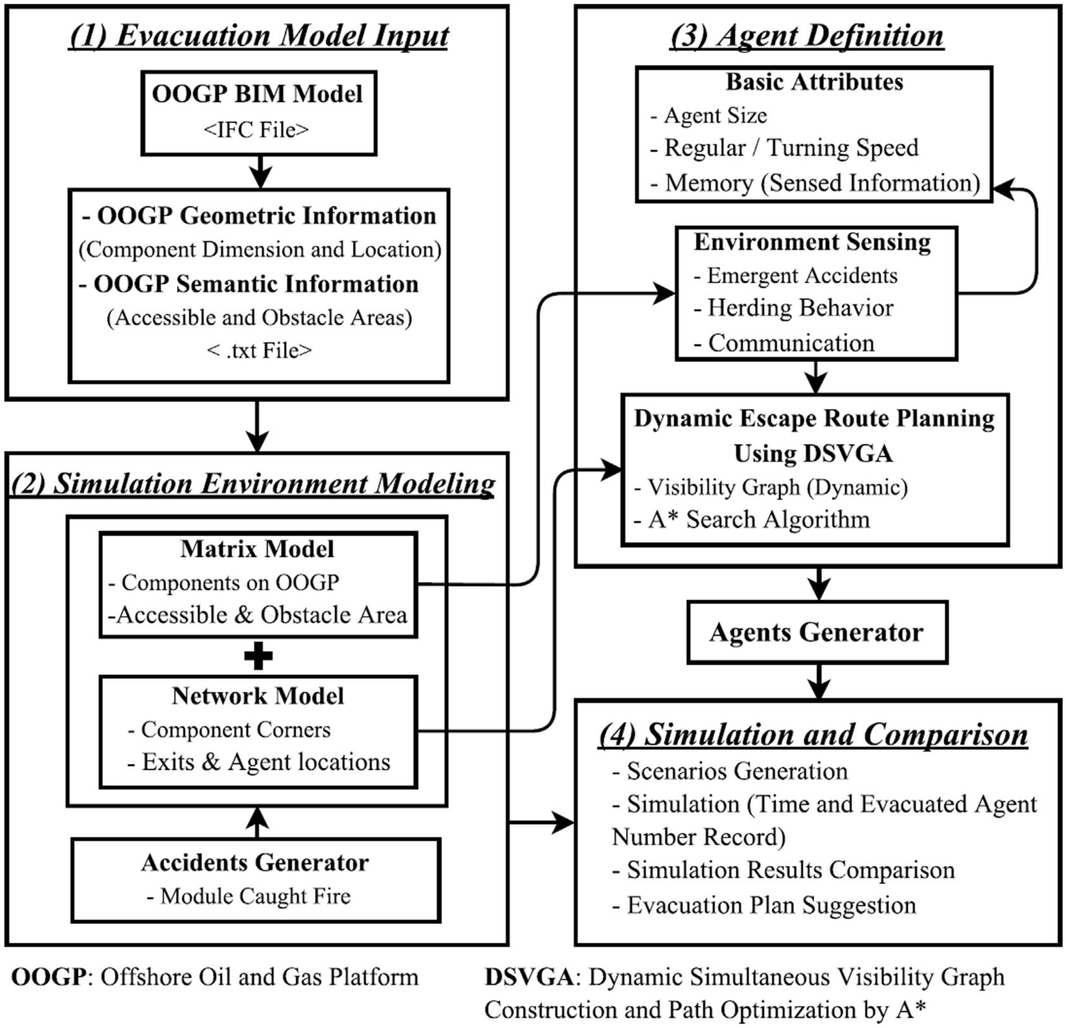

Fig. 2. The developed BIM-based evacuation model for OOGPs.

among AEC/FM software [55]. IFC is designed to represent as much building information as possible through the life cycle and facilitate the data exchange among different BIM-supported software. However, IFC has not been extended to the oil and gas industry completely. *IfcBuildingElementProxy* [56] is usually used to represent elements that have not be defined in IFC entities. The utilization of *IfcBuildingElementProxy* can be obtained by referring to the previous study [49].

3.1.1. Information extraction and simplification

The OOGP BIM model used in this paper has a high level of detail, and the functional modules on topsides can be visualized with detailed features. When conducting evacuation simulation, these functional modules are usually considered as obstacles in the simulation environment. Bounding box approach is commonly used to represent obstacles in a simulation environment. The smallest box that covers all components in a module is obtained by using the extraction and simplification methodology developed in previous study [49]. The purpose of obstacle simplification is to facilitate information input for evacuation model setup. The extracted and simplified results include the length, width, height, and location coordinates of all modules on topsides. In addition to geometric information, semantic information is also extracted. In this study, the considered semantic information is risk level for each module depending on its function. Since escape path will pass by different modules, the risk of exposure to modules will impact evacuation performance. The output of information extraction and simplification is a text file that contains eight attributes (*id*, *x*, *y*, *z*, *l*, *w*, *h*, *r*) for each module and the file is used as the input for evacuation simulation environment modeling. Here, *id* is to identify each module, *l* is the length, *w* is the width, *h* is the height, *x*, *y*, and *z* are the location coordinates, and *r* is the risk level for each module. The risk level of each module is obtained by analyzing historical accident database of offshore platforms. The obtained risk level is then assigned to newly developed property *Risk Level* for each OOGP module in BIM models. An example output format can be seen in Fig. 3.

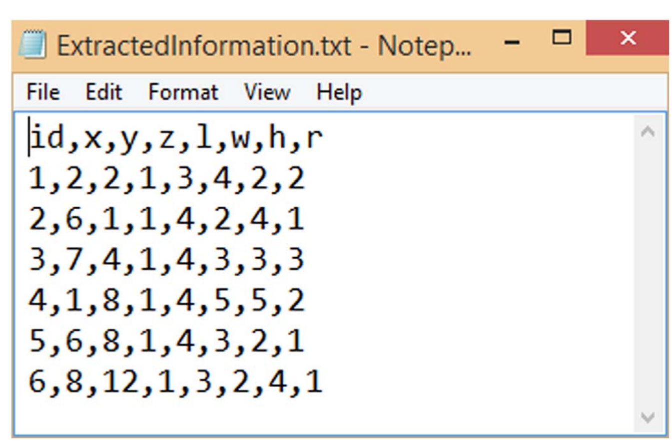

Fig. 3. An example of information extracted from BIM.

3.1.2. Topsides deck transformation

There are many types of offshore platforms around the world, and each type usually has common structural and functional features. Fixed platforms with functional modules supported by steel jacket that fixed directly on the seabed are used in this study. Topsides usually have more than one deck to support various functional modules and these decks installed at different levels are connected by stairs. When conducting evacuation simulation, it is difficult to plan escape paths on multiple levels simultaneously especially when interaction among different levels is required. Therefore, before inputting the extracted and simplified OOGP information to develop the evacuation model, all the decks located at different levels are put to the same level with necessary connections among each other. During the deck replacement, the coordinate transformation is required to guarantee the relative locations of all modules on each deck are not changed. The transformation includes rotation and shift. First, all the coordinates ($x_0{}^i$, $y_0{}^i$, $z_0{}^i$) of modules on deck will be multiplied by -1 to rotate the deck by 180 degrees around deck centroid (x_c, y_c, z_c). Then, the expected coordinate of deck centroid (reference point) (x_t, y_t, z_t) is obtained. The coordinate difference ($\Delta x, \Delta y, \Delta z$) of deck centroid after being transformed can then be obtained and added to all other coordinates ($x_0{}^i$, $y_0{}^i$, $z_0{}^i$) of modules on deck to finish the shift. One example of topsides with two levels of decks is used to show how the deck transformation works (see Fig. 4).

3.2. Simulation environment modeling

The simulation environment is the basic requirement to conduct and evaluate different evacuation scenarios. Therefore, simulation environment modeling is usually considered at the beginning of simulations. The target of simulation environment modeling is to transfer real environment into readable virtual representation formats that can be read and operated by computer programs. Virtual representation formats can be both two dimensions and three dimensions. According to the reviewed evacuation simulation studies (see Section 2.2), multiple models or representation formats can be used to model simulation environments. Matrix model and network model are two commonly used models. As pointed out in Section 2.2, a matrix model has the advantages of implementation and environment information collection as each cell or grid can store predefined attributes to represent surrounding dynamic changes. However, the cell or grid size has an impact on escape path accuracy and computational time, and it is challenging to determine the size. A network model can generate a path that is closer to reality, but collecting dynamic environment changes is difficult. Therefore, it is believed that the integration of both models can provide a better simulation environment. In the following sections, details of each model development and their integration will be presented.

3.2.1. Matrix model generation

The main task of using a matrix model is to divide the simulation environment into cells (or grids, nodes) with proper sizes. Previous research [22,57] have studied grid size determination. A 0.4 m × 0.4 m space, which is the average space size of a person occupied, is used. The reason to consider a person's size on the divided cells is to locate person and search escape path during evacuation simulation. Besides, another common issue considered is to avoid persons occupying the same cell during an emergency. In this paper, the cell size is determined only from the perspective of environment dynamic changes recording. As for person size and person overlapping, the model development platform used in this study namely Unity 3D allows users to define 3D physical person models. A person can easily be located, and no person overlapping would happen as the created person models cannot go through each other. More details of person (or agent) definition are introduced in Part 3. Since dimensions and relative locations of real topsides environment including functional modules that are treated as obstacles have already be extracted, simplified, and written into a text file from Part 1, simulation environment can be easily modeled as a matrix format. An example matrix model is presented in Fig. 5.

To use the generated matrix model to collect dynamic environment changes during evacuation simulation, each divided cell is assigned with necessary attributes that can be updated over time. The attributes defined in this paper include accessibility and risk level. The accessibility attribute is used to determine whether a cell is accessible or not. Accessible cells allow persons to pass through, while inaccessible cells do not. Cells occupied by functional modules (obstacles) and crowded people (herding behavior) are usually inaccessible. The risk level attribute is used to represent how dangerous the area is. During emergencies like fire accidents on topsides of offshore platforms, if a certain module caught fire, the accessible areas around it would become dangerous. Sometimes, when these dangerous areas were used during an emergency, the escape time could be saved, but a person might have a higher level of exposure to fire damage. Therefore, the performance of evacuation plans that use these dangerous areas will be affected. Agents are expected to avoid passing through these dangerous areas.

3.2.2. Network model generation

In building indoor evacuation planning, a network of potential escape paths is usually generated based on building floor plans. Those potential paths will be optimized according to some constraints, and an optimal escape path can be obtained [58]. Different methodologies can be used to generate a path network and four most commonly used ones, including door to door, room to door to room, straight skeleton, and corner graph, were summarized by Rüppel et al. [59]. For example, room to door to room methodology means using central points of rooms and doors to generate a route network. This study aims at improving evacuation performance on topsides of OOGPs, which contain different

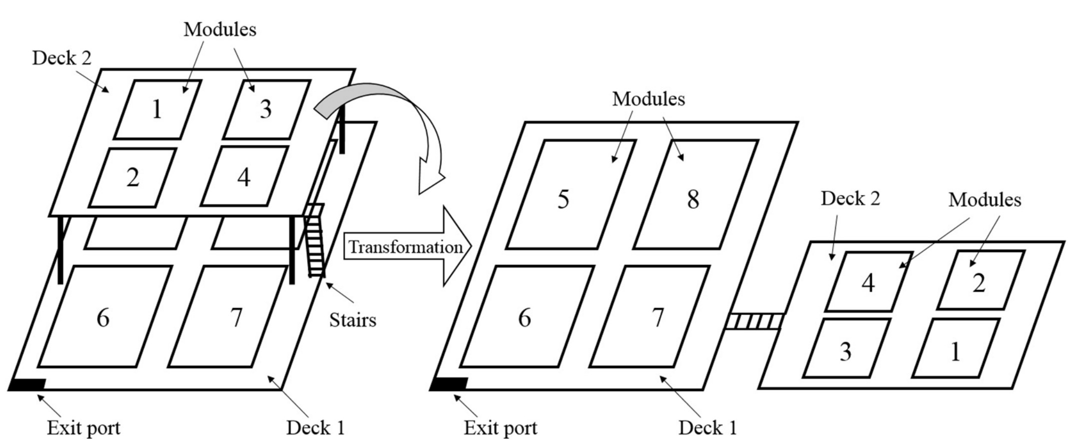

Fig. 4. Illustration of topsides deck transformation.

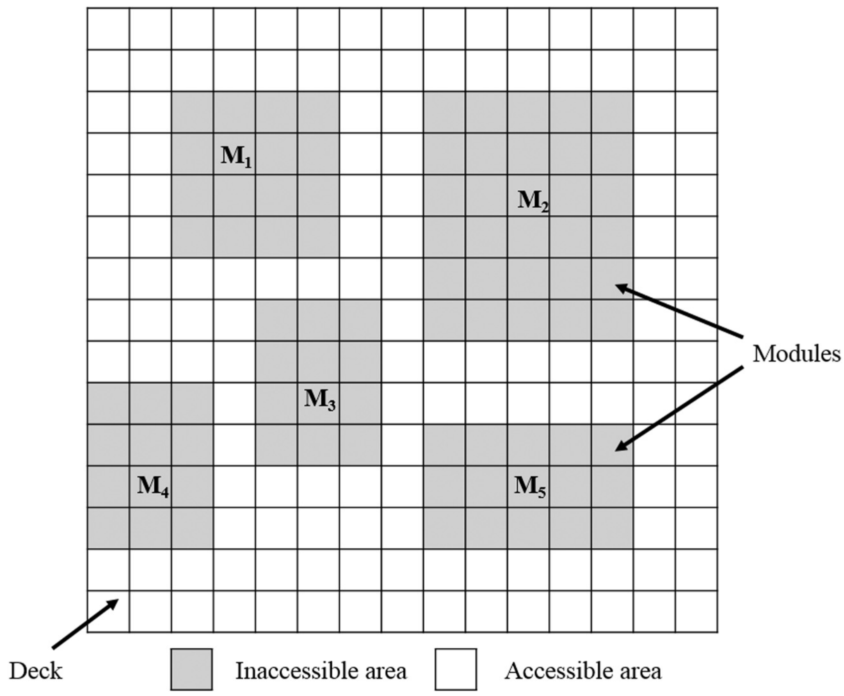

Fig. 5. Generated matrix model illustration.

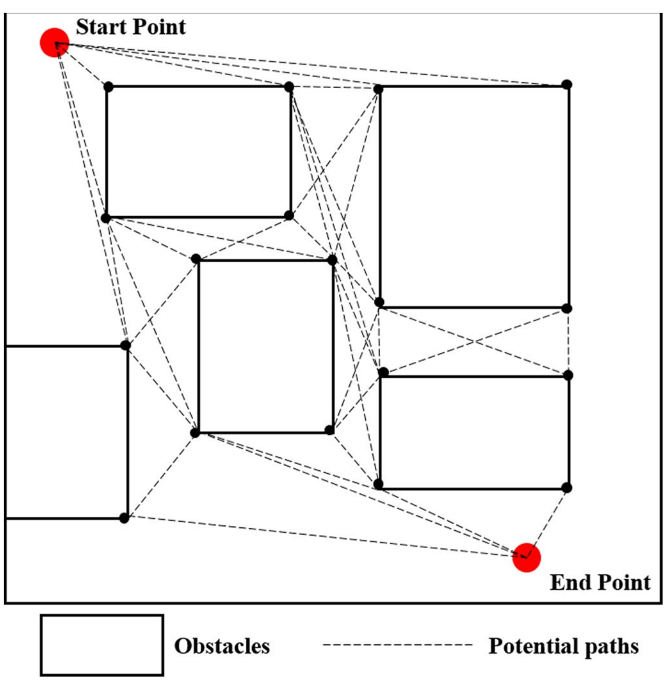

Fig. 6. Illustration of potential path network generation.

functional modules without doors or rooms. Therefore, corner graph methodology that uses the corners of modules (obstacles) to generate a path network is used in this study (see Fig. 6). Based on the generated path network, the escape path is optimized by the developed path planning methodology, which will be introduced in Section 3.3.3.

The matrix model used to store and collect dynamic environment changes over time and the network model used to conduct escape path planning are created respectively. The two created models are then integrated together to model the OOGP topsides environment for evacuation simulation. Dynamic environment changes are also required to simulate the emergency situations. More details of accidents generation are introduced in the next section.

3.2.3. Accidents generator

One common type of accidents on topsides is fire disaster. As modules have various functions, the risk level or possibility of catching fire of each module is also different. As mentioned in Section 3.1.1, the risk level of each module is extracted from BIM. The risk level of each module is obtained by analyzing historical accident database of offshore platforms. The obtained risk level is then assigned to a newly developed property named *Risk Level* for each OOGP module in BIM models. The risk of catching fire is divided into three levels, with level 3 being the highest risk level and level 1 being the lowest. A random number that follows standard normal distribution will be generated at a certain time during the emergency simulation. If the generated random number (R) is in the range of $[-1, 1]$, modules with risk level 1 will be selected. If R is located between $[-2, -1)$ and $(1, 2]$, modules with risk level 2 will be selected. If R is located in other regions, modules with risk level 3 will be chosen. Among the selected modules, the fire accident is randomly assigned to one of them. Related accessible areas around the module on fire will then become inaccessible, which may impact the initial escape paths, and path rescheduling will then be required.

3.3. Agent definition

Another critical component for evacuation simulation using ABM is to define agents in a virtual simulation environment. The workers on OOGP platform is first categorized and represented by different types of agents of specific attributes and behavior rules. The agents are subsequently created in ABM software to simulate their evacuation behaviors during an emergency and to study their interactions with the surrounding environment. The simulation results can further guide the planning of evacuation paths on an OOGP platform and improve the evacuation performance by shortening the escape time and selecting safer escape path. To simulate the real-life situation with agents, attributes and behavior rules that are necessary for the OOGP platform workers are identified and defined in ABM simulation. In this study, basic attributes such as agent size and speed, environment sensing ability to collect dynamic environment changes, and the ability of escape path planning over time are considered in agent definition. More details are introduced in the following sections.

3.3.1. Basic attributes

Agent size is based on the average space size of a person occupies mentioned in Section 3.2.1. A radius of 0.2 m was used in this study. The escape speed usually varies during the emergency when different actions are performed by agents. For example, the escape speed reaches the maximum when escaping in a straight direction and reaches zero when an agent escapes in the reverse direction. Escape speed ranges from zero to the maximum at the corners with different angles or in the crowd with various densities. According to a study conducted by Thompson and Marchant [60], walking velocity of an adult is 1.25 m/s, which is the average of 1.35 m/s of male's speed and 1.15 m/s of female's velocity. Since this study focuses on OOGP evacuation simulations, the target persons are usually men who have already gone through systematically safety training, 1.35 m/s was applied in this study. As for corner speed, a predefined rate of regular speed will be used. The rate is based on the angles of corners. The formula of approximately determining corner speed is presented in Eq. (1).

$$cv = \frac{1.35}{180}\alpha \tag{1}$$

where cv is the corner velocity and α is the angle that an agent passes through. In addition, when passing through the connections (i.e. stairs) between two decks, the escape velocity of agents will also be reduced to reflect the real situation of using stairs in real emergency situations. Memory, another attribute that has not been studied in previous studies, will be defined for ABM simulation in this study. Although persons tend to be panic under emergency, they are willing to communicate with others for more information to make effective escape decisions such as deciding the correct exit to use, the right person to follow, and the speed of escape. Memory is used to store instant sensed environment situations using environment sensing function that is introduced in Section 3.3.2. Memory is stored as an attribute for each agent object and the attribute is presented using the graph data structure, which can represent the simulation environment in real time.

3.3.2. Environment sensing

Timely understanding surrounding environment is important for each person in emergency situations. Accurate surrounding information collection is the prerequisite to understand dynamic changes of the environment. Therefore, a function named environment sensing is developed and assigned to all agents in this study. Before conducting information collection, the types of information required are decided. Two types of information from the perspective of accidents and personal behaviors during an evacuation are considered in this study. Accidents such as fire and choking smoke are the main factors impacting escape, especially for escape path decision. Some potential exits may no longer be accessible when facilities around the exits are on fire. The other type of information is evacuation behaviors, which are usually the outcome of the interaction between agents and the dynamically changing environment. People all tend to choose the shortest path that they are familiar with, and then crowd situation, such as herding behavior, may happen at a certain exit. Such crowd situations may not only increase evacuation time but also cause injury accidents among people. It is better for people to make full use of potential exits rather than being trapped in the crowd. Therefore, sensing accidents and crowd people can help improve evacuation performance.

Accidents and crowd people impact escape path mostly during evacuation and the escape path planning in this study is based on network, also called corner graph as mentioned in the previous sections. Since fire and other accidents usually happen at functional modules on an offshore platform and people tend to be crowded at exits, the surroundings of corners are checked to collect environment information. Mapping this process to the generated potential path network, which is used for escape path planning, requires checking the surroundings of the next vertex of the path for each agent. As the environment has been divided into nodes and each node in the path network contains certain attributes to represent environment status, real-time environment situation can be collected. More details of network definition are introduced in the escape path planning section (Section 3.3.3). Pan et al. [25] used a similar concept, which involves assigning a sensor that has a visual angle of 170° to each agent. However, when a person escapes to an available exit under emergency, they usually intend to reach the next vertex of the path immediately. Therefore, when an agent is getting close to the next vertex of the escape path, the vertex is checked to obtain environmental changes in time.

In addition to obtaining the surrounding environment by checking visible nodes, another methodology using the memory attribute of agents is also developed in this study. As introduced in Section 3.3.1, each agent can store sensed environment information. During the escape, people not only collect information by themselves but also by communicating with others and exchanging known information. Gan and Cheng [61] proposed a negotiation algorithm to enhance the communication between different types of agents for collaborative problem-solving. In this study, negotiation algorithm will be developed to strengthen the communication and information sharing among various agents. A random number between 0 and 1 will be generated when two agents meet with each other. If the random number is over 0.5, communication will be triggered and conducted. On the other hand, if the number is less than or equal to 0.5, no communication will happen.

3.3.3. Dynamic escape path planning

As mentioned in Section 2.3, classic path search on constructed VG is time-consuming and even though studies have conducted to reduce VG construction time, the VG-based path search is usually conducted statically, assuming that evacuation environment will not change, which does not reflect real emergency situations. Therefore, a methodology named dynamic simultaneous visibility graph construction and path optimization by A* (DSVGA) is developed by modifying and improving SVGA proposed in Lv et al. [34]. The path search process of DSVGA is illustrated in Fig. 7.

The developed DSVGA methodology starts with obtaining the current position of each agent. Visibility graph construction and path searching using A* algorithm will then be conducted simultaneously to initialize escape paths for all agents. An escape path usually consists of vertices of obstacles and agents will follow these vertices to get to the end point (exit). When getting close to the next vertex of the escape path, the surrounding environment of this vertex will be checked using the environment sensing function. If the next vertex is inaccessible, an agent will reschedule the escape path based on its current position. If the accessibility of vertex has not changed, agents will keep moving following the current escape paths. Besides, agents can also obtain environment information by exchanging memories among each other during evacuation simulation. Using the developed DSVGA methodology, more reasonable escape paths considering dynamic changes of environment can be obtained and assigned to all agents, thus improving the evacuation performance and safety management on OOGPs.

3.4. Simulation and comparison

Different emergency scenarios can be simulated and evaluated with the developed BIM-based evacuation model. Using the developed accidents generator mentioned in Section 3.2.3, emergency scenarios of catching fire at different areas on an offshore platform can be simulated. Evacuations in different scenarios can then be conducted. The total evacuation time and the number of successfully escaped agents over time of each scenario simulation can be recorded. Then, the simulation results including the total evacuation time and visualization

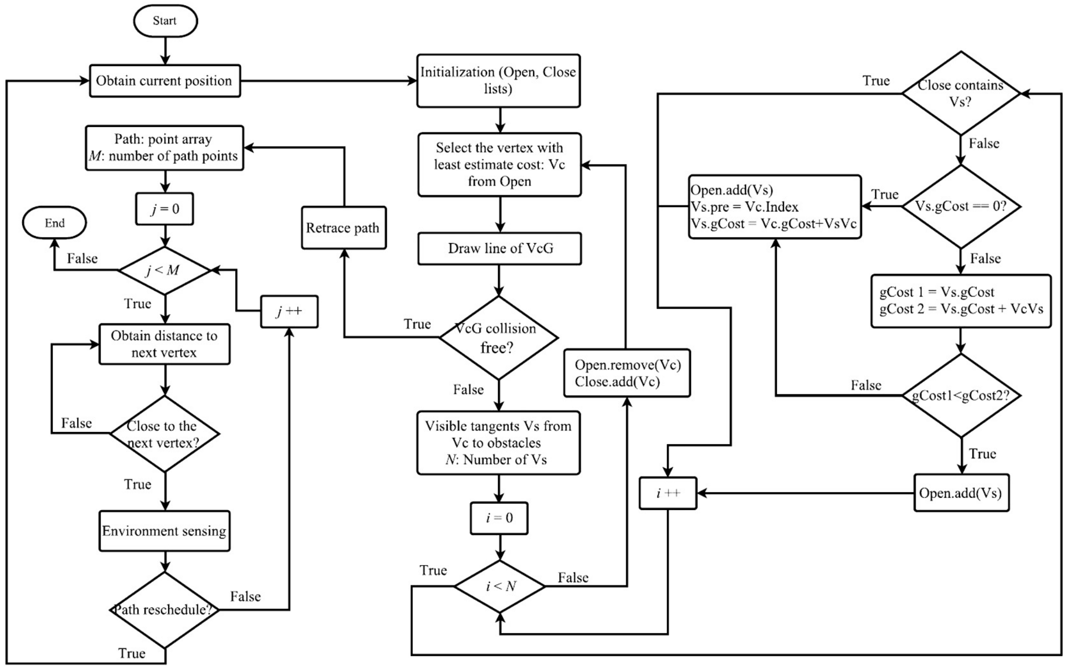

Fig. 7. Illustration of DSVGA process.

of people crowded areas during evacuation simulation of different scenarios can be compared. Finally, the evacuation plan that avoids people crowd and has the shortest total evacuation time of each emergency scenario is proposed to safety manager on offshore platforms to improve the performances of evacuation and safety management.

4. Illustrative example

An illustrative example was used to apply the developed evacuation model. An OOGP model is first created in BIM authoring software, which in turn is transformed into the evacuation model for ABM simulation. The OOGP model in BIM contains two decks (i.e., Deck 1 and Deck 2) that are connected by steel stairs. Seven and five functional modules are located on Deck 1 and Deck 2 respectively. The modules include oil process module, gas process module, crew quarters, and other modules. As described in Section 3.1.2, the transformation of the topsides deck is essential to conduct ABM evacuation simulation. The location of Deck 2 was transformed to the same level as Deck 1 to create the evacuation model. Modules and decks are originally represented in the format of 3dMax. File format preprocessing is required before information extraction and simplification. IFC file format of the topsides and decks was obtained by the preprocessing. Required information for the BIM-based evacuation model development was then extracted and simplified as a text file that can be read by Unity 3D to set up evacuation simulation environment (see Fig. 8). In addition to the simulation environment setup, agents that are used to represent workers on the offshore platform were defined with the attributes described in Section 3.3, including basic attributes such as agent size and speed, and developed attributes such as environment sensing and dynamic escape path planning. Agents were assigned around simplified functional modules in the created simulation environment to assume that they were working when the evacuation was trigged by an emergency alarm (see Fig. 8).

After finishing the evacuation simulation environment modeling, four simulations (S1, S2, S3, and S4) were conducted (see Table 1). S1 was to simulate agent escape under emergency alarm. All agents try to follow the initial paths, which are the shortest path to exit. S2 was also conducted under emergency alarm, but the developed DSVGA methodology was applied during simulation. S1 and S2 were used to illustrate the ability to detect herding behavior and reschedule escape path of the developed BIM-based evacuation model. As illustrated in Fig. 9(a), in S1, all agents tended to use the exit that was circled in the figure, making the exit crowded and more evacuation time was required for agents to pass through. While in S2, some agents used other potential exits to avoid being crowded at one exit. The evacuation time and the number of escaped agents of S1 and S2 were presented in Fig. 10(a). S3 and S4 were also conducted with or without DSVGA, but accidents that will impact escape paths were added to these two scenarios. S3 and S4 were used to show that agents could not only detect herding behavior but also recognize accidents and make reasonable response under emergency in the developed model. As illustrated in Fig. 9(b), all agents could avoid fire on topsides in both S3 and S4, but some exits were crowded in S3 as the developed DSVGA methodology was not applied in S3. In S4, with DSVGA, agents showed a better evacuation performance. The evacuation time and the number of escaped agents of S3 and S4 are presented Fig. 10(b).

The simulation results statistics were summarized in Table 1. According to Table 1, the evacuation time of S2 was reduced by 7.1% compared to S1, which means that the developed evacuation evaluation model performs well on detecting crowded area and rescheduling escape path when initial escape paths were impacted. In S3 and S4, a fire accident happened during the evacuation, which blocked the initial escape paths for some agents. With the developed model, agents successfully chose safer escape paths and avoided herding behavior simultaneously. An 11.6% reduction of escape time was achieved in S4 when compared with S3. According to the simulation results, the performance of the developed evacuation evaluation model was tested and verified. The model could well simulate evacuation on offshore platforms. Therefore, with the developed model, evacuation under different scenarios such as catching fire at different areas on offshore platforms can be simulated and optimized escape paths for each scenario can be proposed. The evacuation performance and safety management on offshore platform were accordingly improved.

5. Conclusions

This paper developed a BIM-based evacuation model to evaluate

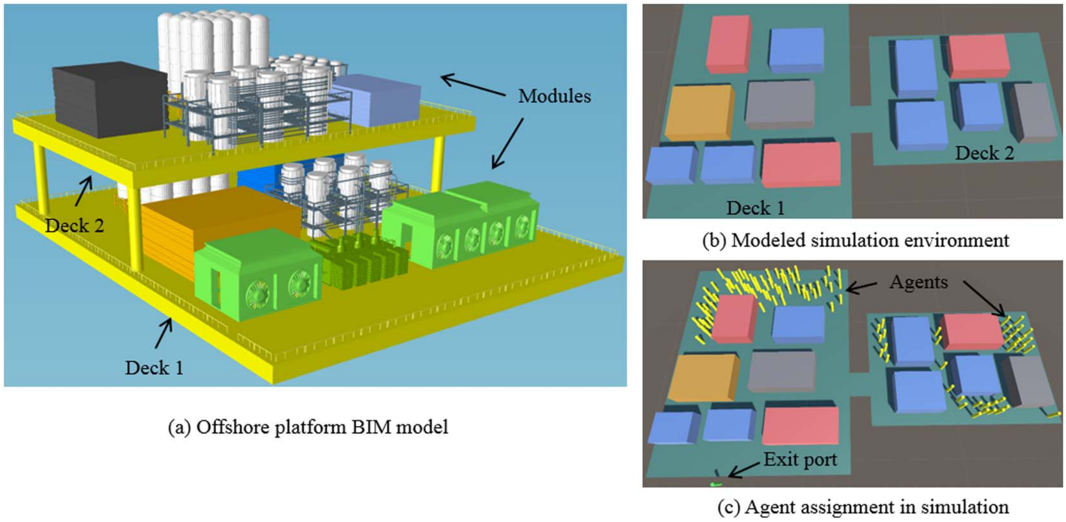

Fig. 8. Illustration of simulation environment setup and agents assignment.

Table 1
Scenarios and simulation results statistics.

Simulations (S)	Emergency alarm	Using DSVGA	Accidents	Total evacuation time (s)	Time reduced
S1	√			48.68	
S2	√	√		45.24	7.1%
S3	√		√	54.04	
S4	√	√	√	48.4	11.6%

different emergency scenarios and to improve evacuation performance and safety management on topsides of OOGPs. BIM technology and agent-based model were integrated into the evacuation evaluation model. To efficiently collect dynamic environment changes and accurately plan escape path, matrix model and network model were integrated. In addition, agent attributes of memory, environment sensing, and dynamic escape path planning methodologies, namely DSVGA, were newly developed and integrated to simulate evacuation behaviors better. An example topsides BIM model was used to illustrate and evaluate the developed evacuation evaluation model. Different emergency scenarios were simulated and evaluated. Compared to real escape drill exercises, the developed model can improve safety management with less cost and risk. In addition to OOGPs, the developed BIM-based evacuation evaluation model can also be applied to emergency simulations in buildings, on construction sites, and other public places such as shopping malls and metro stations. For example, in the AEC industry, construction sites nowadays are increasingly congested. Site layout planning has a severe impact on site safety management performance, especially emergency response such as evacuation plan. Based on the BIM-based evacuation model, congested construction sites can be efficiently modeled, and worker interactions among each other

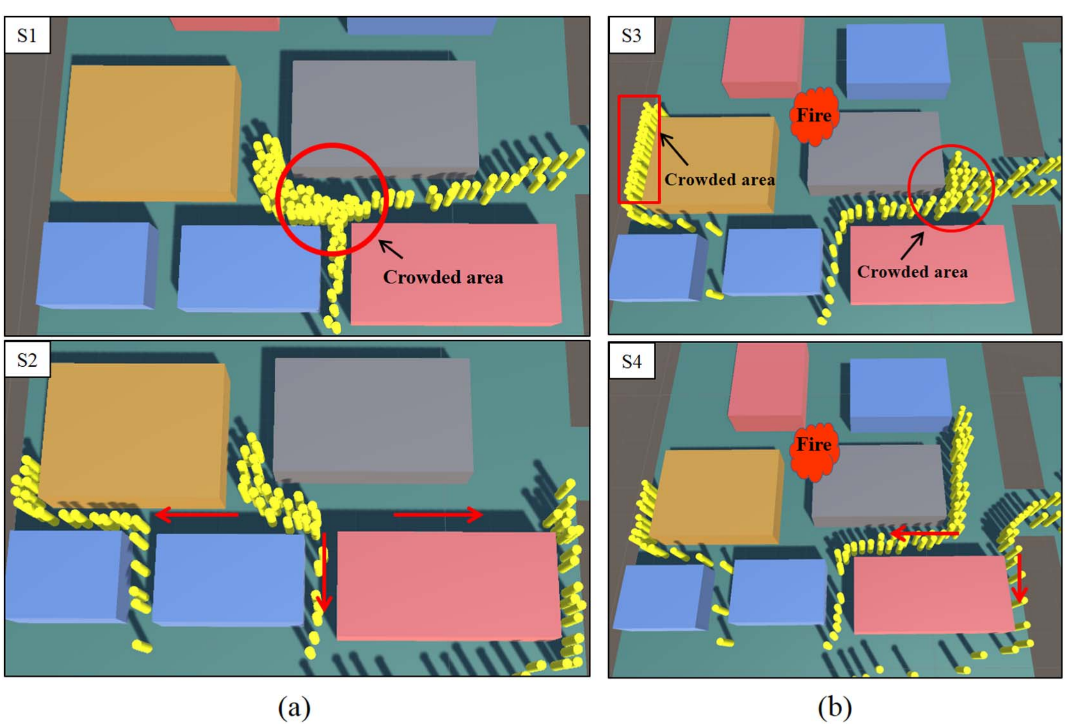

Fig. 9. Illustrations of simulation scenarios. (a) S1 and S2 illustrations (b) S3 and S4 illustrations.

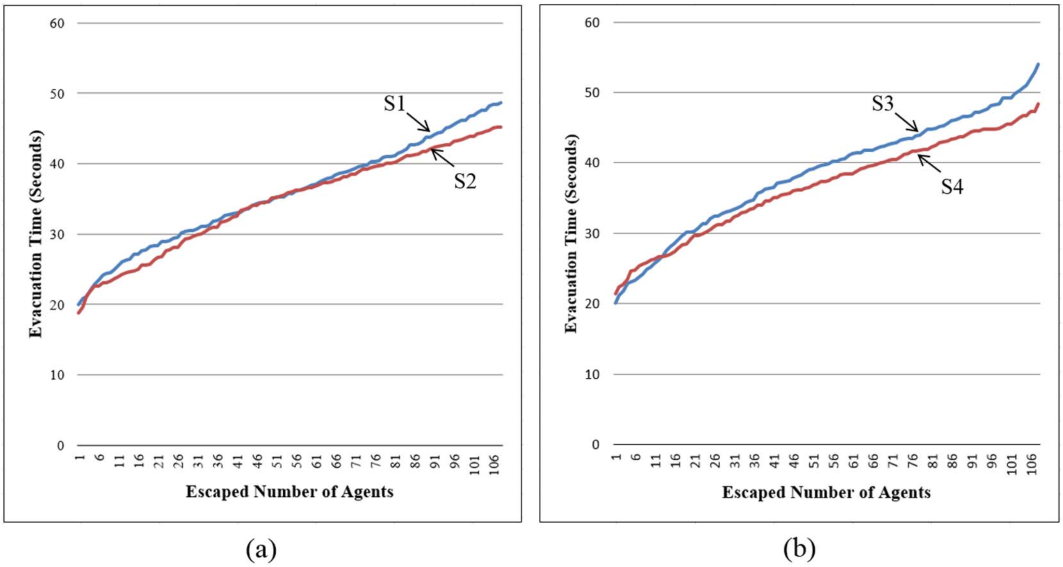

Fig. 10. Simulation results comparison. (a) Results comparison of S1 and S2 (b) Results comparison of S3 and S4.

on construction sites can also be accurately simulated, thus improving the safety performance of construction. Finally, the visualization of various scenario simulations can also help educate and train workers during pre-construction stage.

The developed model can be further enhanced by considering more social behaviors and integrating with accidents simulation applications. This study only considered spatial recognition, herding behaviors, and communications, while other behaviors like queueing have not been studied because of the pre-defined scope of this study. One potential future direction is to integrate more social behaviors to make evacuation simulation more realistic and accurate. The dynamic environment change simulation conducted in this study is only based on a simple accident generator. FDS, as mentioned in the literature review, was commonly used to simulate accidents like fire and smoke spread in evacuation studies. Therefore, FDS is suggested to be integrated into the developed model to further improve the simulation performance and safety management on OOGPs in the future.

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