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Review

3D indoor environments in pedestrian evacuation simulations

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ABSTRACT

Using three-dimensional (3D) indoor environments in pedestrian evacuation simulations is increasingly active. However, a systemic review that reflects the latest advancements in this area is lacking. This paper surveys 3D indoor environments used in pedestrian evacuation simulations. Various physical and space components of 3D indoor environments are investigated by their semantics, topological relations and geometry. The results show reasons for the limited use of 3D indoor environments. First, semantics is oversimplified and lacks standardisation; second, the expression of topological relations is mainly based on the simplified boundary of objects' shape; at last, 3D geometry is insufficient for simulating some pedestrian motions and behaviours in 3D space. This paper itemises three priority areas for future research: 1) to enrich semantics and topological relations, 2) to further investigate 3D geometry, and 3) to foster the standardisation of 3D indoor environments. This work can stimulate more studies using realistic 3D indoor environments.

1. Introduction

Pedestrian safety in buildings is garnering considerable attention due to a dramatic increase in large buildings with complex floor plans and the frequent occurrence of accidents. Over 75 per cent of the world's population lives in towns and cities and spends approximately 90 per cent of their time indoors [1]. Emergencies, such as fires, earthquakes, gas leaks and terrorist attacks, can cause terrifying consequences in indoor environments. For instance, in 2003, arson in a subway station in Daegu, South Korea, resulted in 198 deaths, 146 injured and 298 missing. In 2015, 89 people died in terrorist attacks at the Bataclan theatre in Paris and more than 2,070 people died in the stampede during the 2015 Hajj pilgrimage in Mecca. In 2017, 72 people died, and more than 70 others were injured when a high-rise fire broke out in the 24-storey Grenfell Tower in London. In 2021, the floods in Zhengzhou subway stations in China killed 14 people. Efficient evacuation from indoor environments is pivotal in saving lives and ensuring pedestrian safety in serious emergencies.

Currently, pedestrian evacuation simulations have been used to anticipate where, when and why adverse evacuation events occur, allowing people to evaluate the evacuation status of indoor environments and thus serving as a foundation and basis for architectural design, emergency management strategies and evacuation plans. For evacuation simulation models, it is essential to describe and predict pedestrian evacuations in indoor environments as realistically as feasible. Significant efforts have been devoted to developing various simulation models and tools for this purpose. Nonetheless, most of the simulation models have been created and implemented using the two-dimensional (2D) plans of indoor environments in recent decades. In most cases, the 2D plans do not convey accurate details on indoor environments' geometric, semantic and topological information, thereby lacking realism in representing some likely evacuation motions and behaviours. For instance, furniture with different heights (e.g., desks, chairs), lowered ceilings or inclined walls are hard to accurately represent in 2D plans due to the lack of height information. In emergencies, some people inevitably prefer to crawl beneath or jump over desks to escape imminent danger (e.g., fires, earthquakes, terrorists) or for a quicker escape, while others may tend to bypass desks only. To simulate these motions, the height information of indoor features is absolutely required and is imperative. In response, 3D indoor environments in pedestrian evacuation simulations have become increasingly attractive for researchers, practitioners and the software industry.

Motivated by the increasing number of studies in the field of pedestrian evacuation, a number of literature reviews have been completed in recent years. Several syntheses of research have collectively covered the knowledge domain of pedestrian evacuation. Haghani [2] introduced the structural make-up of crowd dynamics, including its distribution across various disciplines, temporal and historical patterns of development, and pioneering and influential articles and authors. Musse et al. [3] discussed the history, evolution and new directions in

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crowd simulations. Liu et al. [4] used the scientific mapping knowledge domain to depict and assess the knowledge structure and research trends in pedestrian evacuation. Some prior studies [5–15] have also attempted to summarise available evacuation simulation models, relevant theories and specific evacuation modelling approaches. Furthermore, several studies [16–20] have focused on specific pedestrian dynamics, such as the evacuation performance of an obstacle near an exit [18] and the features of various pedestrian behaviours in different building emergency contexts [19].

Meanwhile, studies on 3D indoor modelling have been summarised well. These reviews have covered a relatively broad range of aspects including the generation and reconstruction of 3D indoor environments [21–24], 3D topological models [25], tessellations models in Geographic Information Systems (GIS) [26,27], 3D city models [28–30], integration of GIS and Building Information Modelling (BIM) [31,32] and 3D models for indoor/outdoor navigation [33,34]. It is observed that 3D indoor environments are always closely associated with the specific requirements of a particular application field, such as location-based service [35] and indoor navigation [36–39]. Although such reviews are immensely useful in embodying the fields of pedestrian evacuation and 3D indoor modelling more explicitly, none of the reviews directly link pedestrian evacuation simulations to 3D indoor environments. Therefore, pedestrian evacuations in indoor environments still lack a very important perspective.

This work aims to provide a systemic review of 3D indoor environments used in pedestrian evacuation simulations. To our best knowledge, this is the first literature review that concentrates on the use of 3D indoor environments in pedestrian evacuation simulations. The main contributions of this paper are as follows: 1) we concentrate on more generic properties of 3D indoor environments, namely semantics, topological relations and geometry, to provide a holistic perspective and avoid classification related to building types and functions, allowing readers to better understand various characteristics of 3D indoor environments; 2) we energise and bring further attention to 3D indoor environments within pedestrian evacuation simulations, which seem to be falling behind current studies, helping researchers in this field familiarise themselves with some significant and valuable publications; and 3) we critically identify the reasons for the limited use of 3D indoor environments for evacuation simulations and identify future directions, to prevent pedestrian evacuation research from stagnating and repeatedly surveying the same topics.

The rest of the paper is organised as follows. Section 2 introduces the definition used in this work when applying the term '3D indoor environment'. The research objectives and review methodology are presented in Section 3. Section 4 gives a brief overview of current research efforts. Sections 5 and 6 elaborate on each physical and space component in the light of semantics, topological relations, geometry and how they are used and considered in the simulations. Section 7 discusses the reasons for the limited use of 3D indoor environments for evacuation simulations. Section 8 has concluding remarks and recommendations for further work.

2. What is a '3D indoor environment'

For the scope of this review, we need an agreed definition of 3D indoor environments. Thus, this section explores defining this term more specifically. Notably, spaces in the field of indoor navigation provide a critical insight that an indoor environment is a continuous space consisting of space units or cells, which are divided into navigable (e.g., rooms, corridors and doors) and non-navigable spaces (e.g., walls and columns) [40–44]. Prominent inspiration is presented in two studies [40,41], in which one study [41] introduced a spatial subdivision of 3D indoor environments for indoor navigation by classifying indoor objects and their functions (see Fig. 1). Nevertheless, these uses of '3D indoor environments' do not give a direct point of reference for evacuation research purposes. Since no standard definition exists, we first define the term '3D indoor environment' for evacuation research purposes. Following some previously introduced concepts, this paper uses the following working definition:

'A 3D indoor environment is a subset of the 3D space, digitally described by the property types of semantics, topological relations and geometry. It is composed of physical components (static objects, movable objects and dynamic objects), which are located in space components (non-navigable, navigable under conditions and freely navigable) subdivided by the physical or virtual components (e.g., legal rights, access) and intended to support pedestrian evacuation.'

To manage, analyse and visualise indoor environments for evacuation simulation, 3D digitally virtual representations of indoor environments are necessary and useful. The three property types of 3D indoor environments, i.e., semantics, topological relations and geometry, are of particular importance in the digital description of indoor environments. Semantics identify and reference each physical and space component of 3D indoor environments. Topological relations are used to describe relations between physical and space components. Different relations can occur between physical and physical, physical and space, and space and space components. The 9-intersection model that uses the fundamental notions of general topology is applied in this work to present topological relations systemically. Eight topological relations, including disjoint, meet, contains, covers, inside, covered by, equal and overlap, can be distinguished between 3D objects (see Fig. 2) [25,45]. Geometry is characterised by dimension (2D, 2.5D, 3D geometry), representation (B-Rep, Raster), levels of detail (LOD) and realism (texture mapping, colouring). Specifically, B-Rep, also known as the 'boundary representation', depicts a polygonal shape bounded by its surface and has an interior and exterior consisting of a set of faces, vertices and edges [46]. By contrast, Raster aims to capture indoor environments using an array of discrete cells with equally/multiple shapes and resolutions, including 2D cells and 3D grids (voxels) [47]. LOD refer to geometry details for the digital representation of 3D indoor environments at different scales.

As depicted in the definition of 3D indoor environments, the physical and space components are composed of different objects and spaces, which are described in detail as follows:

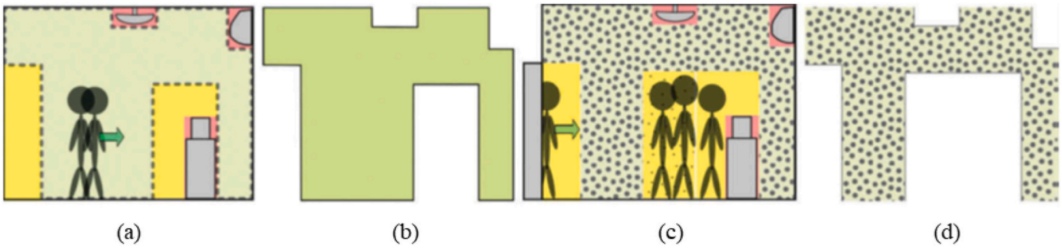


Fig. 1. Spatial subdivision of indoor environments involving non-navigable space (red), navigable space under conditions (yellow) and freely navigable space (light green). (a) 3D indoor environments that do not consider dynamic objects. (b) A freely navigable space without excluding dynamic objects (pedestrians). (c) 3D indoor environments considering movable objects and dynamic objects. (d) A freely navigable space excluding movable objects and dynamic objects ([41]).

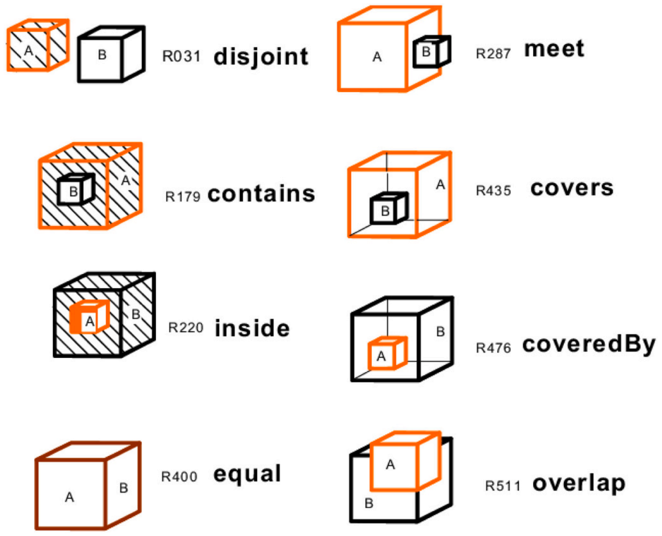


Fig. 2. Eight topological relations between 3D objects ([25]).

1) Physical components: static objects that can neither move by themselves nor rarely be moved (e.g., architectural components such as walls, stairs and columns); movable objects that cannot move by themselves but can be moved according to specific situations (e.g., furniture, machines); and dynamic objects that can move by themselves quickly (e.g., pedestrian queuing, autonomous robots). Physical components are always non-navigable spaces.
2) Space components: freely navigable spaces are obstacle-free and available for a pedestrian to pass through; navigable spaces under conditions are dedicated to the interaction between pedestrians and movable objects, or are occupied by dynamic objects; and non-navigable spaces are occupied by static and movable objects, or parts are non-navigable. Virtual components (e.g., legal rights, access rights) can also influence the navigability of space.

In summary, 3D indoor environments have been proven valuable for 3D indoor navigation and are expected to bring more benefits to pedestrian evacuation simulations [48–53]. This review is performed under the following assumptions. Firstly, events (e.g., fire, smoke, flooding) discussed in this study are presumed to be emergency circumstances, although they can start in a particular area within 3D indoor environments while moving dynamically. Therefore, fire, smoke and flooding are not considered in the composition of 3D indoor environments. Secondly, we concentrate on the walking evacuation mode of pedestrians, and wheeled motion modes (e.g., wheelchairs, scooters, trolleys, prams) are excluded from this work.

3. Research objectives and review methodology

Admittedly, evacuation modelling is one of critical aspects of pedestrian evacuation simulation, yet the objective of this study is to provide a systemic review of 3D indoor environments used in pedestrian evacuation simulations. There are four sub-objectives: 1) to interrogate and differentiate various research efforts related to this topic in the light of their application goals; 2) to elaborate on each physical and space component through semantics, topological relations, geometry and how the objects are used and considered in the simulations; 3) to objectively identify the reasons for the limited use of 3D indoor environments for pedestrian evacuation simulations; and 4) to set out possible priority areas for future research in this domain.

Fig. 3 summarises our framework to review the use of 3D indoor environments in pedestrian evacuation simulations. As mentioned above, 3D indoor environments are thematically decomposed into physical and space components. Three property types of 3D indoor environments (i.e., semantics, topological relations, geometry) are used to investigate these components. Specifically, Section 5 discusses the physical components of 3D indoor environments, including static objects, movable objects and dynamic objects, from the three property types and how each object is used in the evacuation simulations. Space components, consisting of freely navigable spaces, navigable spaces under conditions and non-navigable spaces, are described in Section 6

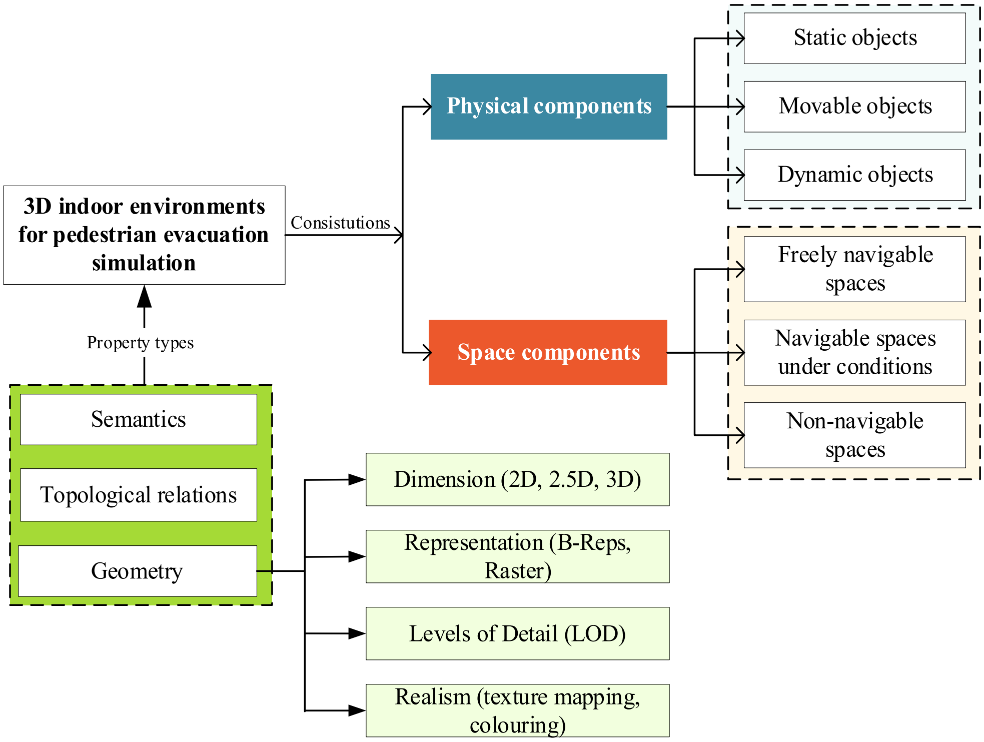


Fig. 3. Review framework for 3D indoor environments used in pedestrian evacuation simulations.

with their specifics in terms of semantics, topological relations and geometry but in the context of pedestrian evacuation. Finally, Section 7 summarises the limited use of 3D indoor environments for pedestrian evacuation simulations from the perspective of the three property types.

In this review, we identified the most relevant publications by the following steps. First, we conducted a comprehensive literature search in terms of 'title/abstract/keyword' via search engines, including the Scopus database and Web of Science Core database. We used combinations of the keywords including '3D OR three dimension*', 'evacuat* OR escap* OR egress', 'simulat* OR model*', 'object OR obstacle OR barrier OR obstruction' and excluded some papers from disciplines that do not focus on our topic such as Medicine, Materials Science, Neuroscience and Energy. To further enrich the search results, a backward and forward snowballing strategy was also applied, based on references and authors of publications that were returned from the search. This review covers a wide range of materials of various types, including journal articles, books, conference proceedings, international standards and technical notes. Only literature published in the English language was considered as it is widely accessible to readers worldwide. No restriction was set on the time span of the search or document type since no previous review articles followed our perspective, and the search was updated for the last time in May 2022.

The second stage of the review involved becoming familiar with the literature by reading. Subsequently, we filtered and refined the above search result by satisfying any of the following selection criteria associated with our topic: 1) using 3D indoor environments in pedestrian evacuation simulations; and 2) the depth and extent of the simulations using 3D indoor environments. By following the above criteria, we excluded papers about evacuation simulations in the outdoors, 3D disaster simulations (e.g., fire scenes, flooding) and evacuation training applying virtual reality techniques. Studies regarding optimal path planning that did not perform evacuation simulations were also considered out of the scope. By applying this process of academic literature review, we obtained the published research on using 3D indoor environments for pedestrian evacuation simulations.

As a result, a total of 106 publications are included in this review. Published between 2001 and 2022, the total includes 2 book chapters, 6 conference papers, 88 journal papers, 4 international standards (scheme) and 6 technical notes. The top five sources of these publications are the following journals: *Physica A: Statistical Mechanics and its Applications* (10), *Safety Science* (8), *Automation in Construction* (6), *Journal of Building Engineering* (4), and *Simulation Modelling Practice and Theory* (4). Journals from geographic information science and transportation disciplines are also important sources, including *ISPRS International Journal of Geo-Information* and *Journal of Advanced Transportation*. Four standards (data schemes) are mentioned: CityGML 3.0, IndoorGML 1.0, Industry Foundation Classes (IFC) 4.3.0 and American Institute of Architecture (AIA) G202-2013 scheme. Six technical notes are related to evacuation simulation software packages widely used in the cited papers, including AnyLogic, Pathfinder, MassMotion, BuildingEXODUS, FDS+EVAC and Unity 3D. The top five countries of origin are Mainland of China (43), South Korea (6), the UK (5) and Singapore (4). Fig. 4 presents the number of book chapters and papers each year. The earliest studies were published in 2001. From 2001 to 2014, the number of related studies is stable at a low level. Many publications emerged recently in the years of 2018 (12), 2019 (16) and 2021 (19), further substantiating that the use of 3D indoor environments in pedestrian evacuation simulations has gained growing traction within recent years.

4. Overview of the literature

The section presents an overview of research efforts using 3D indoor environments for pedestrian evacuation simulations. In the light of the application goal, we classify the research efforts into three areas: 1) simulation of pedestrian evacuation motions and behaviours; 2) 3D optimal evacuation path planning; and 3) creation of 3D indoor environments. Appendix A summarises the 96 reviewed studies (2 book chapters, 6 conference papers and 88 journal papers) discussed in this subsection. The studies are listed in a chronological order according to their year of publication.

The first cluster of studies focuses on the simulation of pedestrian evacuation motions and behaviours in 3D indoor environments. According to spatial dimensions considered in modelling pedestrian motions and behaviours, two categories of studies can be further differentiated as 2D/2.5D pedestrian evacuation simulations and 3D pedestrian evacuation simulations. 2D/2.5D pedestrian evacuation simulations refer to simulating a series of pedestrian motions and behaviours existing in the horizontal dimension and sloped stairs or escalators. Examples are bypassing obstacles, lane formation and stop-and-go waves. In other words, pedestrians are always modelled as walking upright and recognised as moving points or cells in 2D horizontal plans or 2.5D sloped surfaces of stairs or escalators, interacting horizontally with other pedestrians and indoor environments. The

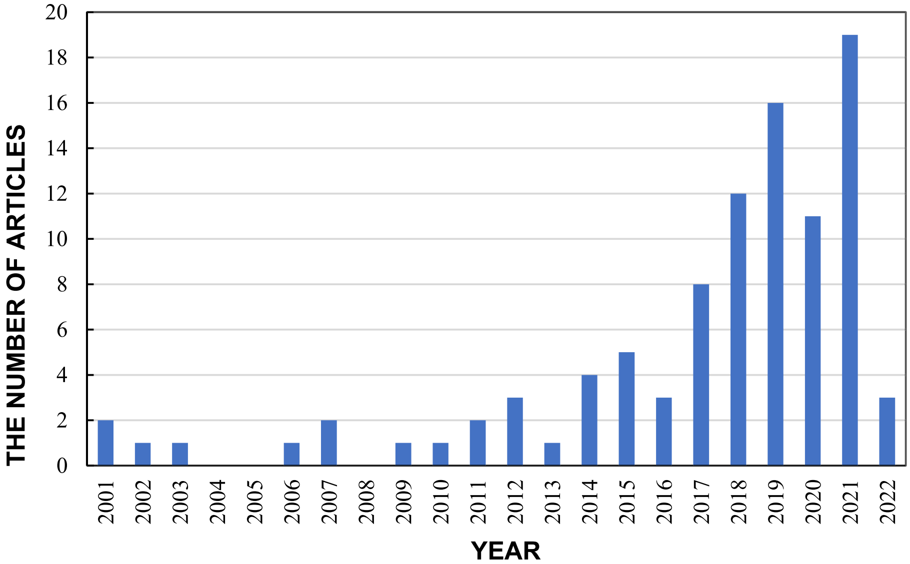


Fig. 4. Number of articles on using 3D indoor environments for pedestrian evacuation simulations published annually.

height information of physical and space components is not fully considered during evacuation modelling. Two groups of studies are distinguished by the various simulation approaches adopted in 2D/2.5D pedestrian evacuation simulations. Most of the studies have been devoted to applying simulation software packages directly, such as Pathfinder, MassMotion and AnyLogic. For example, Rostami and Alaghmandan [54] used Pathfinder to evaluate the evacuation performance of an elementary school to investigate how much the change in geometrical parameters of stairs (width, landing depth, stair forms) influences the optimisation of evacuation time. By comparison, the second group of studies established their own evacuation simulation models. Haghani and Sarvi [55] used empirical data, econometric modelling and 2D evacuation simulation to report the role and nature of individual differences in perception of peer behaviours while facing exit choice. Zhao et al. [56] proposed a social force model to reproduce the swaying behaviour of pedestrians on stairs, yet the motion speed on stairs is calculated based on 2.5D sloped surfaces.

As shown in Appendix A, a few studies deal with 3D pedestrian evacuation simulations using 3D indoor environments. The distinct difference from the 2D/2.5D category is that they take crowds or individuals as a research object and try to advance evacuation simulation models based on 3D space for replicating the likely pedestrian motions and behaviours such as stepping on stairs, crawling, climbing over, or jumping over. For instance, one study [57] configured seven categories of behaviour rules for an individual, such as crawling and moving through, in which an individual chooses to crawl when the height of smoke is capable of influencing walking normally upright (see Fig. 5). Li et al. [58] considered the effect of stairs' 3D geometry on pedestrian behaviours supported by an experimental survey and established a social force model to reproduce pedestrian motions on stairs by integrating a heightmap.

The second cluster of studies sought to determine 3D optimal evacuation paths of indoor environments for emergency managers and rescue teams. These studies [59–61] framed hierarchical and hybrid model architecture. At the macro level, a 3D network of an indoor environment and an optimal path-planning algorithm were adopted to find optimal evacuation paths. At the micro level, regular evacuation simulation models predicted pedestrian motions and behaviours to estimate the pedestrian density in the network (see Fig. 6). This kind of hybrid architecture is expected to provide optimal evacuation paths with a large reduction of computation time while discovering evacuation bottlenecks of 3D indoor environments that are most likely to become non-navigable. Boguslawski et al. [59] applied Dijkstra's algorithm to determine optimal evacuation paths in a 3D network and evaluated the pedestrian density in the network by performing an agent-based model. Two studies [60,61] extracted the networks of 3D indoor environments at the macro level for optimal path planning and conducted evacuation simulations synchronously at the micro level. Normally, evacuation time is the primary measure of the quality of the proposed optimal path planning.

Fig. 5. Simulated crawling motion under smoke conditions ([57]).

The third cluster of studies focused on the creation of 3D indoor environments for pedestrian evacuation simulations. Of the two categories, multiple studies [62–70] aimed to foster data sharing, interoperability and integration between 3D modelling and evacuation simulation models. For instance, a study [63] reported a method to convert IFC entities to a macroscopic evacuation model for simulations. On the other hand, the subdivision and enrichment of 3D indoor environments has received limited attention [71–73]. Gorte et al. [72] demonstrated that 3D voxel models are a good foundation for studying various aspects of evacuation modelling. Another study [71] proposed a method to automatically classify and subdivide the various physical components and subspaces for evacuation simulations.

We recognise that each of the cited papers was conducted with a specific objective, and very few papers focus on the creation of 3D indoor environments. Since the papers provide some clues about the needed 3D indoor environments, we can still analyse them to investigate the characteristics of 3D indoor environments to suit evacuation simulations.

5. Physical components of 3D indoor environments

As pointed out earlier, static, movable and dynamic objects constitute the physical components of the indoor environment. For the scope of this review, these objects are discussed in the following subsections from the perspectives of the three property types (i.e., semantics, topological relations and geometry) and how the objects are used and considered in the evacuation simulations.

5.1. Static objects

In general, the semantics, topological relations and geometry of static objects are rarely updated and changed. In some cases, nevertheless, all these properties may change over a period. For example, static objects in construction sites can be updated daily. Evacuations in such a situation have been simulated in a study [74] using 4D BIM to describe the changes in static objects. After reviewing the cited studies, we identified the basic elements of static objects in the evacuation simulations into floor slabs, walls, columns, ramps, stairs, escalators and lifts. Although escalators and lifts can vertically move up and down, they are usually permanent structures in a stationary position between floor slabs. Accordingly, we consider them static objects.

5.1.1. Floor slabs, walls and columns

Floor slabs, walls and columns mainly correspond to structural and architectural components that provide load-bearing support, separate spaces into parts and classify the parts according to different functions.

A floor slab is semantically defined as a planar and flat part of the structure of a building that can indicate a walkable area where pedestrians are standing. Most of the cited studies and evacuation simulation software packages adopt the term ‘floor’ to refer to a horizontal 2D plan that defines a 2D walkable area for pedestrians, a structural building element or a storey that depicts all the rooms or areas on the same level. However, the term ‘floor’ easily confuses distinguishing between the object and storey. For example, a study [75] not only stated that floors are the structural components of a building but also used a floor to indicate a storey to explain the evacuation time of a storey. Furthermore, a floor slab is a fundamental premise for topologically organising and clustering other objects and spaces. The topological relation of a floor slab with a room, zone or storey can be the inside relation. For example, Tang et al. [76] specified several function zones in a passenger terminal building (e.g., the queuing area for tickets in arrival lounges) that incorporate a collection of objects such as floor slabs and stairs. Additionally, there is the disjoint relation between two floor slabs and the

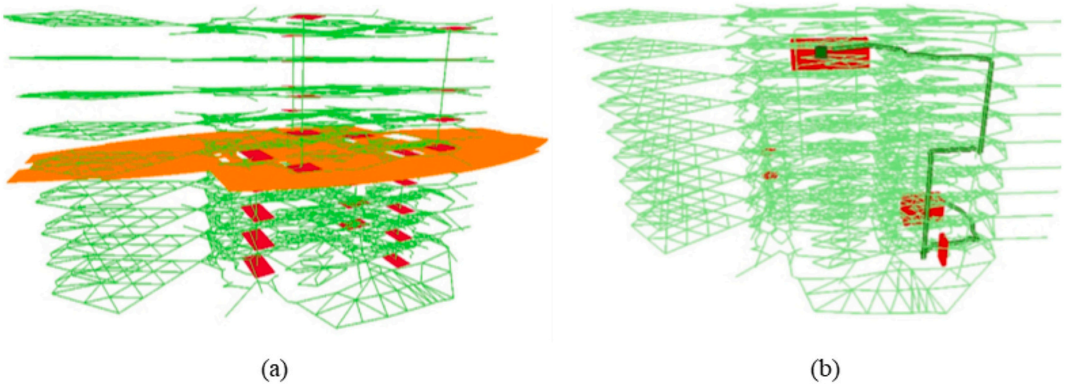


Fig. 6. 3D networks for evacuation simulation and optimal evacuation path planning. (a) The density of pedestrians in the network (orange/red colours represent different density). (b) Optimal evacuation path (dark green) ([59]).

meet relation between a floor slab and its associated walls, columns, stairs, and furniture.

Regarding geometry, floor slabs are usually represented by B-Rep and can be configured with a constant thickness as 3D solids or in the form of 2D polygons. In addition to B-Rep, the voxel representation is used in a study [72] to create floor slabs and stairs with a layer of voxels. Currently, only the constructional part of floor slabs is modelled in the reviewed literature. The upper finish (flooring, roofing) and the lower finish (ceiling) are not reported. Floor slabs can have holes to form courts, atriums, lift shafts, etc. Generally, each floor slab incorporates a separate and distinct aggregation of non-navigable and navigable spaces derived from the 2D geometry of floor slabs' top surfaces. The 2D top surfaces are considered and extracted for evacuation simulations. Moreover, the LOD of floor slabs entail an overall size, thickness parameter and geometry of the floor slabs. Although the colour of floor slabs is commonly applied in the studies, texture mapping is seldom considered to alter the motions and decision-making of pedestrians in the simulations. Only a study by Busogi et al. [77] used a weight affordance to consider the difficulty level in actualising "walk" because of dry or wet floor slabs. So far, sloped floor slabs have not been treated differently in studies. Pedestrians walking on the surface of floor slabs always move at the same horizontal speed regardless of the slope of the floor slabs, meaning pedestrians on both the flat and sloped configurations take the same time to reach the exit.

Semantically, walls and columns are extensively regarded as a type of vertical structure and boundary that may bound or subdivide spaces. An example is from Pathfinder [78], in which each room is bounded on all sides by walls. The topological relation of walls and columns with an associated room, zone and storey is the inside relation, while the relations with other objects (e.g., walls, furniture) are usually the disjoint and meet relations. Regarding geometry, walls and columns are similar to floor slabs with respect to dimension (3D solids, 2D polygons), B-Rep, LOD and realism. Generally, in studies [62,79–85] and each of the simulation software packages the two static objects of walls and columns are defined as a kind of obstacle that restricts pedestrian motions and behaviours (e.g., the obstruction of visual accessibility). For instance, Kwak et al. [62] considered that walls and obstacles block pedestrians' visibility and adopted a visibility field to divide the whole indoor space into subspaces depending on different levels of visibility. Cheng et al. [85] used a visibility graph to realise path planning for pedestrians encountering multiple walls and obstacles.

5.1.2. *Ramps, stairs and escalators*

Semantically, ramps, stairs and escalators are sloped passageways allowing pedestrians to walk or step from one floor slab to another floor slab at a different elevation. In particular, several kinds of semantics related to stairs are used, including 'stair', 'stairway', 'staircase' and 'stairwell'. For example, a study [86] used the terms 'stair' and 'staircase' simultaneously. In comparison, the term 'stair' is the most used in the studies. As the three kinds of objects in the simulations can be placed in a room, zone or storey, the topological relation of the objects with an associated room, zone and storey is the inside. An example is that a lecture theatre in a study [56] contains stairs. Moreover, the objects connect and intersect with related floor slabs, but the interiors do not, so the topological relation between the three kinds of objects and the floor slabs is the meet. Finally, the three kinds of objects in the simulations maintain the disjoint and meet relation with other objects, such as furniture and walls.

In terms of geometry, some ramps, stairs and escalators may have flat landings, whereas handrails are not considered and incorporated in the evacuation simulations. At present, the studies fall into three categories with respect to their geometry (see Fig. 7). A common method is based on B-Rep to represent a stair or escalator flight and a ramp as a 2.5D sloped surface that is continuous, and all locations on the surface can have only one elevation or z-value, per x, y coordinate. A stair-unit model provided by Li et al. [87] describes a stair flight as a 2.5D sloped surface, while another study [88] examined congestion risks in escalators whose flights are handled as a 2.5D sloped surfaces as well. All stair or escalator flights and ramps represented in the reviewed simulation software packages are in the form of 2.5D sloped surfaces to be considered and computed during evacuation simulations. Further to these studies, several studies argued that pedestrians stand perpendicular to the horizontal plane of stairs' steps rather than the sloped surface. Specifically, a stair, including flights and landings, is a 3D surface that can store true 3D or multiple z-values, per x, y coordinate. To extract the 3D surface, several studies [71,89–91] discretised stairs into uniform voxels. In a different approach from voxels, Li et al. [58] introduced a 3D height map, a function of 3D positions to scalar height values, to describe the ground topography of stairs. The LOD of ramps, stairs and escalators can have two categories. The first category is mainly about 2.5D sloped surfaces through approximating overall dimensions and the geometry of landings and flights. The second category is related to the 3D surfaces using voxels and yet does not have clear provided LOD, although the voxels are configured with different resolutions. Finally, the realism of the three kinds of objects is limited to colouring.

A cohort of studies [54,77,92–101] illustrated that the number, positions and geometry of the three kinds of objects can affect pedestrian decision-making processes and evacuation efficiency. For instance, Shams Abadi et al. [99] indicated that when narrower staircases are blocked because of construction or fire, selecting other (wider) exits can speed up the overall evacuation time. Moreover, a study [73] argued that stairs are more costly in time to traverse when pedestrians step on the object. In particular, Hunt et al. [102] established an evacuation model to simulate a scenario in which assistance devices are used to evacuate patients in hospital settings, and pedestrian motions using the

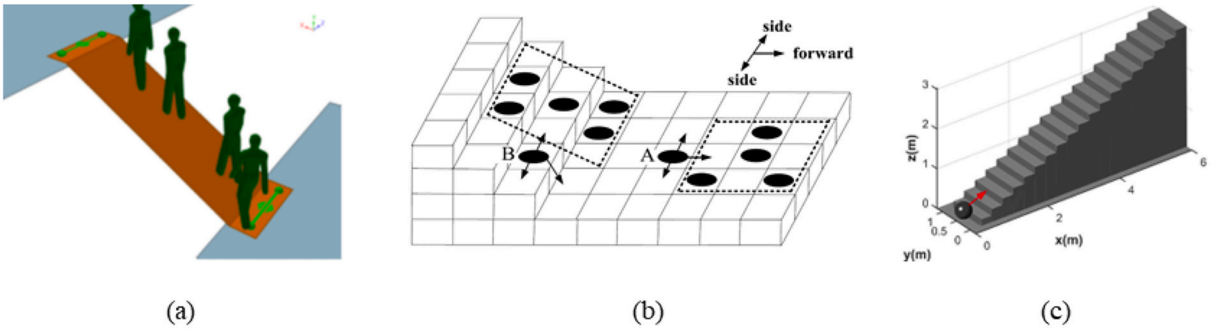


Fig. 7. Three kinds of stairs in pedestrian evacuation simulation. (a) 2.5D sloped surfaces ([103]). (b) Steps discretised into 3D voxels with a certain height ([90]). (c) 3D geometry of stairs using a heightmap ([58]).

devices within stairways have periodical stopping.

5.1.3. Lifts

Lifts transport and move pedestrians vertically, connecting many floor slabs. The term ‘elevator’ is also used in the reviewed studies to indicate the same object. Topologically, lifts mainly retain the meet relation with floor slabs and the disjoint and meet relation with other objects. Commonly, the geometry of a lift shaft is simplified into a rectilinear prism (see Fig. 8). The LOD of lift shafts can be a generic representation of the 3D solids with approximate size, whereas the realism of lift shafts is not considered. Although lifts are not deemed sufficiently safe during evacuation processes, there has been a surge in interest [86,93–95,104–106] in the simulation of lifts to evacuate high-rise buildings, underground spaces and ships. For instance, Kinsey et al. [106] proposed a model to simulate a lift’s motions (i.e., maximum speed and distance, acceleration and deceleration), delay periods and capacity during evacuations. With the help of a simulation software package, Soltanzadeh et al. [93,95] examined the best position and layout of vertical access (stairs and lifts) in high-rise buildings and the performance of the number and location of the access points.

5.2. Movable objects

The semantic information of movable objects is not clearly defined in the cited studies, yet the objects have frequently occurred in simulations for the past few years. Common examples include furniture, fences, automatic ticket gates and signs, which are generally lighter and smaller relative to static objects. Regarding topological relations, movable objects maintain the inside relation with an associated room, zone and storey. As movable objects are mostly placed on associated floor slabs, the relation between the two sorts of objects is the meet. For other static objects and dynamic objects, the disjoint or meet relation can describe their topology with movable objects.

Similar to static objects, movable objects have a geometry of 3D solids or 2D polygons, which are represented by B-Rep. With respect to the LOD of movable objects, they are modelled with approximate nominal size. Colouring and texture mapping can be applied to movable objects, which does not yet affect simulating evacuation motions and behaviours. Most notably, the bounding box approach is extensively used to simplify and generalise the 3D solids of movable objects when they are used in navigable spaces, especially for highly irregular shapes with a large number of faces like desks, chairs and machines. Specifically, the objects are represented geometrically by solids and defined by their minimum bounding surfaces [33]. These surfaces must be non-overlapping, non-penetrating and completely seal a 3D solid without gaps and spaces, thereby occupying spaces and impeding pedestrian motions and behaviours as obstacles. A study [85] particularly looked at using the bounding box approach to simplify the representation of obstacles. Geometric (length, width, height, and location coordinates) and semantic information (risk level) was also extracted in their work. An example from indoor navigation explicitly illustrates the bounding box approach to represent movable objects (see Fig. 9).

Regarding the use of movable objects in evacuation simulations, desk and furniture items are used in two studies [108,109] as obstacles that pedestrians will adapt their path to avoid. A study [68] identified fences and automatic ticket gates as facilities affecting the evacuation efficiency evaluation of metro stations. Through simulations, Selin et al. [70] argued that it is important for pedestrians to go past the exit lines adjacent to the cash desks unhindered in a shopping centre. Further to these studies, Liu et al. [110] implemented a 3D collision avoidance algorithm. If the height of an obstacle is greater than the maximum height that a pedestrian can step over in a horizontal collision, the pedestrian will change motion direction. Otherwise, the pedestrian can stay on his or her path. Vertical collision avoidance ensures pedestrians do not float up or fall through the floor while moving (see Fig. 10). The effect of evacuation signs on pedestrian evacuations in 3D space has

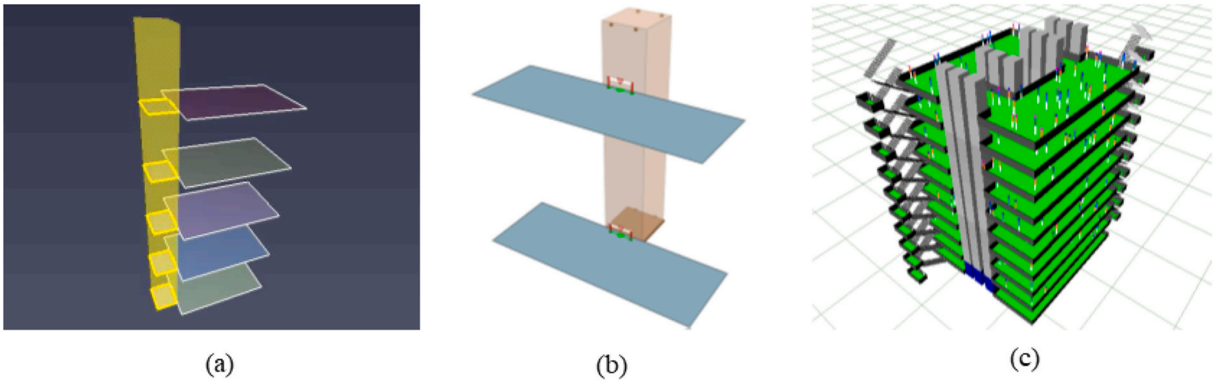


Fig. 8. Geometry of lift shafts in three simulation software packages: (a) Pathfinder ([78]). (b) MassMotion ([103]). (c) buildingEXODUS ([107]).

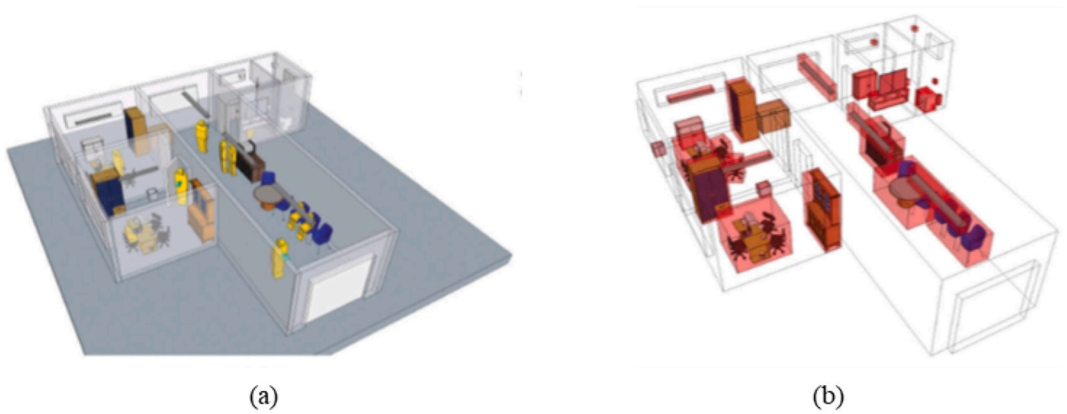


Fig. 9. The bounding box approach to represent movable objects. (a) Original movable objects. (b) Movable objects represented as solids ([41]).

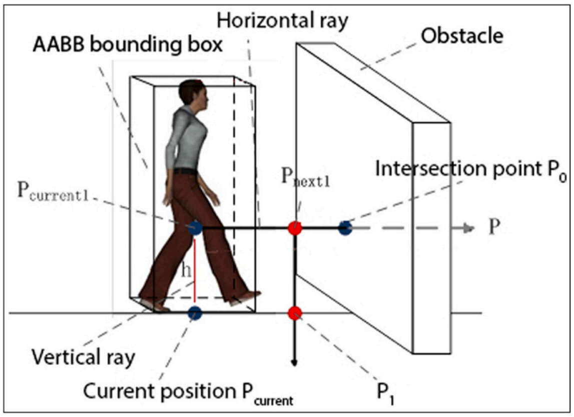


Fig. 10. Diagram of 3D collision avoidance during an evacuation ([110]).

received limited attention in the reviewed literature. Motamedi et al. [83] proposed a sign visibility analysis and optimisation system, which can simulate the movement of pedestrians directed by signs. Becker-Asano et al. [111] reported a model enabling pedestrians to dynamically perceive and check their surroundings for visible signs dynamically. BuildingEXODUS can test where each sign, or combination of signs, is visible in certain areas and evaluate the effect of signs on pedestrian evacuations [107].

5.3. Dynamic objects

From a semantic perspective, no clear information regarding dynamic objects is found in the reviewed studies. A crucial difference that discriminates dynamic objects from movable objects is that dynamic objects must be refreshed in a shorter time frame. In the current literature, it is evident that pedestrians are the primary source of dynamic objects considered in evacuation simulations. Note that we consider a group of pedestrians as one dynamic object in 3D indoor environments instead of each pedestrian as a dynamic object. Mobile machines (e.g., drones, robots that guide the evacuation) and other dynamic objects are not observed. Like movable objects, dynamic objects retain the inside relation with an associated room, zone and storey, the meet relation with related floor slabs and the disjoint or meet relation with other objects. Moreover, the geometry, LOD and realism of a group of pedestrians is not provided in the literature. However, a study [112] established a grouping method of pedestrians. Their algorithm configures individual pedestrians into the 2D plans with relationship and position information. Then, a top-down grid partition is implemented based on a series of weighted relationship density values, forming several pedestrian groups in several 2D grids with various sizes. Finally, each pedestrian is visualised with 3D geometry (see Fig. 11).

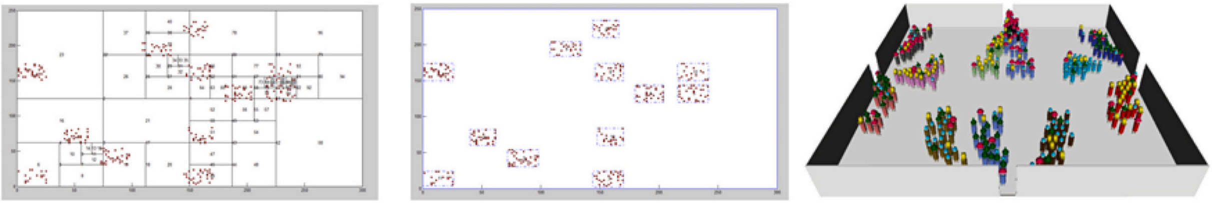
A stream of studies has looked at dynamic objects. A study [113] proposed a system to detect and track pedestrian locations and motions based on smart sensors. Then, the collected data was used for evacuation simulation. Furthermore, dynamic objects are often considered obstacles. A number of the studies [68,114–121] suggested that exits, stairs and escalators can be judged unsuitable for evacuations due to their congestion at high density with a group of pedestrians. Meanwhile, pedestrians who have just passed the exit during the evacuation process can also become a kind of obstacle [122]. Further to this consideration, Haghani and Sarvi [55] argued that individual pedestrians do not simply choose the same alternatives that a group of pedestrians chooses, and individuals have a heterogeneous perception of peer influence when facing binary exits. Three studies [77,104,106] also showed a group of pedestrians as obstacles occupying the waiting areas in front of lifts for a certain time. Finally, several studies [57,105,123,124] considered the phenomenon that some pedestrians may need a pre-movement time to be ready before starting to evacuate in their simulations.

Exploring the above content related to physical components, it is explicitly observed that the standard LOD for physical components are only considered in a few studies, in which CityGML and AIA G202-2013 are referenced as a guide. CityGML has a standard module describing the different accuracies and minimal dimensions of objects in cities using LOD from different levels [125]. Using LOD 4 of CityGML 2.0, Xiong et al. [73] modified IndoorGML classes to incorporate and represent physical components and their relations. By comparison, AIA G202-2013 defines various kinds of LOD to characterise the exact level of the BIM model from levels 100 to 500 [126]. The LOD 200 are applied in two pieces of research [99,123] to create 3D indoor environments for evacuation simulations, while Wehbe and Shahrour [113] employed LOD 300 to yield more details.

To summarise the above analysis, we put each physical component into contrast (see Table 1) based on their three property types, i.e., semantics, topological relations and geometry, consistent with what we have elaborated upon.

6. Space components of 3D indoor environments

Inspired by IFC, CityGML, IndoorGML and existing information [41–44,125,127,128], the binary partitioning of spaces into either navigable/unoccupied or non-navigable/occupied motivates the classification of space components in this work, notably freely navigable spaces, navigable spaces under conditions and non-navigable spaces. So far, an extensive approach in the reviewed studies to identify and subdivide or aggregate the space components is based on the geometry and function of physical components in conjunction with other aspects (e.g., access rights). The three space components are non-overlapping and



(a) (b) (c)

Fig. 11. Grid partition for grouping pedestrians ([112]).

Table 1

Summary of the three property types of each physical component.

Property types			Physical components								
			Static objects							Movable objects	Dynamic objects
			Floor slabs	Walls	Columns	Ramps	Stairs	Escalators	Lifts		
Semantics			?	√	√	√	√	√	√	?	?
Topological relations	Disjoint		√	√	√	√	√	√	√	√	√
	Meet		√	√	√	√	√	√	√	√	√
	Contains		×	×	×	×	×	×	×	×	×
	Covers		×	×	×	×	×	×	×	×	×
	Inside		√	√	√	√	√	√	√	√	√
	Covered by		×	×	×	×	×	×	×	×	×
	Equal		×	×	×	×	×	×	×	×	×
	Overlap		×	×	×	×	×	×	×	×	×
Geometry	Dimension	2D/2.5D	√	√	√	√	√	√	×	√	×
		3D	√	√	√	√	√	√	√	√	×
	Representation	B-Rep	√	√	√	√	√	√	√	√	×
		Raster	√	√	√	√	√	×	×	×	×
	LOD		-	-	-	-	-	-	-	-	×
	Realism	Texture mapping	+	+	+	-	-	-	-	+	×
		Colouring	++	++	++	++	++	++	++	++	×

Note: √ = Has relevant information; × = No relevant information; ? = Unclear information; ++ = Very detailed; + = Detailed; - = Low detail; - - = Very low detail.

represent a complete subdivision of 3D indoor environments, having their own specificities in terms of semantics, topological relations, geometry and specificity about pedestrian evacuations, which are explained in the following subsections.

6.1. Freely navigable spaces

Freely navigable spaces are not only obstacle-free spaces or surfaces where pedestrians can move, but also spaces (e.g., rooms, lifts) which grant access and/or legal rights to an individual during evacuations. The semantic information of freely navigable spaces is not explicit in the literature. In IndoorGML [128], navigable spaces represent indoor spaces (e.g., rooms, corridors, windows, stairs) that a navigation application can use. Two studies [83,84] used navigable areas to represent surfaces where pedestrians stand and move, while a study [65] and CityGML [125] used unoccupied spaces to represent spaces that are not blocked by any physical components. Most of the studies also regard openings that provide indoor and outdoor access as freely navigable spaces. Nevertheless, some studies do not make a semantic distinction between an opening and the physical parts of a door. For example, a study used the term ‘exit’ and ‘exit door’ to present an opening used by students to leave a classroom [108]. By comparison, in IFC [127], CityGML [125] and IndoorGML [128], an opening refers to the space when a door is open, while a door is a built element for closing an opening.

Topologically, freely navigable spaces can be organised in a hierarchical structure according to their functions. For example, a study [119] organised openings, rooms and corridors in part of a fire zone and storey for evacuation simulations. The relation between the freely navigable spaces and spaces at upper levels is the inside relation. The disjoint and meet relations describe the topological relations between freely navigable spaces and non-navigable spaces. Several studies [60,61,129,130] used a space-based topology to define the location of and connectivity between freely navigable spaces. The Poincaré Duality is the theoretical basis for the derivation of navigable networks, which is also the basis of IndoorGML [43]. Nodes represent freely navigable spaces, and edges denote the connectivity relationship between them. The studies consider rooms, corridors, halls, openings etc., as navigable spaces free of movable objects, dynamic objects or other space components. Each room is approximated by a node, and an edge represents the connectivity between the rooms, which may correspond to surfaces between adjacent spaces, doors or corridors between rooms.

Depending on the geometry/structure method employed by the existing studies, freely navigable spaces are differentiated into navigable meshes (2D/2.5D) and discrete cells (i.e., Raster). Firstly, the navigable meshes are derived from the 2D geometry of floor slabs’ top surface and 2.5D surfaces of stairs, escalators and ramps (see Fig. 12a). The meshes are made as being continuous, represented mainly by triangles. After the meshes are created, pedestrians can move horizontally and vertically on a continuous surface covering the entire building. The Voronoi diagram is also one sort of representative mesh applied to segregate freely navigable spaces [131]. A study [59] used the Voronoi diagram to extract 3D networks of indoor environments for 3D optimal evacuation path planning. In their study, meshes are 2D and 2.5D, but their network in 3D space is in a multi-layered structure representing topology such as spatial relations between rooms. The navigable meshes are widely applied in a large body of studies [56,61,79,80,87,88,110,114,116,122,131,132] and several reviewed simulation software packages [78,103,133–135], especially adaptable for the use of social force models and some agent-based models.

The discrete cells subdivide 3D indoor environments into a finite

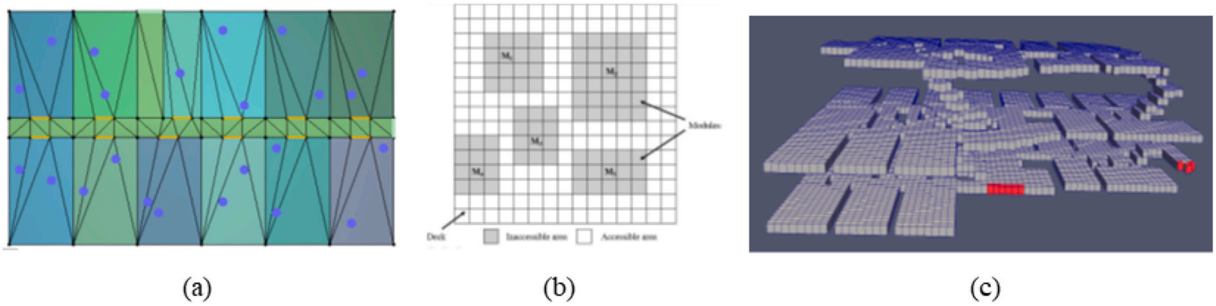


Fig. 12. Types of geometry/structure method for freely navigable spaces. (a) Navigable meshes ([78]). (b) 2D cells ([85]). (c) Voxels ([72]).

number of non-overlapping cells, usually square. Each cell gains semantics according to the underlying objects (e.g., walls, doors). This approach enables precise localisation of physical components and pedestrians if the size of cells is appropriate. Discrete cells can be 2D cells and voxels. 2D cells have been proven to be popular in cellular automata models and some agent-based models. A substantial number of studies [60,62,65,66,85,136–140] and the buildingEXODUS software package [107] are predominantly based on 2D square cells (see Fig. 12b). In the 2D square grids, pedestrians are generally modelled to move between neighbouring grids with fixed movement directions, either in four basic directions (front, left, right, back) or eight (the four basic and four diagonal directions). As well, 2D cells with various shapes and attributes can be applied. A study [57] discretised the geometry of floor slabs' top surfaces into 2D circle nodes. In order to distinguish geometric attributes of horizontal and vertical spaces, Xiong et al. [73] established two categories of square cells, one with elevation and another with elevation and slope. A study by Song et al. [141] applied 2.5D cells that refer to 2D square cells configured with elevation and semantic attributes. On the other hand, voxels are the extension of 2D cells to represent 3D indoor environments, and most of the studies used voxels for stairs (see Fig. 12c). Several studies [89–91] simulated evacuations on stairs and subdivided only stairs into voxels, yet the height of the voxels is not compatible with the riser height of usual stairs in the real world. In a follow-up and more recent publication, Aleksandrov et al. [71] especially looked at a heightmap using voxels to correctly represent stairs' parameters and accurately locate pedestrians on stairs. Only a study by Gorte et al. [72] used voxels not only for stairs. They also created a navigable space by constructing a 5-voxel thick layer of voxels on every floor slab.

Currently, no specific LOD is dedicated to freely navigable spaces in the reviewed studies. However, the resolution of freely navigable spaces can be controlled by the size of the grid. Environment-based and agent-based methods are identified to determine the resolution. For the former, the grid size is configured based on environmental considerations. Only one study [72] adopted the first method using a voxel resolution (4.55 cm) to adapt to indoor environments. In contrast, a large body of research relies on the 2D body dimension of a pedestrian to assign 2D cells' size. One reason to consider a pedestrian's size in the divided cells is to locate pedestrians readily. Another common reason is to avoid multiple pedestrians occupying the same cell [12], satisfying the operational rules of some cellular automata models and agent-based models. A common size of cells is 0.4m × 0.4m, which has been used in many studies [62,65,85,89,90,136–140]. Either larger or smaller cell sizes are also found [66,72,73,91,102,141].

In terms of the use of freely navigable spaces in evacuation simulations, a group of studies [63,91,96,115,117,123,142–145] demonstrated that the width of openings controls the number of pedestrians who pass through openings. However, several studies looked at the influence of openings' physical components. Khan et al. [146] indicated that when there was no proper compartmentation, the rapid smoke propagation from an open fire door increased the required safe evacuation time by about 20% compared to the same fire scenario with closed doors. According to a study [147], the best door plank opening degree is 115°∼135°, which can reduce evacuation time. A recent study [148] revealed that a room with a convex exit is more efficient and safer than a classical plan of exit. Freely navigable spaces can be navigable under conditions and non-navigable because of virtual components (e.g., access, legal rights). For instance, medical staff offices, counselling rooms and medical equipment rooms forbidden for patients to enter are considered in the evacuation simulation of a study [149]. Wang [150] transformed ticket-selling areas in a subway station into non-navigable during evacuation simulations. Finally, freely navigable spaces can be shelters for pedestrians. Based on obtained simulation results, Kim et al. [100] recommended that a shelter using existing spaces in metro stations can be used to prepare for unpredictable and no-notice disasters. An evacuation simulation model proposed by Mao et al. [131] considered a situation where during earthquakes pedestrians on low floors tend to evacuate to the outdoors while pedestrians on higher floors tend to hide in cramped indoor spaces.

6.2. *Navigable spaces under conditions*

Currently, the semantics of navigable spaces under conditions are not provided in the existing studies. In the reviewed studies, navigable spaces under conditions are usually integrated into freely navigable or non-navigable spaces and modified according to whether the conditions can be satisfied (including access and legal rights). Similarly, the topological relations of this sort of space depend on the conditions, but the relations are not provided clearly. Technically, navigable spaces under conditions mainly concern a direct interaction between pedestrians and movable objects or address the changes in the activities of dynamic objects. For the direct interaction between pedestrians and movable objects, the geometry and accessibility of navigable spaces under conditions are significantly determined by the attached movable objects' geometry and function. For example, if a pedestrian chooses to crawl under or jump over a desk, the spaces under and on the desk can be navigable under conditions, while the space under the chair which cannot be accessible is non-navigable. In addressing dynamic objects, navigable spaces under conditions can be accessed only when dynamic objects move, resulting in non-navigable spaces occupied by the objects becoming navigable. In some cases, the geometry of navigable spaces under conditions may be changed since a group of pedestrians can be joined by or left by other pedestrians [80].

Navigable spaces under conditions in the studies are integrated into freely navigable spaces. Zheng et al. [136] simulated evacuations in 3D space considering smoking diffusion. In their study, pedestrians who cannot move since the smoke particle concentration is too high are regarded as obstacles, and the spaces where they stand are non-navigable. Spaces near exits where pedestrians stop moving are assumed to be navigable considering the survival instinct. Tugarinov et al. [151] designed a dynamic navigation mesh in which all navigable spaces are integrated and updated after a certain time so as to address the changes in navigable spaces. Yet, no detailed information on how the dynamic mesh was built is provided. In terms of the integration with non-navigable spaces, channels between automatic ticket gates in a study [68] are passageways when the gates stay open during evacuation.

6.3. Non-navigable spaces

Non-navigable spaces in the reviewed literature are semantically described as occupied areas within the top surfaces of floor slabs, stairs, escalators and ramps and spaces (e.g., rooms, lifts) with limits of access and legal rights that no one can use for evacuations. Non-navigable spaces maintain the inside relation with a higher level of space (e.g., room, zone, storey). The meet and disjoint are the topological relations between non-navigable spaces and freely navigable spaces. Generally, the geometry of spaces with limits of access and legal rights is similar to freely navigable spaces. However, the geometry of non-navigable spaces in most of the studies is 2D/2.5D, considering the geometry of floor slabs and stairs, escalators and ramps. In terms of representation, they are removed from the navigable meshes as 2D/2.5D holes (see Fig. 13) or are recognised as 2D/2.5D non-walkable areas in discrete cells. Overhead objects within certain heights of floors, such as 1.8 m, can also be excluded from the 2D/2.5D top surfaces. Accordingly, there is no specific LOD for the sort of space. Due to the representation in most studies, pedestrians can only bypass physical components. For instance, a study [109] discussed and simulated obstacle and obstacle-free situations of a high-rise teaching building using Pathfinder, in which pedestrians can only bypass obstacles.

In summary, each type of space component above is further compared in Table 2, based on the three property types: semantics, topological and geometry.

7. Discussion

This literature review showed that using 3D indoor environments for pedestrian evacuation simulations is receiving more attention, at least for the simulation of pedestrian motions and behaviours, 3D optimal evacuation path planning and the creation of 3D indoor environments. The analysis of the clusters of existing research efforts (see Appendix A) shows that the simulation of pedestrian evacuation motions and behaviours accounts for the majority of studies using 3D indoor environments in which 2D/2.5D pedestrian evacuation simulations are currently prevalent. In contrast, 3D pedestrian evacuation simulations are increasingly attractive and require more fine-grained 3D indoor environments. However, research efforts on creating 3D indoor environments are insufficient.

To reproduce pedestrian motions and behaviours in 3D space and provide an accurate simulation and prediction of evacuation processes, it is essential to carefully consider the three properties of 3D indoor environments: semantics, topology and geometry. From the perspectives of these three properties, the limitations in the use for 3D indoor environments are discussed in detail as follows.

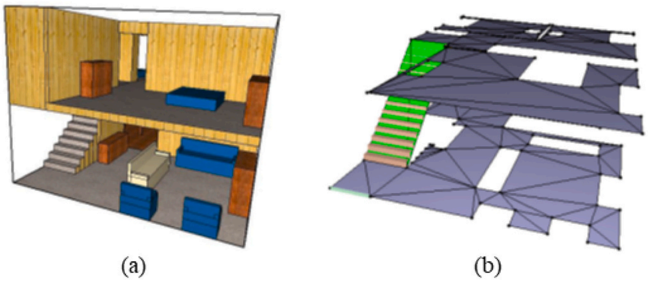


Fig. 13. 3D indoor environment and the corresponding navigation mesh in Pathfinder. (a) 3D geometry. (b) Navigable meshes. ([78]).

7.1. Semantics

Although semantics is one of the most typical and unique properties that can be used to define and distinguish each physical and space component, it is oversimplified and lacks standardisation in the existing studies. Currently, the navigation domain has been paid great attention in establishing adequate semantics of 3D indoor environments. For instance, two studies [152,153] reported detailed and precise semantics of each physical and space component in support of indoor navigation requirements. However, relatively little has been discussed in the evacuation field until recent gaining recognition [154,155] as if physical and space components are not critical in modelling evacuation motions and behaviours.

Firstly, the oversimplification is that the semantics only distinguish physical and space components in the light of the pure functional differences between physical components (e.g., the functional differences between floor slabs and walls) and the simple binary partitioning of space components (navigable/unoccupied and non-navigable/occupied). The semantics of navigable spaces under conditions and parts of physical components (e.g., door planks) are not sufficiently defined. Also, further distinctions of different movable objects such as desks and chairs, which can be used to identify whether the spaces attached to the objects are navigable spaces under specific conditions, are not considered in depth. Recent advancements [156,157] using 2D plans have considered the semantics of movable objects. For instance, a study [157] applied rigid and flexible obstacles to divide physical components, in which flexible obstacles refer to movable objects lighter in weight and smaller in size that pedestrians will attempt to jump over or push away rather than spend more time avoiding them. Nevertheless, the geometry of the objects in the two studies is 2D.

Secondly, the lack of standardisation of semantics easily results in ambiguities. For instance, the term ‘floor’ represents a floor slab and storey simultaneously, and the terms ‘exit’ and ‘exit door’ indicate an opening. By comparison, in the IFC schema, the two kinds of semantics are clearly expressed with *ifcBuildingStorey* and *ifcSlab* and ‘*ifcOpeningElement*’ and ‘*ifcDoor*’. In summary, the oversimplification and lack of standardisation of semantics for physical and space components are one of the reasons why various objects affecting pedestrian motions and behaviours in 3D space have not been further specified and simulated.

7.2. Topological relations

Topological relations between physical and space components have been recognised using the well-known 9-intersection model. Currently, the meet is the most used topological relation in physical and space components, associated with the derivation of navigable spaces. Also, the inside is critical to creating the hierarchical graphs of physical and space components. Some relations are not needed, such as the overlap and equal relations. Therefore, the meet and inside relations can be preserved in a graph or network, yet other relations still deserve further investigation.

Specifically, the expression of topological relations in the reviewed studies is mainly based on the simplified boundary of objects’ shape (e.g., the bounding box of movable objects) rather than considering the complexity of objects. Physical components, especially for movable objects, in the real world are always complex, incorporating separating subparts or navigable spaces under conditions (e.g., spaces under desks), with multiple internal and external boundaries. In 3D space, whether an object and another object/navigable space under conditions are connected to (or separated from) internal or external boundaries is not considered in the reviewed papers, which cannot be distinguished by the 9-intersection model as well. If two movable objects are close (e.g., a chair close to a table) in some cases, what is the topological relation to be derived? Does the meet relation indicate non-navigable while the disjoint corresponds to navigable? The existing studies do not have a metric relation in 3D space that can distinguish which object or space is

Table 2
Summary of the three property types of each space component.

Property types			Space components		
			Freely navigable spaces	Navigable spaces under conditions	Non-navigable spaces
Semantics			?	×	√
Topological relations	Disjoint		√	?	√
	Meet		√	?	√
	Contains		×	?	×
	Covers		×	×	×
	Inside		√	?	√
	Covered by		×	×	×
	Equal		×	×	×
	Overlap		×	×	×
Geometry	Dimension	2D/2.5D	√	√	√
		3D	×	×	×
	Representation	B-Rep	√	?	N/A
		Raster	√	?	√
	LOD		×	×	×
	Realism	Texture mapping	N/A	N/A	N/A
		Colouring	N/A	N/A	N/A

Note: √ = Has relevant information; × = No relevant information; ? = Unclear information; N/A = not applicable.

larger than accessible or whether they are independent of location and assist the derivation of topological relations.

In addition, the topological relations of navigable spaces under conditions are not explicitly described and defined in the existing studies, as observed in Table 2. This leads to the problem that when the navigable space under conditions is incorporated, there could be confusion about the topological relations between space components. For example, is it an independent space cell with the meet and disjoint relation with the other two space components, or is it the inside or covered by relation? In the current topology considered in the studies, there is no concept of direction. However, it is necessary to define the topological relations of navigable spaces under conditions and describe a concept of ‘above’ and ‘below’, which can create evacuation paths for people jumping over and crawling through objects. Several studies [158–162] for navigation applications do not provide a reference point to describe and derive the topologic relations in 3D space. Instead, they ensure that created 3D indoor environments are topologically correct, and that space components do not intersect.

Finally, some reviewed studies using the space-based topology for simplicity only consider freely navigable spaces as independent spaces (e.g., rooms, corridors, openings) and omit navigable spaces under conditions and non-navigable spaces. The arrangement and layout of node locations in the topology significantly affect the length of the connection edges between two nodes. The two inaccuracies mean evacuation simulations are unable to provide the exact length of time of evacuation processes. Overall, exploring topological relations of 3D indoor environments for pedestrian evacuation simulations deserves more effort.

7.3. Geometry

As previously mentioned, the geometry of physical and space components is featured with dimensions, representation, LOD and realism (colouring and texture mapping). The four aspects of the geometry of physical and space components are discussed in detail as follows.

7.3.1. Physical components

Regarding the dimensions and representation, most early-stage studies used 2D/2.5D polygons to represent physical components by B-Rep, particularly in static objects (e.g., 2D floor slabs and 2D walls). Movable objects are rarely observed in their 3D indoor environments. With the growth of different software packages and graphic libraries, contemporary studies usually use 2.5D polygons or 3D solids to reflect more realistic physical components. As shown in the previous section, existing studies rarely create the geometry of ceilings, roofs and dynamic objects (e.g., a group of pedestrians, drones, robots). However, these objects have been evidenced in some studies [163–166] as imperative for pedestrians to perceive the potential risks (e.g., failing ceilings and roofs caused by earthquakes), distinguish overhead objects and appropriate navigable spaces, and decide on evacuation paths and motions in 3D space such as crawling, or bent-over walking. Moreover, pedestrians are mostly assumed in the literature to move within a static 3D indoor environment, where the movable objects and paths toward the exits do not change over time. Empirical data [156,157,167] illustrates that some pedestrians would push away movable objects during evacuations to obtain shorter evacuation paths. Therefore, the temporal geometry of 3D indoor environments is still insufficiently supported.

Although the bounding box approach’s flexibility and low computation burden can be benefits, for a 3D evacuation simulation, such an approach is problematic, especially for movable objects. The dimensions and representation of movable objects are closely associated with extracting non-navigable and navigable spaces under conditions. The geometry of non-navigable spaces could be objective and reflect associated movable objects’ shapes differently. At the finest representation level, a non-navigable space can directly correspond to the original shapes of the related movable objects [41]. Some spaces attached to movable objects with restricted sizes that are inaccessible for pedestrians to move through (e.g., crawling, or bent-over walking) are another critical part of non-navigable spaces. An example is that the space under a chair is impossible for a standard pedestrian to crawl through, and thus it should be non-navigable. By comparison, other spaces attached to movable objects that can be used by pedestrians to step over, crawl through or jump over, are navigable spaces under conditions (see Fig. 14). Consequently, the geometry of movable objects using the bounding box approach makes it difficult to extract space components with granularity for 3D evacuation simulations.

The LOD of physical components are also crucial for identifying space components. While walls, columns and lifts are critical, their simplified description for evacuation simulations may be acceptable since they are usually perceived as boundaries or vertical corridors for pedestrians. This means that the LOD of the three objects do not have to possess demanding granularity such as air chambers in double walls, which will also help reduce the computation burden of evacuation simulations. However, if the quantity, size, shape, location and orientation of movable objects can be measured at a fine-grained level, it has the benefit of considering the accessibility of spaces attached to the objects, which can determine whether pedestrians can move through objects or what motions may occur in 3D space (e.g., stepping over, crawling or climbing over). Therefore, for 3D evacuation simulations it is necessary to provide far greater precision and higher LOD in the

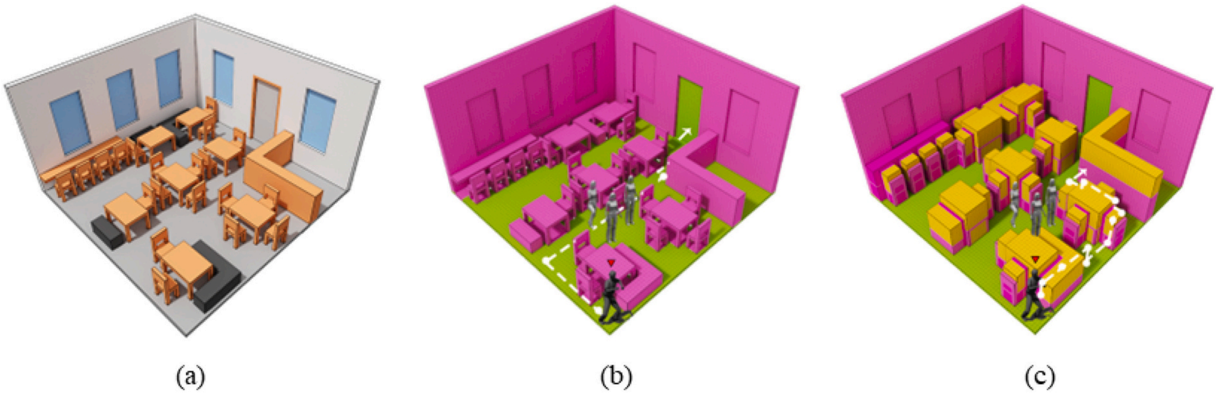


Fig. 14. Diagram of an evacuation from a canteen. (a) Layout of the canteen. (b) An evacuation path in 2D horizonal surfaces. (c) An evacuation path in 3D surfaces. Freely navigable space (light green), navigable space under conditions (yellow), and non-navigable space (red).

objects' representation. However, for the LOD of 3D indoor environments, no specific requirements and consensus exist in the evacuation domain. The LOD from CityGML and AIA G202-2013 are not designed for evacuation simulations. The lack of LOD standardisation results in ambiguity and arbitrariness in 3D modelling, bringing uncertainties to the representation of physical components. For example, in a 3D indoor environment, stairs are represented as simple 2.5D polygons, while desks and chairs are represented as fine-grained 3D solids.

Finally, the realism of physical components is seldom considered in studies. Texture mapping of some objects can help in evacuation modelling for particular scenarios. For example, in a flood scenario, whether floor slabs, stairs and ramps will become slippery when wet can provide information to simulate the difficulty of pedestrian motions on these objects.

7.3.2. Space components

In the real world, pedestrians cannot fly or jump over each other. They stand and move through freely navigable spaces and navigable spaces under conditions. Most of the created 3D indoor environments rely on the 2D/2.5D navigable meshes. Indeed, the meshes can enable pedestrians to move continuously on 2D/2.5D surfaces and in time, yet the geometry has shortcomings. Firstly, the meshes may produce a zigzag effect, which makes evacuation paths wriggly and causes unrealistic pedestrian movement. Secondly, when movable and dynamic objects on floor slabs are critical (e.g., to climb over a table) or pedestrians need to bend-over walk or crawl through a falling ceiling, the 2D meshes may not be adequately realistic, evidenced by any area of the meshes obstructed by the movable and dynamic objects considered as a hole (non-navigable spaces) that pedestrians must bypass. Moreover, the length of the total evacuation path in 3D space differs from that in 2D meshes since pedestrians can step over or climb over a series of movable and dynamic objects that have corresponding path distance. At this moment, the series of individual motions and behaviours may further influence the macroscopic motions and behaviours. As such, it can be extrapolated that evacuation time calculations based on 2D meshes may have a larger deviation. Also, stairs and escalators represented as 2.5D sloped surfaces in the meshes bring new issues in locating the position of pedestrians and calculating the accurate speed of pedestrians, especially in the computation of the effect of physical fatigue on pedestrian speeds during ascending evacuations [168,169].

2D cells are primarily common within discrete cells, which have a better computation efficiency than the meshes. Nevertheless, there are some deficits related to 2D cells. Most studies using cellular automata models and agent-based models adopt a square grid shape. In some cases, it is difficult to accurately depict the pedestrian's action of walking in a diagonal direction. The motion time and displacements of pedestrians between diagonal and straight walking are different, resulting in the different velocities of pedestrians [12]. Furthermore, 2D cells cannot sufficiently support the simulation of stepping over, jumping over or climbing over since height information of related physical components is lacking. In addition, most reviewed studies apply the size of pedestrians instead of adapting to indoor environments to configure 2D cells' sizes. A genuine indoor environment is seldom arranged to adhere to formulaic grids that completely define the size of rooms, floor slabs and stairs horizontally. It usually has some more fine-grained geometric parameters, for example, the thread length and riser height of stairs. Thus, using the size of an individual to configure the grid size readily leads to the coarse representation of 3D indoor environments and thus the variation of evacuation simulation performance. Finally, no standard LOD for space components are considered in the studies. Through the above analysis, we envisage that voxelised space components may be an effective way to support pedestrian evacuation simulations in real 3D space (see Fig. 15).

Overall, the reasons for the limited use of 3D indoor environments are rooted in the homogeneity assumption in the basic thinking of the reviewed papers, that is, 3D indoor environments are separate from evacuation modelling as an independent element and not as important as the evacuation modelling itself.

8. Conclusions and future research

Using 3D indoor environments in pedestrian evacuation simulations has become increasingly attractive for researchers, practitioners and the software industry. The paper presented a systemic review on 3D indoor environments used in pedestrian evacuation simulations. The literature shows three clusters of research efforts on simulation of pedestrian evacuation motions and behaviours, 3D optimal evacuation path planning and the creation of 3D indoor environments. 3D pedestrian evacuation simulations are increasingly attractive and require more realistic 3D indoor environments. Through analysing physical and space components from semantics, topological relations and geometry, our review revealed reasons for the limited use of 3D indoor environments. First, semantics is oversimplified and lacks standardisation. Second, the expression of topological relations is mainly based on the simplified boundary of objects' shape. The topological relations of navigable spaces under conditions are not explicitly described and defined. Using the space-based topology can also omits navigable spaces under conditions and non-navigable spaces. At last, 3D geometry is insufficient for simulating of some likely pedestrian motions and behaviours in 3D space (e.g., jumping/climbing over).

Based on the reasons, three priority areas for future research are summarised and suggested as follows.

1. To enrich the semantics and topological relations of 3D indoor environments needed for evacuation simulations.

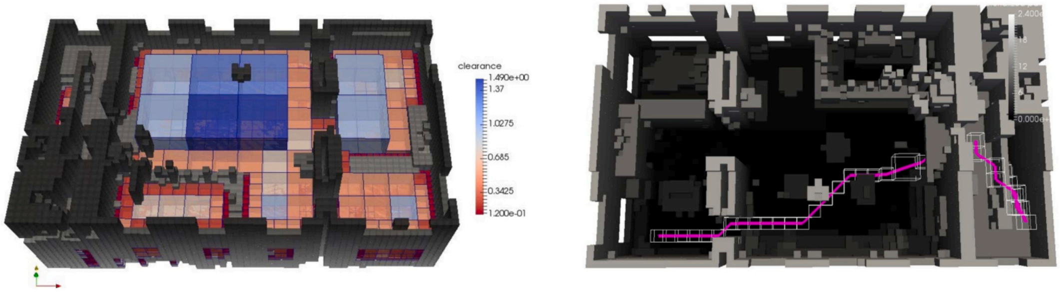


Fig. 15. Voxelisation of 3D indoor environments in octree structure and 3D indoor path planning ([170]).

2. To further investigate the 3D geometry of indoor environments for evacuation simulations.
3. To foster the standardisation of 3D indoor environments for evacuation simulations.

The first new research direction is the enrichment of semantics and topological relations needed by evacuation simulations. In a real environment full of movable and dynamic objects, pedestrians are more able to adjust and flexibly change their evacuation motions and behaviours, potentially triggering paths dispersed across the whole navigable space. Once some objects in the navigable space cannot be crossed over, crawled over or climbed over, pedestrians will avoid and bypass these objects [156,157,167,171,172]. To simulate the likely pedestrian motions and behaviours in 3D space, the relevant semantics and topological relations of indoor environments need to be investigated. First, more detailed semantic distinctions of physical and space components have to be justified and enriched so that their different influence on pedestrian evacuations in 3D space can be discussed further. Moreover, mixed relations between physical and space components should be explored more in 3D space. Topological relations in combination with directional relations and a metric relation are also very useful to help derive evacuation paths in 3D space. Finally, as shown in several studies [59–61], combining the space-based topology of indoor environments and microscopic evacuation simulation models may be an acceptable method for 3D optimal path planning to address the disadvantages of topology and keep the advantage of efficient computation speed.

The second research direction is further investigating the 3D geometry of indoor environments, allowing for a better description of the 3D complexity of indoor environments. Currently, evacuations in the reported studies are primarily for pedestrians who walk in freely navigable spaces. Their evacuation paths are planned with 2D horizontal and 2.5D sloped surfaces. As discussed in a study [173] related to a semantic framework of objects, the size of the bottom area of objects can determine whether pedestrians can bypass them, the height of objects can distinguish whether pedestrians can step over or jump over or not, and the weights of the objects determine whether the objects can be pushed away during the evacuation process. Extending such a framework to specify important geometric attributes required by evacuation simulations may be an attractive option. Furthermore, a voxel model can be generated automatically with the 3D geometry of physical and space components in a specified level of fineness [33,174–177]. To provide an appropriate fineness, defining a grid size should be extended and combined with subdivision with respect to the physical components. As such, current evacuation simulations can be stretched to the genuine 3D space, and thus precise 3D evacuation routes can be derived. An encouraging example is from studies [178,179] on path planning for a drone as the drone can adjust its paths and flight heights in 3D space. The geometric representation of a voxel model allows accurate indoor routing for the drone. The octree structure, which splits each piece of space into eight equivalent subspaces, may be a good option. As shown in Fig.15, each level's subspace (i.e., cell) occupies a distinct part of the space in the octree structure. According to the layers of an octree structure, 3D space may be partitioned into multiple resolutions for the representation of very complicated geometries. Many voxels with the same attributes can be united into a larger cell [180], benefitting realistic and precise indoor space. Moreover, construction sites, movable and dynamic objects and evacuation assessment for optimising architectural design are well-known points that depend on temporal 3D geometry. Another recommendation for future research is to investigate and synthesise temporal 3D geometry so as to model the changes in 3D indoor environments over time. Through investigation and enrichment, an entirely new area of research in pedestrian evacuation simulations may emerge

Finally, to facilitate using 3D indoor environments for evacuation simulations, the information regarding physical and space components should be semantically, topologically and geometrically standardised. First, defining consistent and standard semantic information for the physical and space components can avoid ambiguities, which requires strengthened discussion and collaboration from scholars in pedestrian evacuation and 3D modelling. Furthermore, none of the AIA G202-2013, CityGML, IFC schema, and IndoorGML currently define the LOD regarding evacuation simulations. The AIA schema may be a promising extension. For example, LOD 200 is graphically represented as a generic system for physical components with approximate quantities, size, shape, location and orientation. Finally, different practical applications of evacuation simulations have various specific requirements. Identifying the congestion points and bottlenecks of indoor environments improves reliability, yet the evacuation time calculation needs acceptable computation speed to be reliable [15]. It indicates that different standardised 3D indoor environments can reflect and respond to specific application requirements and hence are suitable for a particular class of applications. Therefore, our suggestion is to complete the standardisation of 3D indoor environments in the evacuation domain, providing more specific and consistent physical and space component attributes that can facilitate pedestrian evacuation simulation.

In conclusion, we hope this work facilitate a better appreciation of the significance of 3D indoor environments for future research in evacuation and promote more realistic pedestrian evacuation simulations to improve safety.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

No data was used for the research described in the article.

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Appendix A. Three clusters of research efforts in the literature

Clusters	Number	Authors (year)	
Simulation of pedestrian evacuation motion and behaviour	83	2D/2.5D pedestrian evacuation simulation	Gwynne et al., 2001 [181]; Kinsey et al., 2012 [106]; Shi and Liu, 2014 [66]; Bai et al., 2015 [92]; Ding et al., 2015 [94]; Wang et al., 2015 [65]; Chiu and Shiau, 2016 [143]; McDaid and Hoffmann, 2016 [182]; Busogi et al., 2017 [77]; Cantrell et al., 2018 [117]; Kallianiotis et al., 2018 [145]; Marzouk and Daour, 2018 [74]; Soltanzadeh et al., 2018 [95]; Ding et al., 2019 [147]; Marzouk and Mohamed, 2019 [75]; Mehmood et al., 2019 [183]; Pan et al., 2019 [144]; Ronchi et al., 2019 [104]; Chen et al., 2020 [96]; Hassannayebi et al., 2020 [97]; Jin et al., 2020 [120]; Qin et al., 2020 [121]; Sun and Turkan, 2020 [123]; Wu et al., 2020 [149]; Xu et al., 2020 [98]; Bina and Moghadas, 2021 [142]; Chen et al., 2021 [86]; Gerges et al., 2021 [105]; Khan et al., 2021 [146]; Kim et al., 2021 [100]; Li et al., 2021 [148]; Rostami and Alaghmandan, 2021 [54]; Shams Abadi et al., 2021 [99]; Soltanzadeh et al., 2021 [93]; Syed Abdul Rahman et al., 2021 [119]; Tang et al., 2021 [76]; Wang, 2021 [150]; Wehbe and Shahrour, 2021 [113]; Zang et al., 2021 [109]; Choi et al., 2022 [124]; Guo and Zhang, 2022 [101]. Musse and Thalmann, 2001 [184]; Murakami et al., 2002 [185]; Braun et al., 2003 [132]; Pan et al., 2006 [80]; Weifeng and Kang Hai, 2007 [140]; Yuan and Tan, 2007 [139]; Chu, 2009 [137]; Yuan and Tan, 2011 [138]; Song et al., 2013 [141]; Li et al., 2015 [88]; Haghani and Sarvi, 2017 [55]; Khademipour et al., 2017 [186]; Li et al., 2017 [87]; Liu et al., 2017 [82]; Xiong et al., 2017 [73]; Cheng et al., 2018 [85]; Kim and Han, 2018 [116]; Liu et al., 2018 [112]; Yuksel, 2018 [79]; Zhang et al., 2018 [130]; Zheng et al., 2018 [136]; Choi and Chi, 2019 [187]; Delcea and Cotfas, 2019 [108]; Mao et al., 2019 [131]; Şahin et al., 2019 [115]; Zhao et al., 2019 [56]; Hunt et al., 2020 [102]; Mao et al., 2020 [188]; Tian et al., 2020 [129]; Sun and Liu, 2021 [122]; Zhao et al., 2021 [114]; Yang et al., 2022 [118].
		3D pedestrian evacuation simulation	Tang and Ren, 2012 [57]; Becker-Asano et al., 2014 [111]; Jun et al., 2014 [89]; You et al., 2014 [91]; Wei et al., 2015 [90]; Zhou et al., 2016 [81]; Kullu et al., 2017 [84]; Motamedi et al., 2017 [83]; Liu et al., 2019 [110]; Tugarinov et al., 2020 [151]; Li et al., 2021 [58].
3D Optimal evacuation path planning	3		Wang et al., 2011 [60]; Zhang et al., 2012 [61];Boguslawski et al., 2018 [59].
Creation of 3D indoor environment	10		Kwak et al., 2010 [62]; Wang and Wainer, 2015 [65]; Zhu et al., 2018 [63]; Lochhead and Hedley, 2019 [67]; Selin and Rossi, 2019 [69]; Selin et al., 2019 [70]; Shi et al., 2019 [64]; Tang et al., 2021 [68]. Gorte et al., 2019 [72]; Aleksandrov et al., 2021 [71].

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