Voxel Size Performance in 3D Indoor Model Creation for 3D Evacuation Simulations

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Abstract

3D voxel models facilitate simulating 3D pedestrian motions within indoor environments with diverse furniture, equipment, and complex room layouts featuring stairs and ramps. Reasonable voxel sizes enable the effective identifications of indoor spaces, navigable surfaces, and vertical links from voxel models for the simulations. However, the performance of different voxel sizes on these identifications has yet to be thoroughly investigated. The choice of appropriate voxel sizes for various 3D evacuation scenarios has to be clarified to avoid unreliable simulation outcomes. Therefore, this paper aims to assess the performance of different voxel sizes on the identifications of the spaces, surfaces, and links. Firstly, we introduce three key metrics for the assessment: accuracy, robustness, and efficiency. Then, three IFC models are selected based on predefined criteria for the tests. Experimental procedures are elaborated to include data preparation, collection, and analysis. The primary findings of this investigation are: 1) with increasing voxel sizes, accuracy decreases, robustness changes, and efficiency increases; 2) larger indoor spaces exhibit smaller changes in accuracy across different voxel sizes, while smaller indoor spaces show more significant changes in accuracy. 3) when the voxel size is tiny, it becomes challenging to complete identifications. Conversely, with relatively larger voxel sizes, some indoor spaces and vertical links cannot be identified. 4) Indoor spaces with complex and non-orthogonal geometries require more identification time. This work is expected to advance the creation of 3D indoor model to facilitate 3D evacuation simulations.

1. Introduction

3D evacuation simulation models have increased appeal (Xie *et al.* 2022a, Xie *et al.* 2022b). These models digitally describe pedestrian motions in 3D space and replicates critical 3D pedestrian motions (e.g., low crawling, bent-over walking, jumping). For instance, a modified social force model (Liu *et al.* 2022) was created to reproduce stepping up/down small objects. Wang *et al.* 2020 suggested a cellular automata model in which two forms of personality traits of pedestrians: aggressiveness and inconsiderateness, are included to represent the tendency to conduct passing over and pushing away, respectively.

A recent study (Xie *et al.* 2023a) defined and characterised 3D pedestrian motions in evacuations that consist of 3D movements and 3D actions. 3D movements correspond to five movements, i.e., walking upright, bent-over walking, knee and hand crawling, and low crawling. By comparison, 3D actions indicate stepping up/down, jumping up/down, and climbing up/down. To simulate the 3D motions, it is necessary to identify navigable spaces above/below physical components (e.g., desks, stairs) and their connections with other spaces. As such, whether pedestrians can move through these physical components and which kind of 3D motions to be adopted could be decided and modelled.

3D voxel models enable fully identifying navigable spaces above or below physical components and deriving their connections because voxels provide a convenient and feasible digital representation of indoor spaces (Xie *et al.* 2022a, Xie *et al.* 2023a). Different voxelisation algorithms (Nourian *et al.* 2016, Gorte and Zlatanova 2016) have been created for geospatial applications, enable 3D voxel models to be increasingly applied in evacuation simulations and indoor navigation (Aleksandrov *et al.* 2021, Aleksandrov *et al.* 2023, Boguslawski *et al.* 2022, Gorte *et al.* 2019, Staats *et al*. 2019, Wang *et al.* 2023, Xu *et al*. 2017). For example, a study highlighted that 3D voxel models could be a practical basis for evacuation modelling (Gorte *et al.* 2019). In specific applications, some studies (You *et al.* 2014, Jun *et al.* 2014, Wei *et al.* 2015) used voxels to represent stairs for simulating pedestrian movements on stairs. Bandi and Thalmann 1998 used a voxel model as a basis to create an optimal path for pedestrians. Two studies (Li *et al.* 2018, Han *et al.* 2022) also used 3D voxel models to plan indoor paths for drones. Furthermore, several studies (Rodenberg *et al.* 2016, Fichtner *et al.* 2018, Zhao *et al.* 2022) utilised the octree structure to discretise indoor spaces for indoor pathfinding. However, they did not investigate how voxel sizes influence their developed methods. Few studies (Homainejad *et al.* 2022, Xie *et al.* 2023b) discussed the influence of voxel sizes on a specific geospatial application, such as heathland, canopy gap, but their focuses are not on indoor spaces.

We are investigating automatic methods to create a voxel-based 3D indoor model to support 3D evacuation simulations. In our study, we have identified freely navigable spaces (P-spaces), navigable spaces under conditions (C-spaces) and non-navigable spaces (N-spaces). In particular, C-spaces represent navigable spaces above/below physical components, where pedestrians can move through using 3D movements in abnormal circumstances. According to the four types of 3D movements, the C-spaces are further classified into C-spaces for low crawling (C_l-spaces), C-spaces for knee and hand crawling (C_k-spaces), C-spaces for bent-over walking (C_b-spaces) and C-spaces for walking upright (C_u-spaces) (Xie *et al.* 2023a).

Then, navigable surfaces and vertical links are derived. Navigable surfaces are represented by a layer of unoccupied voxels identified from the P-spaces and four types of C-spaces. Vertical links are also represented by a layer of unoccupied voxels to connect these space components and their navigable surfaces at different heights. The vertical links are classified into three distinct types according to 3D actions: links for stepping up/down, jumping up/down, and climbing up/down. The created model could apply to evacuation scenarios with various furniture or equipment and complex room layouts using stairs and ramps to connect multiple storeys.

Reasonable voxel sizes enable the effective identifications of indoor spaces, navigable surfaces, and vertical links for the simulations. (Xie *et al.* 2022a). However, we have yet to investigate how different voxel sizes may affect the identifications. Without the rigorous assessment of voxel sizes, we cannot ascertain appropriate voxel sizes for representing space components across various 3D evacuation scenarios. For instance, if a complex, large train station scenario uses a 5 cm voxel size, an excessively high computational cost can be caused. In contrast, when a 40 cm voxel is applied to a small nightclub or café shop scenario, the identified spaces, surfaces, and links may not be accurate and result in evacuation simulations lacking realism.

Thus, we aim to assess the performance of different voxel sizes on the identifications of indoor spaces, navigable surfaces, vertical links, and 3D pathfinding. In doing so, we introduce three key metrics, i.e., accuracy, robustness, and efficiency. Then, critical predefined criteria are elaborated upon to select three appropriate 3D indoor models as test subjects. Finally, we articulate experimental procedures from data preparation, collection, and analysis. By assessing the performance, our contributions are as follows:

- Providing an effective reference to choose appropriate voxel sizes for various 3D evacuation scenarios.
- Understanding the potentials of our developed methods and their possible improvements.
- Advancing the creation of an appropriate 3D indoor model that significantly enhances support for 3D evacuation simulations.

The remainder of this paper is organised as follows. Section 2 introduces the methods from key metrics, selected indoor models, and experimental procedures. Section 3 articulates the assessment results. The paper ends with a discussion and conclusion in Section 4.

2. Methods

This section introduces methods to investigate the performance of voxel sizes on the identifications of indoor spaces, navigable surfaces, and vertical links. For clarity, indoor spaces, navigable surfaces, and vertical links are collectively referred to as the three elements in the following text, which are required elements for 3D pathfinding.

2.1 Key metrics

To assess the performance of voxel sizes, we introduce three key metrics: 1) accuracy, 2) robustness, and 3) efficiency. Accuracy corresponds to the geometric accuracy of identified three elements. The metric directly assesses how well the three elements under different voxel sizes match the original in Industry Foundation classes (IFC) models, helping to understand the capability of voxel sizes in capturing details of the three elements. Then, robustness is used to assess the capacity to identify the three elements successfully, i.e., whether using different voxel sizes can reliably identify the three elements and is manageable to the variations. Finally, efficiency concerns the total time to generate the three elements and the time for 3D pathfinding through the computational cost associated with different voxel sizes.

Precisely, accuracy is quantitively measured through the volume, area, and height difference of an indoor space, navigable surface, and vertical link, i.e., how accurately the voxelised space, surface and link under different voxel sizes fit the original in IFC models (see Equation 1).

$$\begin{cases} V_{d,i} = V_{v,i} - V_{o,i} \\ A_{d,i} = A_{v,i} - A_{o,i} \\ H_{d,i} = H_{v,i} - H_{o,i} \end{cases} \tag{1}$$

Where: $V_{d,i}$, $A_{v,i}$, and $H_{v,i}$ is the volume, area, and height difference of a space, surface and link, respectively; $V_{v,i}$, $A_{v,i}$, and $H_{v,i}$ is the volume, area, and height of the voxelised space, surface and link; $V_{o,i}$, $A_{o,i}$, and $H_{o,i}$ is the volume, area, and height of the original space, surface and link.

Robustness is assessed by whether the identifications of the three elements are completed successfully under different voxel sizes. Each identification succeeds when corresponding 3D pathfinding can be performed. Furthermore, we investigate possible changes in the three elements in each identification, such as whether the number of C-spaces and vertical links decreases and whether the types of C-spaces and vertical links change.

Efficiency, a key aspect of our research, is represented by the processing time. This measure, which indicates the time taken from the start to the end of identifying the elements and completing 3D pathfinding, is intuitive and easy to interpret for users. It provides a clear understanding of the speed in completing tasks.

We do not specifically define a standard to determine whether a particular value of these key metrics is better or not, as this involves personal preferences and needs. Our work is more about informing possible outcomes and discussing strategies for choosing voxel sizes.

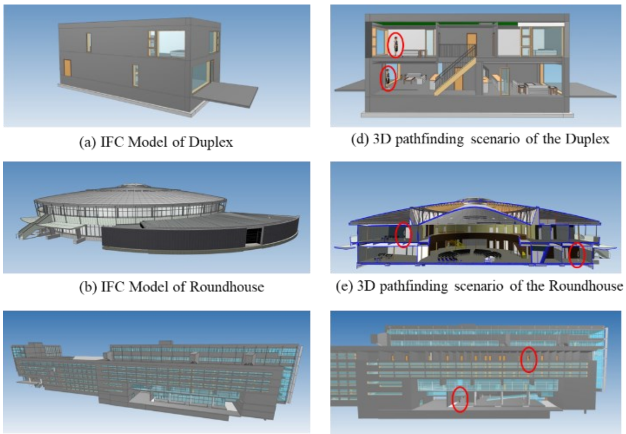
2.2 Selected IFC models

To ensure that the assessment covers various 3D evacuation scenarios, we apply a set of criteria to select three appropriate IFC models with different complexity and scales, including:

- Building function: different functions are related to buildings' spatial layout and evacuation paths. Selecting buildings with varied functions allows assessing voxel sizes to cover different spatial requirements.
- Building scale: various scales could test how the voxel sizes correspond to small buildings with fine-grained details or large buildings with complex and diverse indoor spaces.
- Essential physical components: the presence of furniture, ramps, sloped roofs, or inclined walls ensure that the C-spaces could be identified and classified. Then, we could further investigate the voxel sizes.
- Space shapes: irregular or circular space shapes test the performance of voxel sizes on non-orthogonal geometries, while standardised and common indoor space shapes are associated with rectangular geometries.

After these considerations, we selected three IFC models. We used IFC models because they provide a broad range of geometric and semantic information on building elements (Liu *et al.* 2021). The Duplex model is from the public information model repository (http://openifcmodel.cs.auckland.ac.nz/). The other two buildings (Roundhouse and Red centre) are based on architectural drawings. Their building functions are house, theatre and teaching building, respectively (see Figure 1a, 1b, 1c). Their space shapes are rectangular, cylinder, and rectangular. We added furniture (e.g., desks, tables, chairs) to the Roundhouse and Red Centre to identify C-spaces.

Based on the selected IFC models and investigated voxel sizes, three 3D pathfinding scenarios are further designed (see Figures 1d, 1e, 1f). We set appropriate starting and target points for 3D pathfinding in the models. For example, Figure 1d shows the scenario of the Duplex, where the starting point and target point were arranged on the second floor and the ground floor.



(a) IFC Model of Duplex (d) 3D pathfinding scenario of the Duplex
(b) IFC Model of Roundhouse (e) 3D pathfinding scenario of the Roundhouse
(c) IFC Model of Red Centre (f) 3D pathfinding scenario of the Red Centre

Figure 1. Selected IFC models and 3D pathfinding scenarios.

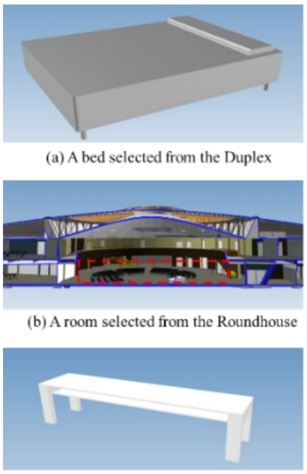
2.3 Experimental procedures

We employed Unity 3D game engine and Microsoft Visual Studio 2022 to identify the three elements. Unity can support using different data structures and provide user-specific rendering (Aleksandrov *et al.* 2022). The hardware environment includes Intel (R) Core (TM) i7-12700K @ 5.00 GHz CPU, a graphic processor NVIDIA GeForce RTX 3080 and 32 GB RAM. Experimental procedures are classified into 1) data preparation, 2) data collection, and 3) data analysis.

In the data preparation procedure, we first transmitted the .IFC format of the three models into the .OBJ format. The models were then imported into Unity. Afterwards, we manually removed some indoor entities in Unity that could bring extra and unnecessary computation burdens in voxelisation, such as roof trusses, stair handrails, sinks, and urinals. Additionally, we selected a bed, a room, and a table from the Duplex, Roundhouse and Red Centre as samples to test the accuracy of their related indoor spaces, navigable surfaces, and vertical links. Spaces above the bed and the table were selected to test (see Figure 2). Regarding 3D pathfinding, we improved the A* algorithm and utilised the unoccupied voxels in the identified navigable surfaces and vertical links to create a navigation graph.

In the data collection, the three experimental 3D models were tested to automatically identify the three elements and perform 3D pathfinding. We used pedestrian parameters shown in Table 1 and Table 2 for each voxel size. Then, four main steps were applied: 1) identify indoor spaces, 2) identify navigable surfaces, 3) identify vertical links, and 4) perform 3D pathfinding. We experimented with a voxel size from 5 cm to 45 cm. The voxel size increased 5 cm at each time. After each test, we collected relevant data required for the key metrics.

Finally, using the collected data, we performed fundamental statistical analysis to explore how the key metrics respond to the changes in voxel sizes.



(a) A bed selected from the Duplex
(b) A room selected from the Roundhouse
(c) A table selected from the Red Centre

Figure 2. Selected bed, room, and table from the three models.

Pedestrian sizes (cm)	Height	Length	Width
Walking upright	170	30	30
Bent-over walking	140	30	70
Knee and hand crawling	90	30	110
Low crawling	40	30	170

Table 1. Pedestrian body sizes used for the identifications.

Vertical motion thresholds (cm)	Stepping up/down	Jumping up/down	Climbing up/down
Maximum height	40	60	140

Table 2. Vertical motion thresholds of a pedestrian.

3. Results

This section presents the assessment results regarding accuracy, robustness, and efficiency. Appendix 1 contains the results of the identified indoor spaces, navigable surfaces, and vertical links from the three models as well as illustration of 3D pathfinding at a 10 cm voxel size.

3.1 Accuracy

Figures 3, 4, and 5 present the accuracy outcomes based on three differences: volume, area, and height. The results indicate that most values increased significantly with larger voxel sizes.

Specifically, Figure 3 shows that volume differences for each selected space were substantially more significant under larger voxel sizes. For example, when the voxel size increased to 35 cm, the volume difference for the space above the bed in the Duplex rose to 1.33×10^6cm³, an increase of approximately 26% compared to its original volume. Additionally, the volume differences were also associated with these spaces’ scale. Larger spaces exhibited a relatively mild influence from increasing voxel size. The volume differences at a 45 cm voxel size amounted to about 43%, 16% and 78 % of their original volumes for the spaces measuring 5.1×10^6 cm³, 1046.25×10^6 cm³, 4.08 $\times 10^6$cm³, respectively, in the three models.

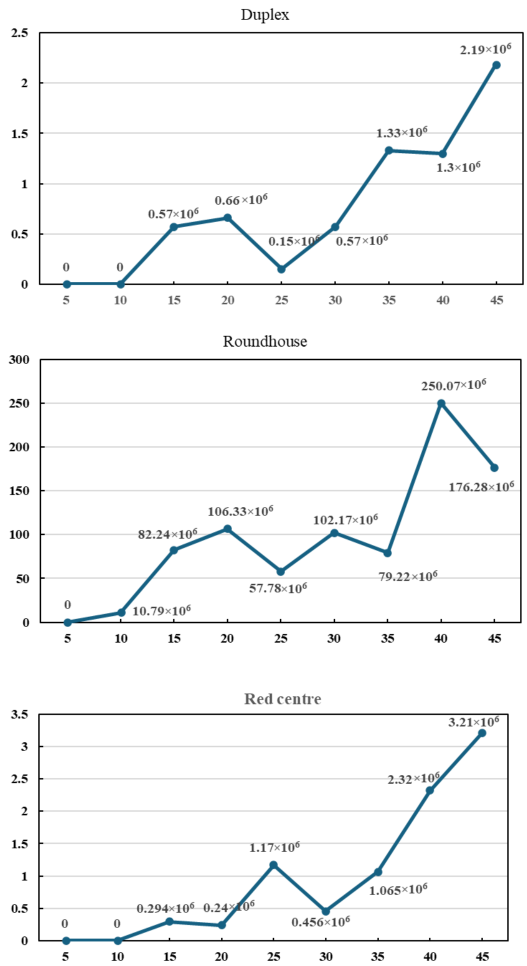


Figure 3. Volume differences of the three spaces.

Area difference for navigable surfaces exhibited the same tendency: as the voxel sizes increased, area differences became larger (see Figure 4). For instance, when voxel sizes increased from 10 cm to 45 cm, the area differences rose from 0% to 68% of its original area in the surface above the table within the Red Centre. Like the volume differences, larger original areas of navigable surfaces exhibited a more minor effect from increasing voxel sizes. For example, the area differences in the Roundhouse only increased from 1% to 10% of the original area.

Lastly, the effect of voxel sizes on height differences of vertical links is similar to the effects seen in volume and area differences (see Figure 5). For instance, with a voxel size of 40 cm, the height difference of a vertical link in the Duplex reached 30 cm. The vertical link was 30% higher than the original height.

3.2 Robustness

The robustness results of the three models under different voxel sizes indicate that the effect of voxel sizes on robustness were significant. For each model, when voxel sizes ranged from 10 to 45 cm, the identifications of the three elements were successful. However, if the voxel size was too small, such as 5 cm, the spaces, links, and surfaces of Roundhouse and Red Centre could not be identified due to computer memory limitations. Although the identification of the needed spaces of the Duplex could be achieved at a 5 cm voxel size, corresponding 3D pathfinding could not be completed because of the influence of stair nosing. The level of detail of the Duplex is higher, so voxels for the nosing of stairs were obtained at a 5 cm voxel size, which did not occur at other voxel sizes (see Figure 6).

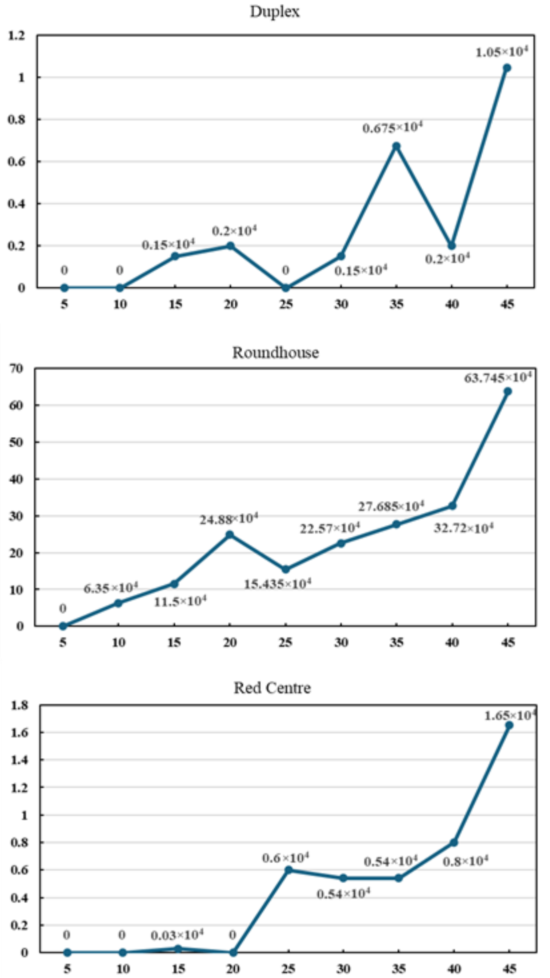


Figure 4. Area differences of the three surfaces.

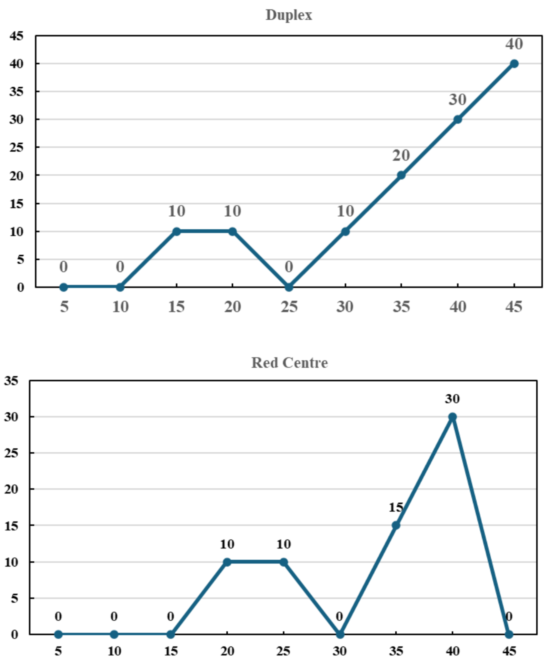
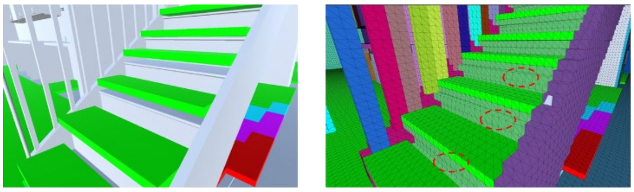


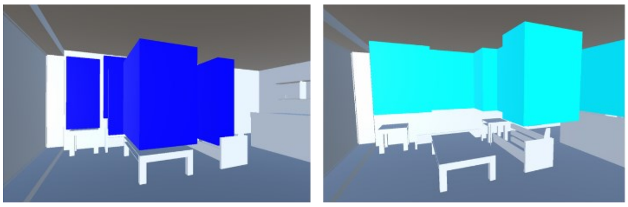
Figure 5. Height differences of the three links.



(a) (b)

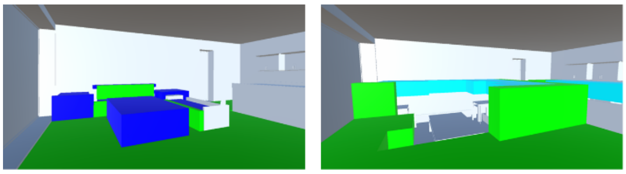
Figure 6. (a) Stair nosing in the original model of Duplex. (b) Voxelised stair nosing at a 5 cm voxel size. Green colour: navigable surfaces of P-spaces.

Additionally, we observed that the number and types of C-spaces and their surfaces and vertical links changed as voxel sizes increased. For instance, when the voxel size was 10 cm, C_u-spaces above sofas and a table were identified. However, the spaces changed to C_b-spaces when a 40 cm voxel size was used (see Figure 7). Meanwhile, a space above the table could not be identified. Additionally, the types of vertical links gradually changed. Some vertical links were not identified. A typical example is shown in Figure 8, where the type of a vertical link changed from jumping up/down (10 cm voxel size) to stepping up/down (40 cm voxel size), and the number of links decreased.



(a) (b)

Figure 7. (a) Identified C_u-spaces at a 10 cm voxel size. (b) The identified C_b-spaces at a 40 cm voxel size. Blue colour: C_u-spaces. Cyan colour: C_b-spaces.



(a) (b)

Figure 8. (a) An identified link for jumping up/down at a 10 cm voxel size. (b) The link changed to stepping up/down at a 40 cm voxel size. Green colour: navigable surfaces of P-spaces and links for stepping up/down. Blue colour: navigable surfaces of C_u-spaces and links for jumping up/down. Cyan colour: navigable surfaces of C_b-spaces.

3.3 Efficiency

The outcomes associated with the efficiency of the three elements' identifications and completing 3D pathfinding are presented in Appendix 2, 3, 4 and 5, respectively. The results from both the identifications and pathfinding indicate that as voxel sizes increased, the times required to identify the three elements and pathfinding decreased. Among the three elements, the times required for indoor space identifications were significantly greater than for the others. Additionally, for larger and more complex 3D models, the identifications and pathfinding times were substantially longer.

For indoor space identifications, when the voxel size was 5 cm, only the indoor spaces of the Duplex could be identified. When voxel sizes increased from 10 cm to 15 cm, the identification times for the three models decreased significantly to approximately 13%, 9%, and 21% of the times required at a 10 cm voxel size. Subsequently, with larger voxel sizes (20-25 cm), the identification times for Duplex changed insignificantly, while the identification times for models 2 and 3 continued to decrease significantly. Additionally, with its complex, diverse, and non-orthogonal indoor space geometries, the Roundhouse required more identification times than the Red Centre, which has a larger scale and more rectangular indoor space geometries.

The required times for surfaces and links identifications seem to be very short under different voxel sizes. Similarly, when voxel sizes increased from 10 cm to 15 cm, the identification times for both surfaces and links significantly reduced. Unlike indoor space identifications, the Red Centre, with its larger indoor scale, required more times for surface and link identifications compared to the Roundhouse.

Finally, the times required to complete 3D pathfinding showed a significant decrease with increasing voxel sizes. For instance, the pathfinding time for the Red Centre at a 15 cm voxel size (3.142 s) was approximately 4.6 times that at a 20 cm voxel size (0.682 s). The mean pathfinding times for the three models was 0.009 s, 0.156 s, and 1.401 s, respectively. Given that the Red Centre has the largest scale among the three models, with a longer distance between the starting and ending points for pathfinding, its mean pathfinding time was significantly higher than that of the other models.

4. Discussion and conclusions

This paper investigated the performance of voxel sizes on the identifications of indoor spaces, navigable surfaces, vertical links, and 3D pathfinding using three key metrics: accuracy, robustness, and efficiency. This work continues our previous research (Xie *et al.* 2022a, Xie *et al.* 2023a) where we are developing automatic methods for creating a voxel-based 3D indoor model to support 3D evacuation simulations. The primary findings of this investigation are: 1) with increasing voxel sizes, accuracy decreases, robustness changes, and efficiency increases; 2) larger indoor spaces exhibit smaller changes in accuracy across different voxel sizes, while smaller indoor spaces show more significant changes in accuracy; 3) when the voxel size is tiny, such as 5 cm, it becomes challenging to complete identifications. Conversely, with larger voxel sizes (greater than 25 cm), some C-spaces cannot be identified, and the type of some C-spaces and vertical links changes; 4) complex and non-orthogonal geometries of indoor spaces require more time to identify. However, these geometries do not significantly affect time required to identify navigable surfaces and vertical links or impact the 3D pathfinding time.

Based on these findings, we propose several strategies for selecting an appropriate voxel size:

- For relatively small buildings (e.g., pubs, houses, cafés, specific rooms/halls), a 5-15 cm voxel size range is recommended if a fine-grained and realistic 3D evacuation simulation is required. This range offers a good balance of accuracy, robustness, and efficiency. However, if high realism is not necessary, voxel sizes of 20-30 cm can be a suitable option to identify some C-spaces.
- For medium-scale buildings or those with complex, non-orthogonal geometries (e.g., canteens, teaching buildings, theatres), a voxel size range of 10-20 cm should be adopted if a realistic 3D evacuation

simulation is desired. Otherwise, voxel sizes larger than 20 cm may be chosen to prioritise efficiency.

- For large and complex buildings, such as commercial complexes, high-rise buildings, and airports, 25-35 cm voxel sizes are appropriate for performing 3D evacuation simulations. This range provides a practical balance between detail and computational feasibility.

Several points warrant attention in our research. Firstly, a more comprehensive and precise quantitative assessment method for robustness must be investigated. This could include measurements such as the number of C-spaces that change as voxel size increases and identifying which types of C-spaces are most prone to change. Specific measurements can more effectively illustrate robustness, providing better guidance for voxel size selection.

Secondly, a larger variety of buildings models have to be tested. We will select IFC models with different levels of detail for subsequent testing. Our research indicates a potential correlation between the appropriate voxel size and levels of detail. For example, at a 5 cm voxel size, details like the nosing of stairs become apparent, leading to unsuccessful identification of navigable surfaces related to stairs. Additionally, we pre-processed the models by removing specific entities to reduce unnecessary information. For instance, we excluded the Roundhouse roof truss structure, the Red Centre's stair railings, and glass curtain walls. Further analysis is needed to determine the appropriate levels of detail for IFC models used in evacuation simulations.

Lastly, space identification proved to be the most time-consuming process in our study. Inspired by studies (Li *et al.* 2020, Gorte 2023), we propose establishing a voxel database to store and manage voxels for identified indoor spaces to address this. By segmenting and managing voxels according to specific semantics, we can perform a one-time identification for complex models and store the results. This database would facilitate convenient querying for subsequent surface and link identification processes. In summary, our future research directions are:

- Investigating the performance of IFC models with various levels of detail on the automatic methods.
- Establishing a voxel database to store identified indoor spaces.
- Developing a 3D evacuation model for more complex testing.

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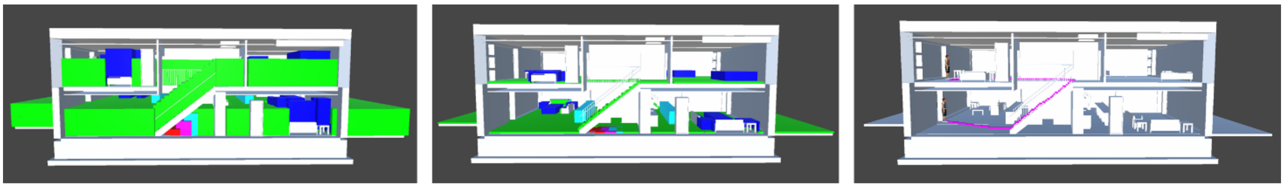
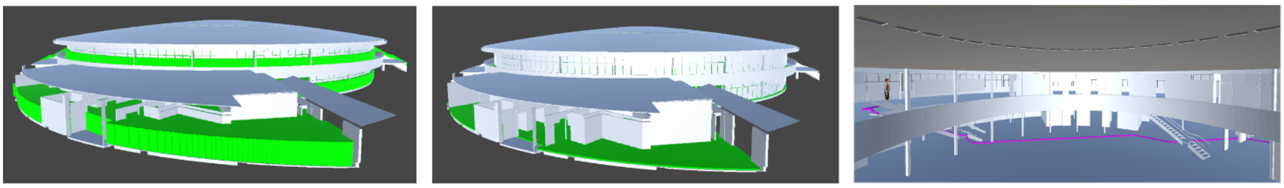
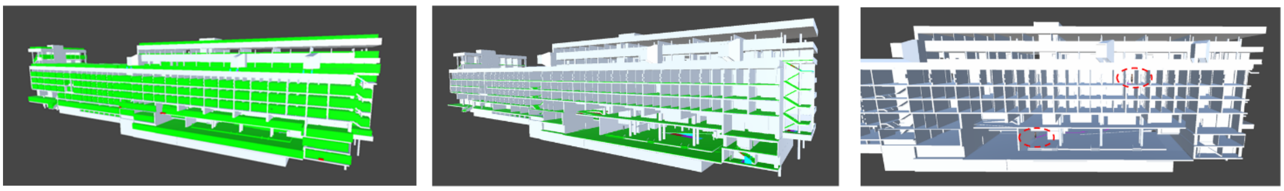
Appendix 1. Identified indoor spaces, navigable surfaces, vertical links and 3D pathfinding at a 10 cm voxel size. Green colour: P-spaces, navigable surfaces of P-spaces, and links for stepping up/down. Blue colour: C_u-spaces, navigable surfaces of C_u-spaces, links for jumping up/down. Cyan colour: C_b-spaces, navigable surfaces of C_b-spaces, links for climbing up/down. Magenta colour: C_k-spaces, navigable surfaces of C_k-spaces; Red colour: C_l-spaces, navigable surfaces of C_l-spaces. Purple colour: 3D paths.



(a) Extracted indoor space, navigable surfaces, vertical links and 3D pathfinding in the Duplex



(b) Extracted indoor space, navigable surfaces, vertical links and 3D pathfinding in the Roundhouse



(c) Extracted indoor space, navigable surfaces, vertical links and 3D pathfinding in the Red Centre

Appendix 2. Time used to identify indoor spaces under different voxel sizes.

Model name	Time of indoor spaces subdivision (s)								
	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm	40 cm	45 cm
Duplex	945.698	40.447	5.255	1.738	1.66	1.36	1.59	1.21	0.07
Roundhouse	/	1383.218	123.163	50.506	18.737	13.33	5.802	3.717	1.745
Red Centre	/	254.78	54.394	14.451	6.213	1.957	1.394	0.904	0.643

Appendix 3. Time used to identify navigable surfaces under different voxel sizes.

Model name	Time of navigable surface identification (s)								
	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm	40 cm	45 cm
Duplex	0.433	0.053	0.014	0.005	0.002	0.001	<0.001	<0.001	<0.001
Roundhouse	/	2.16	0.537	0.258	0.148	0.069	0.047	0.036	0.038
Red Centre	/	3.902	1.117	0.463	0.245	0.144	0.104	0.08	0.048

Appendix 4. Time used to identify vertical links under different voxel sizes

Model name	Time of vertical link identification (s)								
	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm	40 cm	45 cm
Duplex	0.063	0.008	0.003	0.001	0.001	<0.001	<0.001	<0.001	<0.001
Roundhouse	/	0.301	0.093	0.048	0.023	0.015	0.014	0.007	0.005
Red Centre	/	0.656	0.164	0.075	0.033	0.019	0.017	0.009	0.009

Appendix 5. Time used to perform 3D pathfinding under different voxel sizes

Model name	Time of 3D pathfinding (s)								
	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm	40 cm	45 cm
Duplex	/	0.026	0.017	0.016	0.008	0.004	<0.001	<0.001	<0.001
Roundhouse	/	0.589	0.274	0.199	0.069	0.043	0.042	0.022	0.016
Red Centre	/	6.013	3.142	0.682	0.445	0.367	0.208	0.198	0.16