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3D INDOOR-PEDESTRIAN INTERACTION IN EMERGENCIES: A REVIEW OF ACTUAL EVACUATIONS AND SIMULATION MODELS

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ABSTRACT:

Pedestrian motions and behaviours in evacuations are compactly interrelated indoor environments. According to how pedestrians interact with indoor environments in three-dimensional (3D) space, 3D indoor-pedestrian interaction is defined as five sorts of specific pedestrian motions, i.e., stepping over, crawling, bent-over walking, jumping over and climbing over. However, the occurrence and prevalence of the interaction in actual evacuations have not been identified, and the degree of effectiveness and practicality of the evacuation simulation models regarding the interaction is yet to be evaluated. Understanding the interaction and simulating it realistically bring apparent benefits to support informed policymaking, building safety optimization and emergency relief efforts. Therefore, this article aims to review the 3D indoor-pedestrian interaction in actual evacuations, assess the capabilities and performance of the evacuation simulation models for the interaction, and identify their limitations and challenges for future work. We first demonstrate that the fundamental relationships between the decision-making process of a pedestrian, object distance and object size/shape in 3D space are unclear yet, and the scarcity of experimental investigation for local routes choices and each motion is vast. Subsequently, the comparisons between Social Force models, Cellular Automata models and Agent-based models suggest that these microscopic models can yield the 3D indoor-pedestrian interaction, but the height dimension of 3D space is not explicitly considered during the evacuation modelling. This article is expected to advance the understanding of pedestrian evacuations in 3D space, ultimately improving pedestrian safety in indoor environments.

1 INTRODUCTION

Pedestrian safety in indoor environments has been increasingly recognised in the past two decades as urban populations are growing faster than ever and urban residents spend approximately 90% of their time indoors (Klepeis et al., 2001). Knowing how to effectively evacuate pedestrians from indoor environments in crises and emergencies (e.g., fires, terrorist attacks, earthquakes) is of utmost importance to ensure pedestrian safety.

Understanding pedestrian motions and behaviours in evacuations and simulating them as realistically as feasible bring apparent benefits to support informed policymaking, building safety optimisation and emergency relief efforts. Pedestrian motions and behaviours in evacuations are compactly interrelated with indoor environments. In the real world, some interactive motions and behaviours are three-dimensional (3D) as opposed to two-dimensional (2D). As a prominent example, some pedestrians crawl beneath or jump over desks to elude dangers or for more quick evacuation, while others prefer to avoid desks only. From the perspective of emergencies, when there are floating smoke and fires, or falling ceiling caused by earthquakes, pedestrians have to choose between crawling or bent over walking. The series of interrelated and reciprocal actions in 3D space between indoor environments and pedestrians are, in fact, the 3D indoor-pedestrian interaction. According to how pedestrians interact with indoor environments in 3D space, the 3D indoor-pedestrian interaction in the article is defined as five sorts of specific pedestrian motions, i.e., stepping over, crawling, bent-over walking, jumping over and climbing over, with six categories of placement relations between an individual and indoor object, namely front, back, above, beneath, left and right, respectively.

In order to simulate the 3D indoor-pedestrian interaction, 3D spatial information related to indoor environments is required and imperative, which can be adopted to generate realistic environmental contexts and create a 3D operational virtual space for reproducing pedestrian evacuations (Ghawana et al., 2018). 3D spatial information has been generated and extracted in existing studies, particularly indoor evacuation and navigation domains (Xiong et al., 2017; Gorte et al., 2019; Zlatanova et al., 2020; Aleksandrov et al., 2021). For instance, Aleksandrov et al. (2021) automated the abstraction of indoor environments required for pedestrian evacuation simulation. In terms of navigation domains, 3D indoor navigation, 3D seamless indoor/outdoor navigation, path computation considering movable obstacles, etc. have a thirst for fine-grained 3D spatial information (Liu and Zlatanova, 2015; Wang and Zlatanova, 2016; Aleksandrov et al., 2019; Yan et al., 2019; Yan et al., 2021; Yan et al., 2021). Even in urban environments, the sort of spatial information plays a significant role, such as visibility analysis and safety assessment (Aleksandrov et al., 2019). Regarding the 3D modelling approaches for indoor environments, Building Information Modelling is commonly used to obtain 3D spatial information since it contains and depicts 3D geometry, topological relations, semantic information and properties of indoor environments (Abou Diakité and Zlatanova, 2016; Liu et

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al., 2021; Wu et al., 2021). Hence, it is readily to find that 3D spatial information related to indoor environments has a relatively strong foundation.

Nevertheless, from the perspective of pedestrian motions and behaviours, the 3D indoor-pedestrian interaction received little attention over the last decades. Although multiple research efforts have made immense contributions to provide various discussions and reviews of actual evacuations in real emergencies and experiments and evacuation simulation models with respect to a series of evacuation behaviours, it appears that different evidence supporting the occurrence and prevalence of the 3D indoor-pedestrian interaction has not been identified and the extent of effectiveness and practicality of the simulation models for the interaction has yet been to be evaluated (Gwynne et al., 1999; Pelechano and Malkawi, 2008; Zheng et al., 2009; Bellomo et al., 2012; Radianti et al., 2013; Kuligowski, 2016; Vermuyten et al., 2016; Haghani and Sarvi, 2018; Li et al., 2019; Lin et al., 2020; Xie et al., 2020; Zhu et al., 2020; Haghani, 2020a; Haghani, 2020b; Chen et al., 2021, Jiang et al., 2022). Similarly, in the transportation discipline, the interaction has not been considered in some traffic behaviours, accessibility and pedestrian flow motions (Chia and Lee, 2020; Yoo et al., 2022). More work seems necessary to identify the occurrence and prevalence of the 3D indoor-pedestrian interaction in actual evacuations and assess the simulation models for the interaction to establish evidence-based approaches in corresponding evacuation modelling.

Driven by this motivation, the main objectives and potential contributions of this article are as follows: 1) to review the 3D indoor-pedestrian interaction occurring in actual evacuations that provides a vital premise and basis for assessing and supporting the developments of evacuation simulation models, which consequently refrain from arbitrary or subjective modelling approaches; 2) to evaluate the capabilities and performance of evacuation simulation models for the 3D indoor-pedestrian interaction by assessment factors extracted from the review of actual evacuations and a current study, which thus foster the potentials to establish more accurate and realistic simulation models; 3) to identify limitations and challenges of the evidence and simulation models regarding the 3D indoor-pedestrian interaction, which would pave the way for future research.

The remainder of this article is organized as follows. Section 2 briefly presents the research method. A review of actual evacuations is introduced in Section 3, consisting of evidence from real emergencies and experiments. Section 4 describes the assessment factors regarding the capabilities and performance of simulation models for the 3D indoor-pedestrian interaction. Then, the comparisons between three sorts of models are elaborated upon in Section 5. At last, Section 6 wraps up this paper with the unresolved limitations and challenges for future work.

2 METHOD

In line with the objectives mentioned above, the electronic database of the publications was primarily obtained from the Scopus database and Web of Science Core database. A systemic search in terms of articles' title, abstract and keywords was conducted by using combinations of the following keywords including '3D OR three dimension*', 'evacuat* OR escap* OR egress', 'step OR crawl OR bent-over OR stoop OR climb OR jump', and the search outcomes were filtered out subsequently in the light of the main criteria for inclusion and exclusion, namely 1) be published in the English language; 2) address at least one sort of five motions within the 3D indoor-pedestrian interaction from real emergencies, experiments or evacuation modelling. To further enrich the review of actual evacuations, the articles that had been identified and cited by previous reviews (Haghani and Sarvi, 2018; Haghani, 2020a; Haghani, 2020b) on empirical methods and human behaviour were considered one by one were checked in the Web of Science Core database to identify possible missing evidence. This search was performed in April 2022. As a result, a total of 28 papers were involved.

The simulation models were compared in this work in terms of their capacities to model the 3D indoor-pedestrian interaction. Three categories of assessment factors were used to measure a model's capabilities and performance. First and foremost, an evaluation was conducted based on the motions that frequently occur during the interaction between pedestrians and indoor environments in 3D space. In order to achieve the evaluation, we first reviewed some actual evacuations to provide more information concerning the interaction. In relation to the data source and observe approach, we prudently observed the original source/database of video recordings of real emergencies provided and mentioned by the reviewed literature and the figures and text information about experiments from some cited papers. In this intuitive manner, we identified the occurrence and prevalence of the interaction. Furthermore, placement relations between pedestrians and indoor objects (e.g., furniture, automatic ticket gates) are essential to locate pedestrians' positions and derive potential evacuation routes. Referential expressions that describe the placement of pedestrians and objects were employed in this article to nuance the notion of placements (Sithole and Zlatanova, 2016). As a result, the models were graded in their capacities to consider the placement relations. Subsequently, we delved into greater detail on the specific operational characteristics to assess the models. All of the information regarding the evacuation simulation models used in this comparison is extracted from the papers that describe them. We focus on the advantages and disadvantages of evacuation simulation models with respect to simulating the 3D indoor-pedestrian interaction that an ideal simulation model should be able to capture.

3 3D INDOOR-PEDESTRIAN INTERACTION IN ACTUAL EVACUATIONS

A review regarding the 3D indoor-pedestrian interaction in actual evacuations is collected through observing the video recordings of real emergencies and the figures and texts about experiments in the cited studies. We provide a broad but not exhaustive overview of actual evacuations incorporating the interaction. The analysis is classified according to the motions, i.e., stepping over, crawling, bent-over walking, climbing over and jumping over.

Several video recordings provided by the studies were observed to illustrate the 3D indoor-pedestrian interaction in real emergencies. In a surveillance video of the shootings (Monahan, 2006) at Columbine High School in 1999, some students crawled beneath to elude terrorists and climbed above/over desks for quicker escape. A real earthquake data of a classroom in China, used in two studies (Li et al., 2015; Wang et al., 2020), show that some students tried to push away desks and chairs for sufficient space to evacuate, and two students stepped over chairs and jumped over desks, respectively. Databases for earthquake evacuations (Zhou et al., 2018; Bernardini et al., 2019) recorded a high occurrence frequency of each 3D indoor-pedestrian interaction. A video of a university library (Song et al., 2021) in the moderate earthquake in Wuhan, China, explicitly demonstrates that some students climbed above automatic ticket machines for evacuation. A video data (Wang et al., 2019) of the terrorist attack event in Kunming train station in China was observed that terrorists, belongs, fences, stools, etc. , resulted in stepping over, jumping over and bypassing motions. A video (Liu et al., 2022) recorded a shooting at an Apple Store located in a New York mall in 2016, in which stepping over boxes and low crawling beneath desks were well observed and prevalent.

In addition, a group of experiments were identified as covering a relatively specific 3D indoor-pedestrian interaction. Notably, crawling was heavily investigated in the experiments, including knee and hand crawling, foot and hand crawling and low crawling. Crawling evacuation is evidenced as more physically demanding than walking, because it has lower speed and causes more damage to body joints than other motions. Meanwhile, males move faster and attain longer distances than females during crawling (Jia et al., 2019; Wang et al., 2020). Different crawling postures and speed for evacuation modelling references have been provided in some experiments (Nagai et al., 2006; Kady and Davis, 2009a; Kady and Davis, 2009b; Gallagher et al., 2011; Davis and Gallagher, 2014; Cao et al., 2018). A study (Guo et al., 2021) performed two experiments with 20 males. In the first experiment, participants were required to crawl by knee and hand. Another asked the participants to walk upright. In their observations, the crawling density around the exit during the evacuation process was lower than the walking density. By comparison, Kady (2012) generated the fundamental speed-density relationship of crawling evacuation.

For other motions, a study (Ding et al., 2020) conducted a series of evacuation experiments and compared three situations of obstacles, namely, obstacles-absence, obstacles that pedestrians can choose to pass by or step over and obstacles that pedestrians can only pass by. Their study is one of the few that looked into the height of obstacles. They observed that when obstacles with low height are close to the exit, it can benefit the reduction of evacuation time. Another study (Delcea et al., 2020) experimented with evacuation from a classical and collaborative classroom. The authors observed that the chairs were pushed onto the aisle and partially blocked it, which caused students to bypass it, and the chairs fell on the aisle and completely blocked the aisle, which made students jump over it during the evacuation process. The above analysis explicitly shows that the results of experiments mainly focus on crawling and stepping over and their characteristics (e.g., speed, pedestrian density). The other three kinds of motions and six placement relations are not investigated sufficiently, and the relations between the decision-making process and adaptive route choice of a pedestrian, object distance and object size/shape in 3D space remain unclear.

In summary, we can argue that the 3D indoor-pedestrian interaction is prevalent in actual evacuations. To summarise the abundance of the interaction in actual evacuations, a visual summary with respect to the interaction is shown in Appendix 1.

4 ASSESSMENT FACTORS FOR SIMULATION MODELS

To compare the advantages and disadvantages of evacuation simulation models for the 3D indoor-pedestrian interaction, we assess the evacuation simulation models through three categories of factors. In the light of the review of actual evacuations, we first employ five distinct motions and six types of placement relations between pedestrians and indoor objects. Besides, a series of operational characteristics with respect to an evacuation simulation model are extracted and chosen from a review (Duives et al., 2013).

4.1 Motions

The previous section has reviewed studies and experiments with the five sorts of motions. The motions covering the whole range of individual movement when interacting with indoor environments in 3D space were used to assess evacuation simulation models. Whether a motion is considered in an evacuation simulation model is evaluated according to Table 1.

×	Not possible to model this motion using this model
√	Possible to model this this motion using this model
?	Unknown whether the model can simulate this motion

Table 1. Rating scheme of simulation models on motions

4.2 Placement relations

Besides distinct motions, similarly, the placement relations between pedestrians and indoor objects (e.g., furniture, automatic ticket gates) can be separated. In our study, six categories of placement relations from an individual perspective in the relative reference of indoor objects have been mentioned: front, back, above, under, left and right (Sithole and Zlatanova, 2016). For example, a pedestrian steps over an object in front of him/her, crawls beneath a computer desk, or jumps over/above an automatic ticket machine. The placement relations considered in the models are rated based on Table 2.

×	Not possible to model this placement relations using this model
√	Possible to model this this placement relations using this model
?	Unknown whether the model can simulate this placement relations

Table 2. Rating scheme of simulation models on placement relations

4.3 Operational characteristics

We chose and extracted six categories of operational characteristics of evacuation simulation models based on a study (Duives et al., 2013). Note that we did a minor revision to these characteristics so that these can adapt to the context of the interaction. Because we focused on the interaction between indoor environments and pedestrians, some characteristics, such as crowd phenomenon, pressure and groups within a crowd, were not considered in this article. For each the operational characteristic, their notions are briefly introduced in the following text, all of which are consequently incorporated in the assessment of simulation models.

(a) Decision-making process concerns the capacities of simulation models to represent pedestrians' decisions resulting from physiological, psychological, or physical considerations occurring in the 3D indoor-pedestrian interaction. (b) Adaptive route choice is used to assess which simulation models can realistically simulate the adaptive changes in pedestrian route choice, both globally and locally, when they encounter congestions, spreading smoke, etc. (c) Collision avoidance is set out to assess whether the simulation models can reproduce the behaviour of pedestrians to avoid collisions with indoor environments. (d) Heterogeneous pedestrian classes are with respect to simulating different pedestrian characteristics (e.g., age, gender, speed, disability). (e) Computation burden focuses on the complexity of the simulation models' mathematical structure instead of computational speed. (f) New infrastructure rates the capacities of simulation models to be applied in new buildings that they have not originally been calibrated for. Based on the descriptions, it is possible to make two kinds of distinctions in Table 3.

Operational Constraints	Rating scheme			
Decision-making process	×	√	?	/
Adaptive route choice	×	√	?	/
Collision avoidance	×	√	?	/
Heterogeneous pedestrian classes	×	√	?	/
Computation burden	++	+	-	- -
New infrastructure	++	+	-	- -

Note: ×: Not possible to model this; √: Possible to model this; ? :Unknown. For computation burden: ++: Very low; +: Low; -: High; - -: Very High. For new infrastructure: ++: Without difficulties; +: Slight adaptations; -: After recalibration; - -: Never without a complete situation analysis.

Table 3. Rating scheme of simulation models on operational characteristics

5 SIMULATION MODELS OF 3D INDOOR-PEDESTRIAN INTERACTION

This section discusses the simulation models for the 3D indoor-pedestrian interaction in evacuations. We classify these models into Social Force models, Cellular Automata (CA) models and Agent-based models based on the simulation approaches. Appendix 2 contains the results of the comparison.

5.1 Social Force models

Social Force models are continuous microscopic models with deterministic force-based interactions in which agents, as Newtonian particles, have the desired velocity in the direction of their destination and different forces act through their acceleration and deceleration. Firstly, Social Force models are capable of simulating stepping over, crawling and climbing over motions. For example, a study (Liu et al., 2022) developed a Social Force model to simulate the evacuation in a complex environment based on observed data. Pushing-away and stepping-over behaviours occurring in the interaction between pedestrians and movable objects were modelled (e.g., chairs, boxes placed on the ground). Regarding placement relations, only one Social Force model (Guo et al., 2021) was developed to consider that pedestrians move beneath smoke and fires using crawling motion. Almost all the models are able to maintain the other five generic forms of placement relations. Technically, these motions and placement relations can be simulated since the attractive and repulsive forces from indoor environments can be readily represented.

For operational characteristics, most of the models integrate a pedestrian decision-making process in their models. For instance, Song et al. (2021) developed a multi-stage decision-making mechanism for pedestrians (i.e., habitual, mild, and radical stages) in conjunction with a modified three-layer Social Force model to reproduce the interaction between pedestrians and automatic ticket machines. In the adaptive route choice and collision avoidance columns, it is seen that Social Force models perform well. The prominent study of Liu et al. (2019) presented how to implement a 3D collision avoidance algorithm. If the height of an obstacle is greater than the maximum height that an agent can step over in a horizontal collision, the agent will change motion direction. Otherwise, the agent can keep on his or her way. Vertical collision avoidance ensures agents do not float up or fall through the floor while moving. Regarding heterogeneous pedestrian classes, the models are partly based on the crowd and less on the individual features of each agent, such as ages, gender, decision making, and velocities. When studying computation burden, it is clear that models considering the decision-making process are rated quite badly on this characteristic. Finally, due to using the evidence-based method and focusing on specific scenarios, three studies are required to recalibrate their models or need a complete situational analysis of the new buildings.

5.2 Cellular Automata models

CA models are microscopic simulation models taking individual agents into account. The main components of CA models incorporate cells, cellular space, cellular state and cellular state evolution rules. The models use a discrete grid representation to partition the simulated indoor environment. Time is discretized into each time step in which agents can either travel to an adjacent grid or stay in their present location. This means that the spatial interaction and time causality are local. CA models are not defined by a fixed physical formula or function but set by a series of local state update rules that are the most critical component, which consists of selecting influence factors (e.g., barrier wall, fire and smoke) and setting coupling mechanism (e.g., lattice gas models, floor field models) (Li et al., 2019). Because of the discrete and local characteristics of the models, stepping over, crawling and bent-over walking motions can be simulated in a realistic way. However, climbing over and jumping over motions appear absent in the existing models related to CA models since the height information of objects in 2D discrete grids that are important to incorporate the placement relations where pedestrians move above objects is not considered.

As can be observed in Appendix 2, only a model indeed involves the decision-making process. Wang et al. (2020). suggested a modified CA model in which two forms of personality traits of pedestrians, aggressiveness and inconsiderateness, are included to represent the tendency to conduct stepping over motion and pushing away behaviour, respectively. For the adaptive route choice and collision avoidance, CA models can readily reproduce because an agent's choice is restricted by the condition of the nearby grids where motion only occurs when all agent conflicts have been resolved. In terms of the computation burden, a model (Nagai et al., 2006) enables a crawling pedestrian to occupy two discrete grids and used different speeds compared to walking upright, which means its computational load grows linearly with the number of pedestrians. Notably, CA models have a high computational efficiency due to their simple structure. The two models (Nagai et al., 2006; Zheng et al., 2017) are less dependent on original scenarios and data a lot, so they are relatively adaptable to new infrastructure.

5.3 Agent-based models

Agent-based models are usually composed of three components, i.e., heterogeneous agents (e.g., demographic features, various preferred speeds), interactions among agents and corresponding environment and the environment (providing information for the decision making and perceptions of agents). This kind of models takes a bottom-up approach in which only the variety of behaviours of each pedestrian is modelled, and the resulting interaction between them determine the macroscopic behaviour. The capacities of Agent-based models to simulate the most range of motions and placement relations positively, benefiting from that the models can define and represent a series of complex behaviour of individual pedestrians. Tugarinov et al. (2020)

simulated an agent with low health changes. The speed in this state decreases, and the agent moves at a crawl. Tang and Ren (2012) developed an Agent-based model to reproduce the nine categories of pedestrian evacuation, namely, pre-evacuation activities, evacuation, following the crowd, moving through, crawling, turning back, waiting, etc. In their model, an agent can make decisions dynamically. For instance, agents crawl when they encounter smoke and fire at a lower height.

Also, in the Agent-based models the decision-making process, adaptive route choice, collision avoidance and heterogeneous pedestrian classes can be captured and applied at a higher level (See Appendix 2). Nevertheless, a model (Delcea et al., 2020a; Delcea et al., 2020b) receive a negative score on the decision-making process. They conducted an experiment in classroom scenarios and created an agent-based model to simulate two scenarios in the presence of an obstacle: 1) chairs may have been pushed on the aisle, partially blocking it, allowing agents to bypass them; 2) and chairs may have fallen on the aisle and thus, they blocked the aisle completely, which made the agents jump over them. However, the decision-making process of a pedestrian was not incorporated in their model. Moreover, a common disadvantage of Agent-based models is the high computation burden due to the bottom-up approach. Similarly, because the models use individual agents' motions and behaviour as the premise and basis of evacuation modelling, rather than using the new infrastructures to deduce the behaviour of pedestrians itself, the models perform well in adapting to new scenarios.

6 CONCLUSION AND DISCUSSION

This article has illustrated the occurrence and prevalence of the 3D indoor-pedestrian interaction in emergencies, supported by a review of actual evacuations based on real emergencies and experiments. Subsequently, assessment factors, including motions, placement relations and operational characteristics, were extracted from the review of actual evacuations and an existing study. Finally, an assessment of Social Force models, CA models and Agent-based models was conducted based on their capacities and performance in the simulation of the interaction with respect to a series of assessment factors.

Currently, the evidence of the 3D indoor-pedestrian interaction in actual evacuations used for evacuation modelling is still insufficient. Dealing with predicting and replicating the interaction is indeed intrinsically complex and multi-faceted. In the real world, when there are no objects (e.g., desks, chairs) in indoor environments, pedestrians have a preference to choose a route to an exit through a straight line for the shortest distance (Zhu et al., 2020). Nevertheless, pedestrians flexibly change their evacuation motions and behaviours according to the indoor objects in an environment full of objects, potentially triggering the paths dispersed across the whole indoor environment. Once there are some objects in indoor environments that cannot be stepped over, crawled over or climbed over, pedestrians will avoid and bypass these objects. Therefore, one influential aspect is the various decisions of pedestrians and the difference of the motions that various individuals display in similar situations. Unfortunately, the fundamental relationships between the decision-making process and adaptive route choice of a pedestrians, object distance and object size/shape are at best unclear yet, and the scarcity of experimental investigation and observations on the choice of motions is vast. As a result, more experiments and data extracted from real emergencies about the relationships that can improve behavioural realism of evacuation simulation models are a must.

Besides, from the perspective of evacuation modelling, the following are the characteristics of evacuation simulation models for modelling the interaction as follows: 1) The models discussed above have the capacity to yield different motions and placement relations of the interaction; 2) The developed simulation models are capable of both simulating the decision-making process and adaptive route choices; 3) Agent-based models enable the structured and modularized representation of pedestrian heterogeneity (both as individuals and as groups) toward motions, behaviours and placement relations in 3D space; 4) Based on Agent-based models, each motions of 3D indoor-pedestrian interaction can be readily and conveniently included in the behavioural repertoire of pedestrians.

At last, according to the comparison results (See Appendix 2), modelling 3D indoor-pedestrian interaction is limited as well: 1) from the perspective of motions, bent-over walking, climbing over and jumping over that are common in actual evacuation are seldom considered and modelled in the different kinds of simulation models; 2) For placement relations, pedestrian motions above/beneath objects cannot be sufficiently supported; 3) Most simulation models are based on horizontal planes to model the 3D indoor-pedestrian interaction. In particular, agents are always modelled as moving points or cells in horizontal planes, interacting horizontally with other agents and indoor environments. The height dimension of 3D space is not explicitly considered during evacuation modelling, and how the various objects in indoor environments affect pedestrian motions and behaviours and how pedestrians with different characteristics interact with the objects in 3D space are limited; 4) Pedestrian evacuation routes on floors are based on 2D and thus are calculated by horizontal distance in the models. The length of the entire evacuation route in 3D space is different from that in 2D since agents can step over, crawl through or climb over a series of indoor objects that brings corresponding route distance; 5) In terms of the operational characteristics, as shown in Appendix 2, the decision-making process and adaptive rout-choice behaviour of pedestrians in 3D space when interacting with surrounding are not fully considered. More specially, how pedestrians decide to choose different motions, how pedestrians perceive 3D space, how pedestrians utilise different motions to adjust evacuation routes, etc., are not clear; 6) Regarding heterogeneity and computation burden, models best describing heterogeneous individual behaviour and motion are also the models with the greatest computational burden; 7) None of the models is currently capable of supplying all characteristics necessary for the 3D indoor-pedestrian interaction, and few models can be applied in new infrastructures. These limitations and challenges hinder simulating the 3D interaction as realistically as possible.

Overall, the abovementioned limitations and challenges need to be closed. It is expected that the discussion on the topic would pave the way for future research on the combination of observed data that provide the correct knowledge sources and the development of simulation models to display the 3D indoor-pedestrian interaction realistically.

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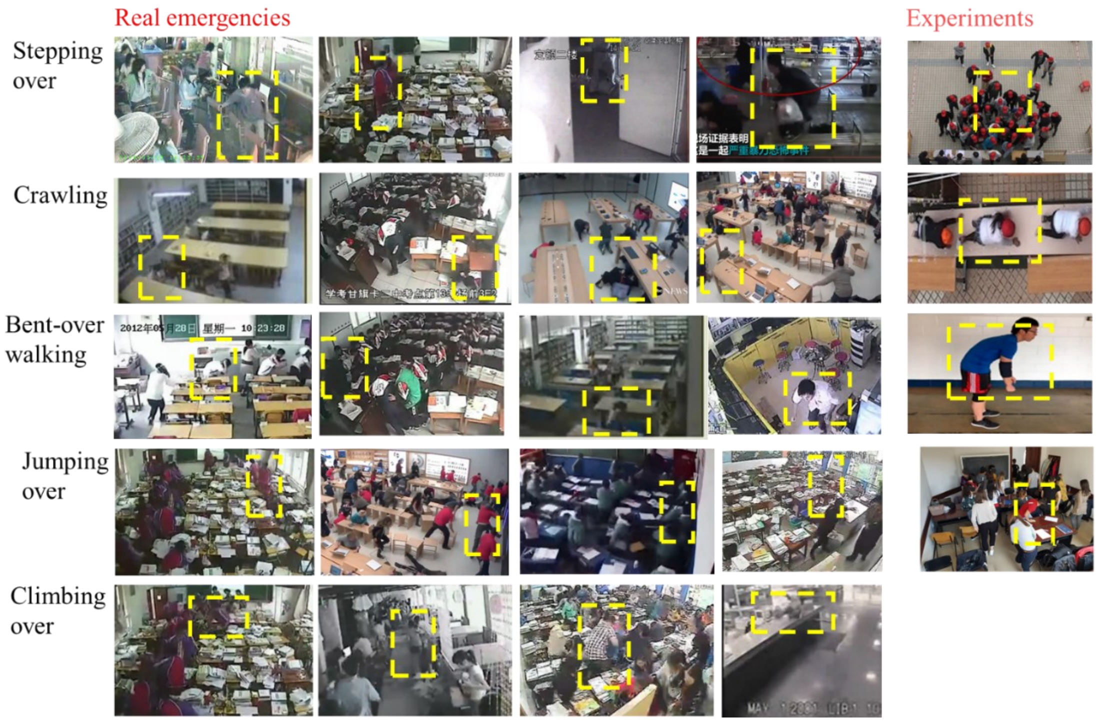
APPENDIX 1 A SELECTIVE SUMMARY OF REVIEW OF ACTUAL EVACUATIONS FROM THE CITED STUDIES



APPENDIX 2 COMPARISON RESULTS BETWEEN THE EVACUATION SIMULATION MODELS

Study		Liu et al., 2019	Guo et al., 2021	Song et al., 2021	Liu et al., 2022	Nagai et al., 2006	Zheng et al., 2017	Wang et al., 2020	Delcea et al., 2020a, Delcea et al., 2020b	Tugarinov et al., 2020	Tang and Ren, 2012
Category		SF model	SF model	SF model	SF model	CA model	CA model	CA model	AB model	AB model	AB model
Motions	Stepping over	√	×	×	√	×	×	√	×	?	×
	Crawling	×	√	×	×	√	√	×	×	√	√
	Bent-over walking	×	×	×	×	×	√	×	×	?	×
	Climbing over	×	×	√	×	×	×	×	×	√	×
	Jumping over	×	×	×	×	×	×	×	√	?	×
Placement relations	Front	√	√	√	√	√	√	√	√	√	√
	Back	√	√	√	√	√	√	√	√	√	√
	Above	√	×	√	√	×	×	√	√	?	×
	Beneath	×	√	×	×	√	√	×	×	√	√
	Left	√	√	√	√	√	√	√	√	√	√
	Right	√	√	√	√	√	√	√	√	√	√
Operational characteristics	Decision-making process	√	?	√	√	×	×	√	×	√	√
	Adaptive route choice	√	×	√	√	×	√	√	√	√	√
	Collision avoidance	√	√	√	√	√	√	√	√	√	√
	Heterogeneous pedestrian classes	√	×	×	×	×	×	×	√	√	√
	Computation burden	– –	+ +	–	–	+ +	+	–	–	– –	– –
	New infrastructure	+	– –	–	–	+	+	– –	– –	+	+

Note: SF model: Social Force model; CA model: Cellular Automata model; AB model: Agent-based model.