Digital Twin of Buildings and Occupants for Emergency Evacuation: Framework, Technologies, Applications and Trends

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Abstract

Buildings face threats from various emergencies, with emergency evacuation being a key measure for occupant safety. However, enhancing evacuation efficiency necessitates detailed studies of building characteristics and human behaviors. Despite this, a systematic review of digital twin technologies for emergency evacuation is still lacking. Therefore, by collecting and analyzing literature from 2004 to 2025 using PRISMA methodology, this study first proposes a conceptual digital twin framework that integrates buildings, occupants, and their interactions, encompassing the entire loop of sensing, updating, simulation, and decision-making. The current research has made significant progress in areas such as basic virtual modeling, one-way data mapping, and preliminary bidirectional interaction. However, studies and applications of digital twins remain in the developmental stage, with most at maturity levels L0-L2, while L4-L5 applications are still relatively scarce. It is suggested that the future development of digital twin-based evacuation systems must rely on multidisciplinary collaboration to achieve breakthrough, including optimizing underlying mechanisms to enhance data and system integration; improving sensor accuracy and developing adaptive algorithms; integrating emerging artificial intelligence technologies while addressing data ethics; and enhancing computational efficiency to strengthen system robustness.

Keywords: Digital twin; Emergency evacuation; Conceptual framework; Review

1. Introduction

Buildings face various natural and man-made disasters(Asimakopoulou and Bessis, 2011), along with other emergency threats. Natural disasters include typhoons, floods, earthquakes, etc. (Yang et al., 2018). Man-made disasters encompass fires, hazardous chemical leaks, nuclear accidents, and terrorist attacks (Liu et al., 2012). In serious emergencies, emergency evacuation is key to ensuring occupant safety (Chu and Yeh, 2012). However, emergencies can lead to chaos, blockages, and even stampedes, resulting in tragedy (Grosshandler et al., 2005; Mydans, 2009). Additionally, the evacuation process imposes significant physical and psychological pressures,

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making it challenging for actual evacuation behavior to align with the plan (Luh et al., 2012; Pelechano and Badler, 2006). Thus, refining emergency evacuation strategies requires a thorough understanding of the built environment, pedestrian flow patterns, and their interactions.

Emergency evacuation research aims to efficiently organize and guide occupants to quickly and safely evacuate dangerous areas during emergencies. The two main methods of emergency evacuation research are evacuation experiments and virtual simulation. Evacuation experiments primarily observe and collect data on evacuation behavior in real environments. Virtual simulation uses computer technology to simulate and analyze the evacuation process based on specific theories and assumptions. While evacuation experiments more accurately reflect the complexity and diversity of evacuation, they are time-consuming, potentially dangerous, and have other limitations. Consequently, many researchers opt for virtual simulation to conduct comprehensive emergency evacuation studies using computer models. However, traditional methods face significant limitations. Conventional evacuation plans are often static, based on predetermined paths, and may not take into account real-time changes such as fire spread, smoke, and other obstacles. The behavior of people during the evacuation process is also difficult to predict using models. These methods struggle with integrating real-time data, adapting to dynamic environments, and accurately representing complex human behaviors during emergencies. These limitations have led researchers to explore more advanced technologies that can bridge the gap between virtual simulations and real-world conditions, providing more accurate and responsive evacuation strategies.

The introduction of digital twin technology provides a more dynamic and real-time approach for emergency management, offering opportunities to continuously update building data, simulate the progress of disasters, and optimize evacuation strategies. The concept of digital twin was first proposed in 2003 and has been continuously refined (Gabor et al., 2016). Digital twin refers to digital replicas of physical entities or systems in a virtual environment, with the two connected through data, enabling real-time interaction and synchronization. With the development of technologies such as Internet of Things (IoT), big data, artificial intelligence, and cloud computing, digital twin technology has moved from concept to practical application (Stavropoulos and Mourtzis, 2022). Its core characteristics include: (1) High fidelity simulation: accurately replicating the geometric features, physical properties, and behaviors of physical entities; (2) Real-time synchronization: enabling bidirectional data flow between physical entities and digital models through sensor networks; (3) Closed-loop optimization: optimizing the performance and operation of physical entities based on data analysis and simulation predictions; (4) Full lifecycle management: covering the entire process from design, manufacturing to operation and maintenance. Digital twin technology has already been widely applied in manufacturing (Jones et al., 2020; Papacharalampopoulos et al., 2023). Digital twin applications are classified according to their maturity levels, from L0 to L5 (Tao et al., 2022). These maturity levels provide a framework for evaluating the sophistication and implementation status of digital twin applications in various fields. With the continuous progress of related technology, digital twin technology has since expanded to various domains, including the Architecture, Engineering, and Construction (AEC) field (Fan et al., 2018; Yitmen et al., 2021), where scholars have increasingly applied it to emergency evacuation research. Digital twin technology can help us better understand the characteristics of the building environment and how it interacts with pedestrian. From the perspective of buildings, digital twin enables high-precision simulation of complex evacuation scenarios and disaster situations. From the perspective of occupants, digital twin provides a sophisticated framework for simulating human behavior during the evacuation process, which has strong application potential in disaster sensing, modeling, simulation, and decision-making.

As urbanization accelerates and building complexity increases, traditional evacuation methods can no longer meet emergency evacuation needs in complex building environments, and the industry urgently needs more intelligent and dynamic solutions. Despite significant advancements in both emergency evacuation research and digital twin technology, several critical research gaps remain unaddressed. (1) There is a lack of comprehensive frameworks that integrate both building and occupant perspectives within digital twin applications for emergency evacuation. (2) While various technologies supporting digital twin implementation exist, a large number of review articles have been published on digital twin in manufacturing, clarifying their definition, research directions, trends, and application status (Cimino et al., 2019; Holler et al., 2016; Kritzinger et al., 2018; Negri et al., 2017; Tao et al., 2018), there is limited systematic analysis of how these technologies can be effectively integrated specifically for evacuation scenarios. (3) The maturity levels of existing digital twin applications in emergency evacuation contexts remain unclear, hindering practitioners' ability to assess implementation feasibility. These research gaps highlight the need for a comprehensive review that synthesizes existing knowledge and provides direction for future research and practical applications.

Based on the identified research gaps, this study aims to address the following research questions: (1) How to construct a digital twin concept framework that integrates building and occupant? (2) In the digital twin of building and occupant, how are key technologies (including sensing, modeling, updating, simulation, and decision-making) applied? (3) What is the maturity of existing application scenarios? What are the future development trends? The expectation is that through this research, the potential of digital twin technology in the field of emergency evacuation will be revealed, providing a theoretical foundation and a technical framework for the application of digital twin technology in emergency evacuation, and offering directional guidance for the development of related technologies.

The remainder of the paper is organized as follows. Section 2 summarizes the related research work. Section 3 introduces the literature review method and the paper's structure. Section 4 introduces the conceptual framework for digital twin in emergency evacuation. Sections 5 and 6 analyze the current status of related technologies from the perspectives of building and occupant digital twin, including application cases. Section 7 details typical applications within the comprehensive digital twin framework. Section 8 summarizes the research and outlines future directions. Section 9 concludes the paper and assesses the main findings.

2. Related work

Digital twin technology in emergency evacuation can connect the physical building environment with its digital representation in real time. It combines various advanced technologies, including sensor networks, data analysis, artificial intelligence, and visualization technology, to create dynamic, interactive digital models of buildings and their occupants, providing a more comprehensive, real-time solution that can monitor building status, personnel locations, predict disaster development paths, and optimize evacuation strategies.

Existing research on the application of digital twin technology in the emergency evacuation process mainly focuses on the development and application of computer simulation models, and the integration of emerging technologies. Common computer simulation models include STEPS, PathFinder, buildingEXODUS, FDS+Evac, and EXIT89(Ronchi and Kinsey, 2011). These models adapt their methods and parameters to simulate human evacuation characteristics on both micro and macro levels, suited to various research goals and scenarios. However, significant issues arise, primarily in: (1) Model simplification: To reduce computational complexity and enhance efficiency, models often simplify the evacuation environment, pedestrian characteristics, and behavior rules, overlooking details and variations, which affects their applicability and accuracy (Y.Li et al., 2019b). (2) Parameter selection: Models require input parameters to describe the evacuation environment, pedestrian characteristics, and behavior rules. These parameters, often based on experience, hypotheses, or statistics, may not always align with reality (Ma and Wu, 2020). (3) Dynamic change: It is crucial to timely adjust the model's parameters and outputs to reflect the dynamic changes in the evacuation environment, pedestrian characteristics, and behavior rules, ensuring the model's effectiveness and adaptability (Sagun et al., 2011; Z. Liu et al., 2018). However, current models lack the capability for sensing and adaptation to real situations, making real-time updates and optimization challenging. In summary, while computer simulation models offer an effective approach for emergency evacuation research, their shortcomings, such as difficulty in timely parameter adjustment, limit the accuracy of risk assessments and efficient emergency response decision-making. Compared to traditional computer simulations, digital twin technology can continuously receive real-time data from sensor networks, allowing the model to automatically adjust parameters based on real-time observed deviations, with broad application prospects.

Recent advancements in information technology have opened new opportunities and challenges for emergency evacuation research. In the field of AEC, Building Information Modeling (BIM) technology serves as a comprehensive 3D modeling tool, facilitating digital management across the building's lifecycle. (Doumbouya et al., 2017). Geographic Information System (GIS) technology enables 3D modeling on a broader environmental scale. The integration of BIM and GIS facilitates merging 3D spatial information at various levels, significantly enhancing virtual modeling and data sharing efficiency and accuracy for both indoor and outdoor environments. Additionally, technologies like 3D reconstruction and the Internet of Things (IoT) introduce new possibilities for swiftly remapping indoor and outdoor spaces. For instance, combining LiDAR, 3D laser scanning, and photogrammetry with BIM and GIS can create an environmentally aware building information database with dynamic updating features (Z. Liu et al., 2018; Tang et al., 2019; Ramírez and Ferreira, 2021), architectural optimization, path planning (Baik, 2017; Mijic et al., 2017; Liu et al., 2021), and other application scenarios. Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and other technologies also provide new methods for dynamically sensing indoor environment parameters, tracking and monitoring human behavior, and optimizing paths (Ahmad et al., 2020; Candanedo and Feldheim, 2016; Georgievski et al., 2013; Li et al., 2014; Qi et al., 2018). These studies show that cross-domain applications of digital twin technology are creating new possibilities.

Although previous reviews have focused on the applications of digital twin in the sensing and modeling of buildings and human behavior, as well as the analysis of digital twin applications in manufacturing and their characteristics，as shown in Table 1. They failed to address the specific context of emergency evacuation (Deng et al., 2021; Sepasgozar, 2021). These reviews often overlook the integration of building characteristics and pedestrian behavior in their analysis. In *contrast, our study takes a more comprehensive approach by proposing a digital twin framework that incorporates both buildings and occupants, including aspects of sensing, updating, simulation, and decision-making. Furthermore, while existing reviews discuss digital twin technologies in isolated domains, our study systematically classifies and analyzes current applications into five maturity levels (L0 to L4), providing a clearer understanding of the developmental stages of digital twin technologies in emergency evacuation contexts.*

By employing the PRISMA methodology, this review goes beyond merely summarizing existing technologies; it offers a structured and systematic analysis that covers not only technological perspectives but also integrates insights into their maturity and challenges. This provides an essential contribution to the field, guiding future research directions and addressing the gaps identified in prior reviews.

Table 1 The existing literature review

Reference	*Buildings*	*0ccupants*	*Building occupant interaction*	*Sensing and updating*	*Modeling*	*Simulation*	*Decision-making*
[18]	✓	✓			✓		
[107]		✓			✓		
[175]		✓			✓		
[123]		✓			✓	✓	
[137][209]	✓	✓		✓			
[147]		✓		✓			
[25][49][82][152][189]	✓			✓			
[43]		✓		✓			
[45]		✓		✓			
[44][87][115][159]				✓	✓		
[104]							
Our review	✓	✓	✓	✓	✓	✓	✓

3. Methodology

Using the PRISMA method, this paper gives a comprehensive literature review on digital twin technology and its application scenarios in emergency evacuation. The process of PRISMA mainly includes identification, eligibility, and screening.

3.1 Database selection and retrieval strategy

Since Scopus database covers more than 77,000 publications and covers a wider range of literature, its data are often used to evaluate scientific research output and performance, and its authority is widely recognized in the academic community, so the search of this study was completed in Scopus database.

With the introduction of the industry 4.0 concept, the manufacturing industry has become one of the main application scenarios for digital twin technology. Therefore, a broad review of the literature in the field of digital twin technology in manufacturing and emergency evacuation has been conducted to distill the basic keywords (Radianti et al., 2013; Ronchi and Nilsson, 2013; Bayram, 2016; Kritzinger et al., 2018; Cimino et al., 2019; Kaur and Kaur, 2022), comprehensively covering the key technologies and application scenarios involved in digital twin emergency evacuation research. For building digital twin, initially, foundational modeling technologies such as BIM and GIS are selected as key terms because they provide basic 3D visualization and information integration capabilities. Subsequently, technologies that enable real-time data collection and transmission, such as 3D Sensing, Simultaneous Localization and Mapping (SLAM), IoT, Sensor Network, LiDAR, UWB, RFID, etc., are chosen as key terms. These technologies are crucial for connecting the physical and virtual spaces within the digital twin system. For occupant digital twin, key terms related to crowd modeling and simulation, such as Evacuation Model, Network Model, Cellular Automata, Social Force Model, Agent-Based Model, Video Motion Capture, Indoor Positioning, VR/AR/MR, which are collectively known as Extended Reality (XR), etc., are selected. These technologies are essential for analyzing crowd behavior, locating personnel positions, and optimizing evacuation strategies. For application scenarios, key terms reflecting the main use cases and research focuses of digital twin technology in the emergency evacuation process, such as Path Planning, Indoor Navigation, Training, Monitoring, Facilities Management, Decision-making, Reliability Assessment, etc., are chosen. The selection of these key terms strikes a balance between the breadth and depth of research, ensuring comprehensive coverage of relevant technologies. By using these key terms in literature searches, the most relevant and influential research works in this field can be identified, laying a solid foundation for subsequent analysis and discussion. The keywords are as shown in Table 1.The final search formula selected is: KEY (BIM OR GIS OR "3D Sensing" OR SLAM OR IOT OR "Sensor Network" OR LiDAR OR UWB OR RFID OR "Evacuation Model" OR "Network Model" OR " Cellular Automata" OR "Social Force Model" OR "Agent-Based Model" OR "Video Motion Capture" OR "Indoor Positioning" OR XR OR "Path Planning" OR "Indoor Navigation" OR Training OR Monitoring OR "Facilities Management" OR "Decision-making" OR "Reliability Assessment") AND TITLE-ABS-KEY ("Emergency Evacuation") AND PUBYEAR > 2004 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA,"ENGI").

Table *2* Literature classification table

Classifications	Keywords	The role of digital twin
Building digital twin	BIM	Provide a 3D information model of the building as the data foundation for the virtual space.
	GIS	Provide geospatial information and integrate indoor and outdoor environmental data.
	3D Sensing、SLAM	Achieve spatial perception and high-precision 3D reconstruction, maintaining consistency between the physical space and the virtual space.
	IoT、Sensor Network	Real-time monitoring of parameter changes, supporting the real-time update mechanism of digital twin technology

	LiDAR、UWB、RFID	Specific sensing technologies offer high-precision capabilities for spatial measurement, positioning and identification.
Occupant digital twin	Evacuation Model	Mathematical Model of Crowd Evacuation Behavior
	Network Model、Cellular Automata、Social Force Model、Agent-Based Model	Different evacuation models simulate the behaviors of people at different scales.
	Video Motion Capture、Indoor Positioning	Realize personnel behavior perception and location tracking, and provide real-time data input for occupant digital twin.
	XR	Provide an immersive interactive environment, supporting evacuation training and behavioral data collection
Application scenarios	Path Planning、Indoor Navigation	Path planning and navigation applications based on digital twin, optimization of evacuation decisions
	Training、Monitoring	Support personnel training and environmental monitoring application
	Facilities Management	Facility management based on digital twin technology can enhance the performance of buildings.
	Decision-making、Reliability Assessment	Support data-based evacuation decision-making and reliability assessment

3.2 Inclusion and exclusion criteria

Subsequently, to ensure that the included literature comprehensively covers the key aspects of digital twin technology in building and personnel emergency evacuation, we have established clear inclusion criteria to select the most relevant literature to the research purpose. First, the main criteria for inclusion and exclusion based on the abstract are as follows: (1) the publication language is English; (2) the research topic is directly related to the sensing, modeling, simulation of building or occupant digital twin, and their application in emergency evacuation; (3) the keywords in Table *2* are mentioned multiple times. Second, the main criteria for screening based on the full text content are as follows: (1) the research content includes specific application scenarios of the relevant technology, such as behavior perception and training, disaster risk assessment, pre-disaster monitoring and early warning, etc.; (2) the research method is primarily case analysis and simulation experiments, not pure theoretical research.

3.3 Literature screening process

By employing the snowballing method, one can start with a set of highly relevant initial literature and continuously discover more related studies through citations. This approach overcomes the limitations of keyword searching, which may omit relevant literature that uses different terminology. It also compensates for the shortcomings of using a single database (Scopus) in this study, thereby enhancing the comprehensiveness of the literature search. Therefore, we initially conducted a broad search that yielded 342 articles. Subsequently, by integrating the snowball sampling method, we obtained a total of *601* academic articles.

During the screening process, we strictly followed the aforementioned inclusion criteria and individually screened each of the 626 preliminary retrieved articles. Two researchers independently completed the screening and compared the results. For articles with significant discrepancies, consensus was reached through discussion or by consulting a third-party expert. After the first round of screening based on abstracts, we removed duplicate studies and excluded irrelevant literature. Subsequently, during the second round of careful full-text screening, we eliminated any literature that did not align with the core focus of the research. Finally, 96 articles with typical application scenarios were selected for in-depth analysis, and *230* articles were retained.

3.4 Framework of literature analysis

The trend of annual publications number is shown in Figure 1 (a), and the top eight source journals for the *230* articles are shown in Figure 1 (b). The increase in the number of annual publications indicates a significant upward trend in the research enthusiasm in this field, especially since 2015 when a notable growth occurred. The sources of literature cover multiple fields such as automation and safety, suggesting that the research on digital twin emergency evacuation has the characteristic of interdisciplinary integration. The structure of the paper is shown in Figure 2. After conducting data collection based on the PRISMA method, we proposed a conceptual framework for the digital twin of buildings and occupants. Subsequently, we outlined the concept of digital twin, focusing on the perspectives of buildings and occupants. Specifically, the digital twin of buildings refers to the creation of a digital replica of the building in virtual space using technologies such as BIM, GIS, and the IoT, enabling real-time monitoring, simulation, and optimized management of the building's structure, facilities, and environment. The digital twin of occupants refers to the creation of a digital replica of the building's inhabitants in virtual space using evacuation models, simulation software, sensors, and other technologies, enabling real-time sensing of their location, behavior, physiological status, behavior collection, and interactive guidance. Following this, we analyzed typical application scenarios and summarized the current state of research and future development trends.

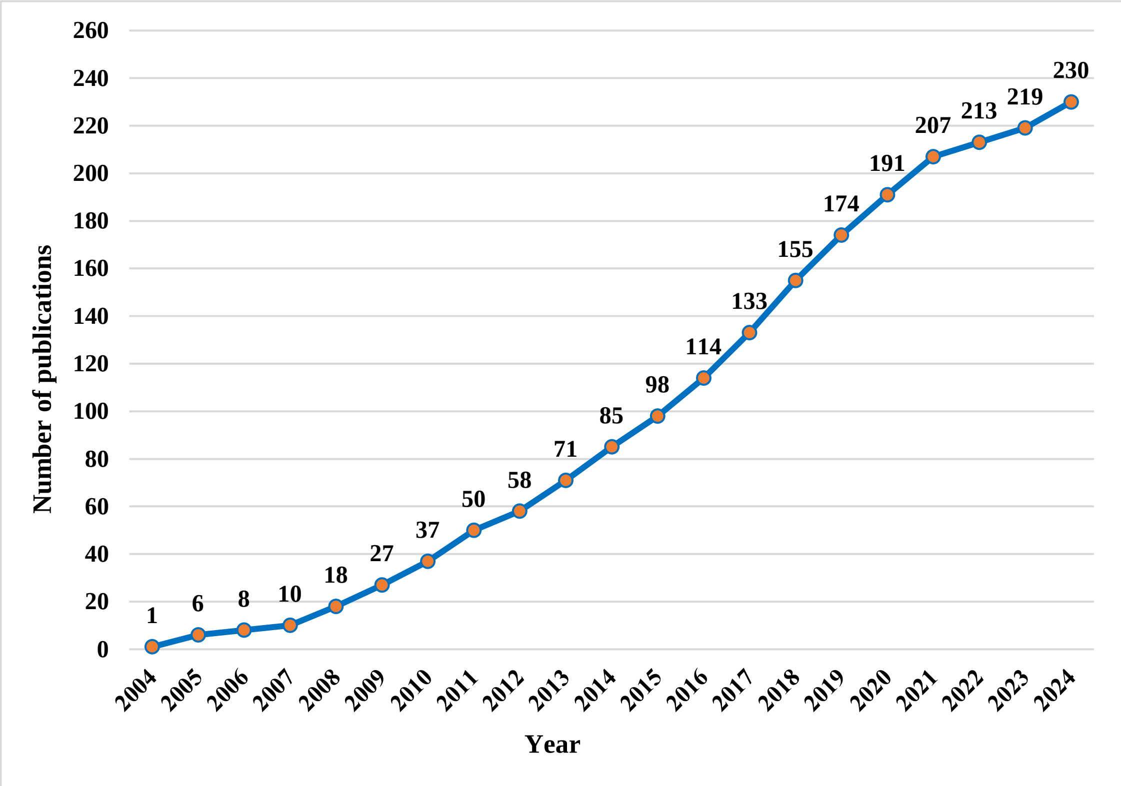

Figure 1 (a) The trend of annual publications number

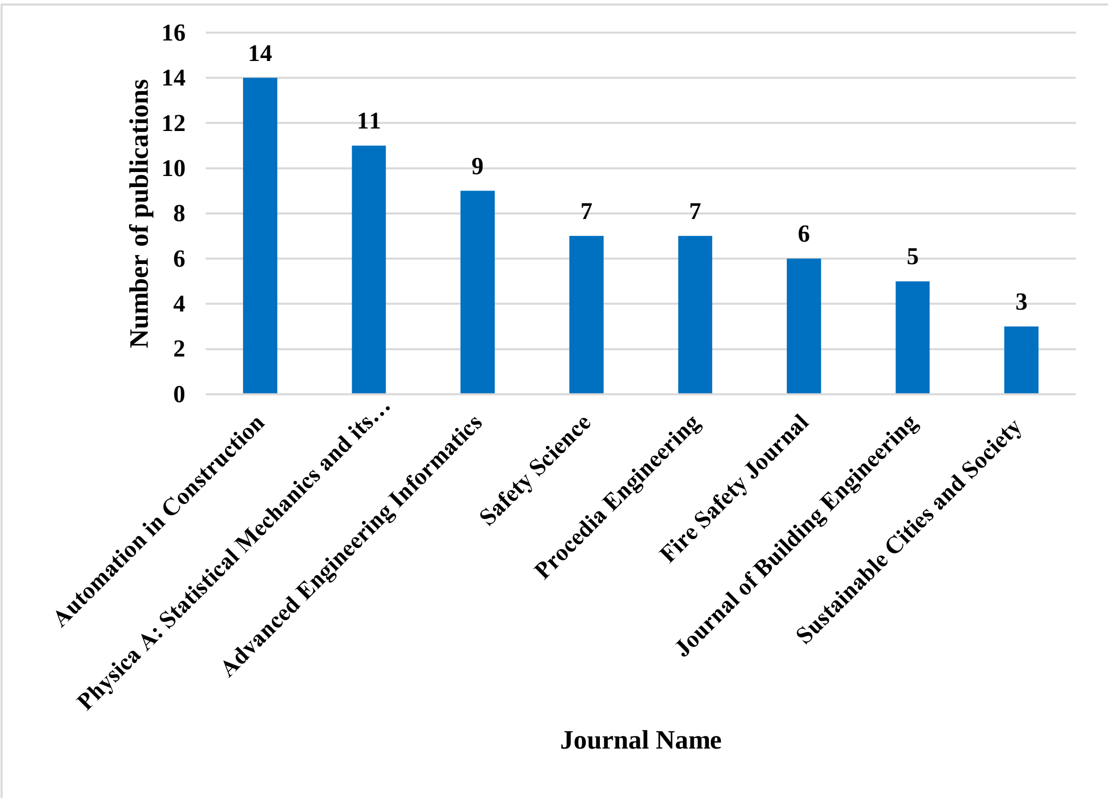

Figure 1 (b) The top eight source journals

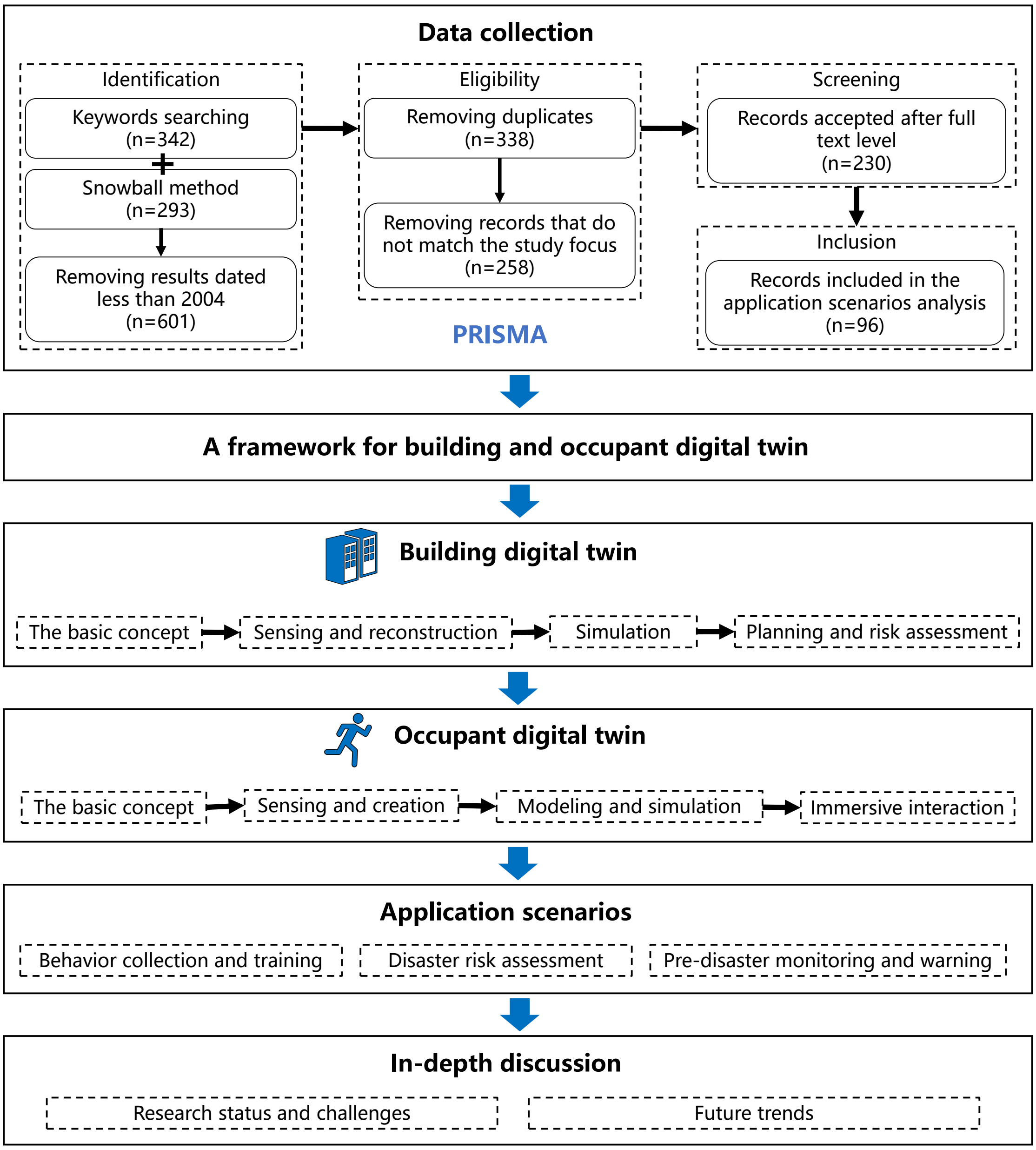

Figure 2 The Organizational framework of the review

4. Framework for buildings and occupants digital twin

The two most important aspects of emergency evacuation are the building environment and human behavior, and they interact with each other. The design and planning of the building environment affect the feasibility, safety, and efficiency of human evacuation, and the development of disasters affects the cognition and decision-making of human evacuation. For instance, the number and location of exits, the width of corridors, smoke produced by fires, and high temperatures can all alter the evacuation routes of occupants. In turn, the dynamic distribution of pedestrian traffic can change the actual capacity of various regions within the built environment. To ensure rapid, orderly, and safe evacuation in emergencies, it is necessary to consider the dynamic changes in both the built environment and human behavior comprehensively. Digital twin relies on the sensor network to monitor and perceive the changes in the physical space, so that cyber space can be reconstructed and the refined simulation of the physical space can be realized. Therefore, through the analysis of cyber space, the physical space situation can be reliably predicted and even adjusted.

We will propose the conceptual framework of building and occupant digital twin from the perspectives of building environment and human behavior, similar to the recent successful application of digital twin frameworks in building fire safety management (Ding et al., 2023), as shown in Figure 3. However, compared with methods that are limited to fire scenarios only, our framework has the following differences: (1) Our framework systematically integrates two key dimensions, namely the built environment and human behavior. (2) Our framework is not limited to a single disaster type (such as fire), but can adapt to various emergency scenarios. (3) Our framework builds a complete digital twin closed loop, from physical space perception to virtual space update, and then to simulation analysis and decision optimization. The sensing and updating layer is used to sense the physical space and update the virtual data in the cyber space, which is the basis of modeling the digital twin model, so it is used as the first layer. The modeling layer is mainly concerned with the modeling techniques required to create cyberspace, which is the basis for subsequent simulation and application and to ensure the consistency of the digital twin model with reality, so it is used as the second layer. The simulation layer is mainly used for building environment and occupant simulation in the evacuation process, which is the core of emergency evacuation. Using the sensed information and the constructed model, the accuracy of the environment and personnel data required for the simulation can be guaranteed, so it is used as the third layer. Based on the real-time data and simulation results obtained by the simulation layer, the decision-making layer evaluates the feasibility and safety of the current evacuation plan, so as to optimize the evacuation path and strategy, and warn the potential risk. It is based on the specific application of the previous three layers, so it is regarded as the fourth layer. Based on the analysis of typical application scenarios, this paper divides them into three main areas: behavior collection and training, disaster risk assessment, and pre-disaster monitoring and early warning. Emergency evacuation usually includes three important stages: post-disaster training and evaluation, in-disaster response, and pre-disaster warning. Behavior collection and training can reproduce disaster scenarios, help summarize lessons, and improve residents' emergency awareness and skills. Disaster risk assessment corresponds to the response phase of the disaster, aiming at assessing the disaster situation and optimizing decision-making. Pre-disaster warning corresponds to the pre-disaster preparation phase, which aims to identify risks in advance and formulate plans. These three scenarios cover the key links of the whole process of emergency evacuation, which is comprehensive and representative.

Hierarchical architecture facilitates the abstraction and decoupling of problems. By dividing the complex emergency evacuation problem into several layers, each focusing on specific sub-problems or functions, the complexity of the problem can be reduced, and the research and implementation can be more targeted. At the same time, the layers are interlocking and support each other. The sensing and updating layer provide data for the modeling layer, the modeling layer provides digital twin model for the simulation layer, and the simulation layer provides a basis for the decision-making layer. In addition, the decision-making layer may need to adjust the parameters of the simulation layer, as well as the parameters of the modeling layer and the devices of the sensing and updating layer to explore different scenarios. This hierarchical structural design can clarify the functional positioning and interrelationships of each layer, making the application process of digital twin technology in emergency evacuation more systematic and structured.

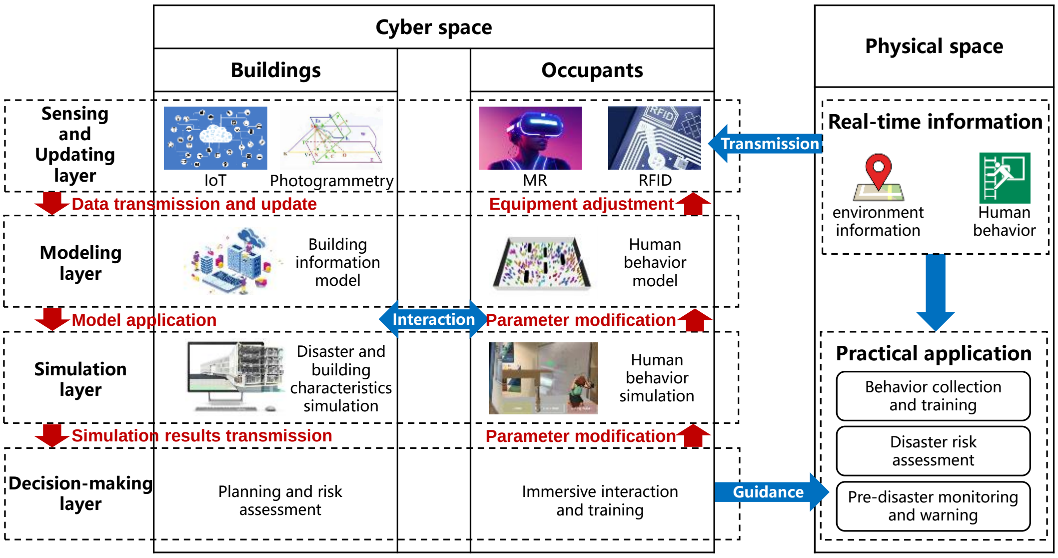

Figure 3 The proposed conceptual framework of digital twin emergency evacuation technology

5. Building digital twin

The building digital twin framework in emergency evacuation consists of three components: sensing and reconstruction methods, disaster simulation methods, planning and risk assessment methods. Information models can be built based on BIM and GIS technology, and sensor networks composed of sensors and visual sensing devices such as IoT can collect data in real time, sense and update the situation of building space. On this basis, a variety of simulation methods can be used to simulate the occurrence and development of disasters in building, and decision-makers can optimize evacuation plans and building layout according to the simulation results. The distribution of literature by year and field is shown in Figure 4. There is a relatively large number of studies on the application of BIM and GIS, as well as planning and risk assessment. In contrast, there are fewer studies on the sensing and reconstruction of building digital twin, and on disaster simulation based on building digital twin. In addition, the literature on building digital twin shows a notable uneven distribution across years, with the absence of literature in 2005 and 2012 possibly due to limitations in the literature retrieval and screening process. Overall, there was relatively little literature during 2008-2011, which may be related to BIM technology still being in its early development stage, with low industry awareness and adoption rate. The publication volume is concentrated between 2014 and 2021, with continuous improvement in the level of technology integration and application depth.

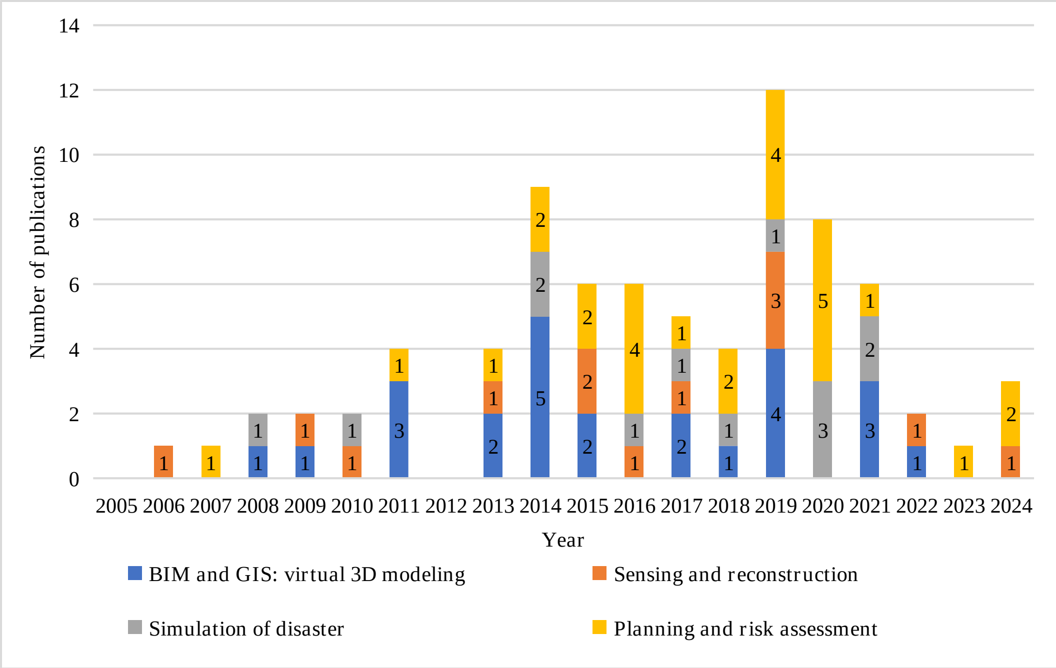

Figure 4 Literature field and year distribution of building digital twin

5.1 BIM and GIS: virtual 3D modeling for building digital twin

BIM encompasses the geometric information and spatial relationships of buildings, permeating the entire lifecycle of a project (Succar, 2009; Bryde et al., 2013; Jung and Joo, 2011). It creates virtual 3D models that support interdisciplinary collaboration and resource management (Azhar, 2011; Kim and Lee, 2019) , while also enabling information sharing with tools like EvaluationNZ and Pyrosim (Dimyadi et al., 2016; Lotfi et al., 2021; Ahn et al., 2024). Although the combination of BIM with XR technologies has created immersive environments for data collection and pedestrian training (Rüppel and Schatz, 2011; B. Wang et al., 2014; Liu et al., 2014; Zhang and Issa, 2015; Y.Li et al., 2019b; Lorusso et al., 2022), the inability of BIM to incorporate macro-geographical environmental elements limits its ability to simulate evacuation scenarios that involve both indoor and outdoor environments.

GIS processes geographic data, and when integrated with BIM and temporal dimensions, it supports the optimization of evacuation scenarios (Shi and Liu, 2014; Tang et al., 2021; Kim and Lee, 2019). By integrating spatial and semantic data from BIM and GIS, it allows for better evacuation planning, path optimization, and the creation of evacuation instructions (Uno and Kashiyama, 2008; Atila et al., 2013; Shimura and Yamamoto, 2014; Cheng et al., 2018; Deng et al., 2021). The combination of BIM, GIS, and XR technologies also facilitates disaster response and monitoring (Liu and Zhu, 2014; Yenumula et al., 2015; Cheng et al., 2017).

Currently, BIM and GIS integration relies on data format conversions, such as City Geography Markup Language (CityGML) and Industry Foundation Classes (IFC). However, information loss remains a key challenge in this transformation process, and integrated applications are still in the early exploration stage, unable to ensure a dynamic and seamless information sharing process. (M. Wang et al., 2019; Park et al., 2024).

5.2 Sensing and reconstruction of building digital twin

The sensing and reconstruction methods of building digital twin can be divided into two types: spatial sensing, and environmental information sensing and updating. The former is mostly used to reconstruct the building model to make it conform to the actual situation, while the latter can directly obtain the disaster and its development data to update cyber space.

5.2.1 Spatial reconstruction

Accurately perceiving architectural spatial coordinates to achieve high-precision model reconstruction is crucial for building digital twin. *Point cloud data, fundamental in 3D reconstruction, is primarily captured using laser measurement and photogrammetry technologies* (Lu et al., 2019; Bosché et al., 2015).

Laser measurements, including laser scanning and LiDAR, is the most common method for acquiring high-density point cloud data (Pu and Vosselman, 2006; Rottensteiner, 2003). It offers robustness but can lead to slow reconstruction processes and imprecise surface reconstruction. Photogrammetry, mainly through Unmanned Aerial Vehicle (UAV) for multi-angle photography, achieves the construction of high-resolution models (Sun et al., 2017; Xu et al., 2022). However, this method is greatly affected by environmental factors and lacks the capability to model small objects accurately. *Improvements in equipment precision and point cloud correction algorithms can reduce errors* (Chen et al., 2019). Combining various point cloud and image acquisition methods with deep learning approaches such as YOLO, PointNet, and GAN (H. Wang et al., 2019) can significantly improve the accuracy of modeling. Nevertheless, current research methods still struggle to capture all details precisely, and there is no universally applicable method for three-dimensional reconstruction yet.

For existing buildings with created BIM models, point cloud data can be integrated into the BIM system through feature recognition or machine learning (Brilakis et al., 2010; Xiong et al., 2013; Bosché et al., 2015), achieving precise registration and fusion of point clouds and BIM, thereby updating and optimizing the evacuation environment.

5.2.2 Environmental information sensing and updating

During emergency evacuation processes, the sensing and updating of the environment depend on continuous environmental monitoring and reliable data transmission. The deployment of Wireless Sensor Network (WSN) is relatively easy and cost-effective, possessing ubiquitous sensing and communication capabilities, and has been widely used in environmental sensing and updating (Wang et al., 2016). Primarily utilizing thermal sensors, smoke detectors, and other devices, data is integrated into BIM through the IoT and short-range wireless communication technologies, enabling real-time monitoring of environmental data such as temperature, humidity, and smoke. Factors such as hazard levels and evacuation capabilities are comprehensively considered to guide emergency evacuations (Silvani et al., 2015; Wang et al., 2016; H. Wang et al., 2019). Moreover, combining WSN with network cameras can precisely locate disasters and assess their impact range (Chen, 2009; Wang et al., 2016). However, the computational, storage, and transmission capabilities of WSN nodes are limited, and they are susceptible to attacks and signal interference. In the future, 5G technology and edge computing can be introduced to reduce data transmission delay and improve system reliability(Ding et al., 2023).

5.3 Simulation of disaster based on building digital twin

Emergency evacuation simulation can be divided into disaster simulation and evacuation process simulation. This section mainly focuses on how to simulate the evolution law of disasters. The simulation related to the pedestrian and evacuation process is included in Section 6.

BIM and GIS platforms provide spatial and semantic information for simulating sudden events, aiding in evacuation and rescue. This information can be input into software like Fire Dynamics Simulator (FDS), AnyLogic, and Pathfinder to simulate disaster and evacuation environments (Shen et al., 2008; Papinigis et al., 2010; Jiang et al., 2014; Liao et al., 2014; Avdeeva et al., 2020; Rahman et al., 2021; Rostami and Alaghmandan, 2021), *Fire simulation is the most common, using BIM for visualization and real-time feedback* (Chen et al., 2018; Sun and Turkan, 2020). *However, previous studies didn't consider both building geometry and disaster development together, limiting simulation accuracy and evacuation time assessments. Recent research combining BIM technology with evacuation software has improved simulation outcomes* (Chen et al., 2018; Sun and Turkan, 2020). Nonetheless, due to insufficient model precision and other simulation details not being considered, as well as simplifications made to shorten computation time, the simulation results still do not align with actual situations.

Additionally, combining BIM and GIS with time series models enables simulation of meteorological impacts on building safety (Rahman and Lateh, 2017; Zou and Gui, 2020), as well as the assessment of disaster losses (Amirebrahimi et al., 2016). *Integrating BIM development with Navisworks allows direct simulation of engineering accidents, enhancing safety and emergency planning* (Deng et al., 2019). *However, the research is still in early stages, identifying only potential hazards.*

5.4 Planning and risk assessment based on building digital twin

This section focuses on evacuation path planning and disaster risk assessment based on disaster sensing information, and decision-making processes related to pedestrian and evacuation processes are included in Section 6. Various technologies of building digital twin can help to make actual decision-making in the field of disaster emergency evacuation, mainly focusing on path planning and pre-disaster warning.

5.4.1 Path planning

BIM and GIS can concurrently provide 3D data and topological relationship information for both indoor and outdoor spaces, enabling the integration of various path planning algorithms for evacuation and rescue planning. This integration facilitates the generation of targeted evacuation routes for different stages of an emergency (B. Wang et al., 2014; Teo and Cho, 2016; Kim and Lee, 2019).

Graph-based shortest-path algorithms aid in forming group evacuation strategies (Hu and Liu, 2018) and can be combined with BIM to implement visual guidance (Ma et al., 2017). The Dijkstra algorithm, known for its simplicity and wide applicability, is often used to search for evacuation paths (Cheng et al., 2016; Ma and Wu, 2020), and when integrated with IoT-distributed devices, it can sense the development of disasters (W. Wang et al., 2019) to determine the optimal evacuation paths, albeit at a high computational cost. In large-scale grids, the number of nodes n in the Dijkstra algorithm is very large, which causes the computation time to grow quadratically and becomes very time-consuming (Ammar et al., 2016). An improved Dijkstra algorithm (Samah et al., 2015) maintains its effectiveness while reducing computational costs, but it does not take pedestrian behavior into account.

The heuristic A* algorithm significantly reduces computational costs and is commonly used to calculate the shortest directed paths in network graphs, taking into account environmental information from fires to select optimal evacuation paths (Roan et al., 2011; Kim and Lee, 2019; Zhou et al., 2020; He et al., 2024). However, the A* algorithm needs to maintain an open list, from which the minimum value needs to be found in each iteration, which incurs additional computational costs when the list is large. Therefore, the A* algorithm is not suitable for large-scale search scenarios and does not consider the influence of pedestrian behavior(Ammar et al., 2016). Heuristic algorithms based on Strongly Connected Component (SCC) and Shortest Path Tree (SPT) are used for evacuation planning in poor communication environments (Takayama and Miwa, 2014), reducing the likelihood of congestion in evacuation routes, but the assumption that occupants will act entirely according to instructions may not align with actual situations. Multi-objective evacuation models based on GA (Y.Li et al., 2019a; Nahum et al., 2020) are suitable for multi-objective shortest path problems with random paths (Guo et al., 2023), it can minimize the time gap between the actual evacuation route and the optimal evacuation route ,but the studies involve a limited number of pedestrians and overlook the impact of pedestrian behavior. Evacuation planning methods based on improved artificial bee colony algorithms (H. Liu et al., 2018b) consider interactions among individuals in a crowd. In complex scenes and large-scale crowd situations, it performs better than the A* algorithm in terms of computational efficiency and performance, but struggle with dynamic grouping of people and utilizing automatically updated path information.

In addition, other algorithms have also been used in various studies. They mainly include distributed evacuation computation and navigation method based on WSN (Barnes et al., 2007), which consider both the development time of disasters and the evacuation time of occupants, yet do not take pedestrian behavior into account. Graph construction methods combining the Visibility Graph (VG) and Medial Axis Transform (MAT) (Chen and Huang, 2015; Chen and Chu, 2016), can significantly save computational time in large-scale problems but are unable to handle irregular components and do not consider the dynamic development of evacuating individuals and risks. Density-based navigation algorithms for evacuation planning (Sun and Liu, 2021) take into account the positions of pedestrians and are suitable for studies of multi-exit problems, but they are not applicable to complex and constantly changing scenarios. Most implementations of the shortest path selection are based on 2D models, which are insufficient for 3D environments. 3D network analysis methods based on CityGML data (Atila et al., 2013) have achieved visualization of indoor spaces in 3D-GIS and provided evacuation paths, but they have not fully considered pedestrian behavior.

In summary, most of these methods rely on traditional shortest path planning methods to generate evacuation paths, based on the assumption that pedestrians are aware of the evacuation routes and will act entirely according to instructions, without fully considering pedestrian behavior and the development of disasters. This aspect requires more attention and improvement in future research.

5.4.2 Pre-disaster warning

Based on digital twin technology, real-time monitoring video images can be presented, combined with real-time monitoring data of meteorology, geology, hydrology, atmosphere, etc., to provide data support for risk assessment and early warning information release for the auxiliary command center. When emergencies occur, various simulation methods can be used to visualize and dynamically deduce the relevant elements of the plan and the command process, assess the disaster losses (Amirebrahimi et al., 2016), support emergency management resource allocation, path planning, key target determination, and other decisions, and improve the emergency response capability and level.

In addition, by using big data and machine learning algorithms, early warning models can be developed, and an integrated emergency command and management system can be established, to evaluate the disaster risk in advance, and realize the prediction and prevention dispatch of emergency events. Currently, the evaluation and early warning through data monitoring have been applied to fields such as production supervision (Hu et. al., 2020), tunnel monitoring (Liu et al., 2020; Zhang et al., 2024b), ventilation early warning (Costa et. al., 2023), evacuation simulation (Dong et al., 2024), etc. However, the above research only focuses on the small scenario application of a single disaster. Due to the high complexity of constructing digital twin and the lack of hardware, software, and computing power, the realization of cross-domain, multi-disaster and whole-process risk assessment, monitoring and early warning still faces great challenges.

By integrating the above methods of sensing, simulation, and decision-making, a complete building digital twin system can be formed. Specifically, through space and environment sensing, all kinds of information in the building can be obtained in real-time. The refined disaster simulation can obtain the development information of disaster situations, further obtain the scientific emergency evacuation and rescue plan, and provide path planning and guidance for emergency evacuation. The key technologies of each component are shown in Table *3*.

Table *3* Summary of literature related to building digital twin

Key components	Application scenarios	Methods	Advantages	Disadvantages
Environment sensing and reconstruction	Indoor modeling based on BIM	Virtual environment modeling Model information extraction	Realize information sharing and integration	Unable to consider the overall indoor and outdoor environment
	Integration of GIS and BIM	Data format conversion	Consider both indoor and outdoor environments	Information may be lost
	Spatial reconstruction	Laser measurement	Obtain high-density point cloud data Strong robustness	Slow reconstruction process Inaccurate surface
		Photogrammetry	High resolution	Susceptible to environment Insufficient ability to model small objects
	Environmental information sensing and updating	WSN	Easy to deploy Low cost Strong sensing and communication	Limited storage and transmission capacity Vulnerable to attack and signal

			capabilities	interference
Simulation of disaster	Fire simulation	Input building information into simulation software	Achieve fire simulation and real-time information feedback	Building geometry and disaster development process are not considered at the same time
		Combine BIM and evacuation software	Integrated consideration of disaster development and evacuation simulation	Insufficient modeling accuracy
	Meteorological disaster simulation	Combine building information with time series model	Effectively assess disaster losses	Ignoring the unpredictable
	Engineering safety accident simulation	Combine BIM secondary development with Navisworks	Provide an emergency plan for engineering construction	Only some of the hidden hazards are considered
Decision-making	Path planning	Dijkstra	Simple thinking Applicable to many scenarios	High computing cost Pedestrian behavior is not taken into account
		A*	Significantly reduce computing costs	Not suitable for larger scenarios Pedestrian behavior is not taken into account
		Heuristic algorithm based on SCC and SPT	Reduce the likelihood of congestion on evacuation paths	The assumption is not consistent with the reality
		GA	Suitable for multi-objective shortest path problem	Pedestrian behavior is not taken into account
		Improved artificial bee colony algorithm	The interactions between individuals are considered	It is difficult to dynamically group groups of people
	Risk assessment	Early warning through data monitoring	The prediction and preventive scheduling of emergency events are realized	It can only be applied in small scenarios for a single disaster

6. Occupant digital twin

The occupant digital twin framework in emergency evacuation consists of three components: behavior sensing, modeling and simulation, immersive interaction, and training. The basic parameters of occupant modeling and simulation can be obtained based on the sensing of human behavior and movement, and the situation of occupant evacuation can be analyzed by using macro, micro, and meso evacuation models as well as corresponding computer simulation methods and software tools. Combined with the simulation of evacuation situation, evacuation training and evacuation guidance can be carried out for the emergency evacuation process of occupants. The distribution of literature by year and field is shown in Figure 5. There is a relatively large number of studies on modeling and simulation of human behavior. In contrast, there are fewer studies on the human behavior sensing to create occupant digital twin, immersive interaction and training based on occupant digital twin. The publication volume is concentrated between 2008 and 2020.

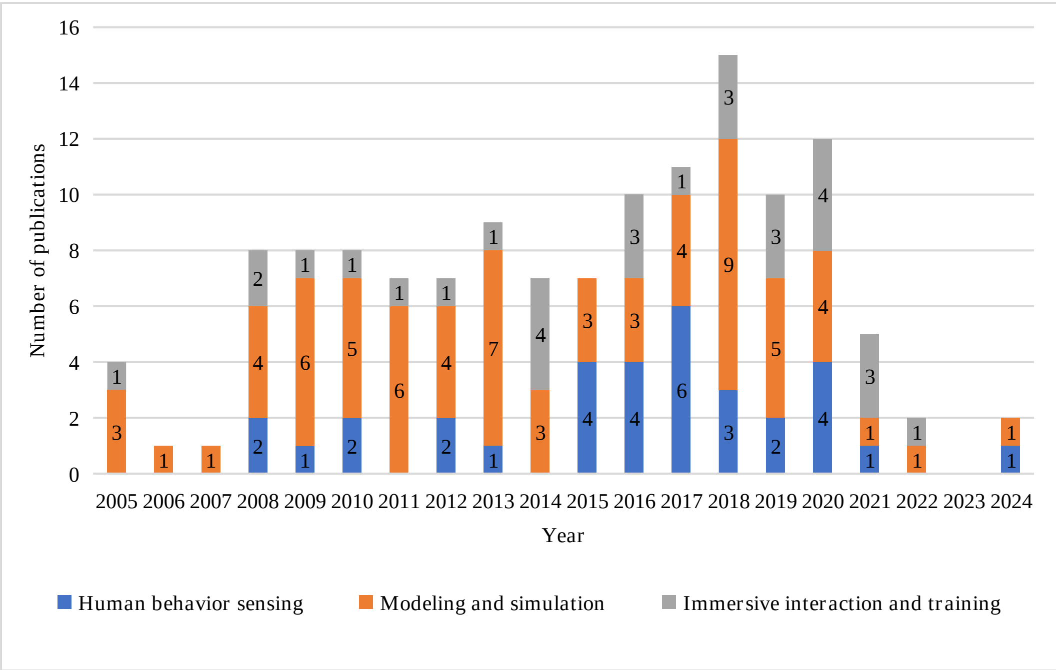

Figure 5 Literature field and year distribution of occupant digital twin

6.1 Human behavior sensing to create occupant digital twin

In digital twin emergency evacuation, human behaviors and motion sensing are the necessary links between computer simulation and reality. The commonly used sensing methods of human behaviors and movement can be divided into motion capture and indoor positioning, video-based sensing, and other biometric sensing. Among them, motion capture indoor positioning, and biometric sensing are mainly for single-person behavior and posture sensing, while video-based sensing is mainly for crowd characteristics.

6.1.1 Motion capture and indoor positioning technology

Human motion capture technology can capture the posture changes of pedestrians during the evacuation process, including two main methods: optical and inertial sensors. Optical motion capture uses cameras to record movement and match it with the human skeleton (Kirk et al., 2004). It is divided into calibrated and uncalibrated types. The calibrated type requires wearing clothing and using studio equipment but can provide higher accuracy (Eichelberger et al., 2016; Aurand et al., 2017). The uncalibrated type uses depth cameras, which are less accurate and costly, and suitable for XR systems (Colyer et al., 2018). However, this approach is vulnerable to environmental influences. The core device of the Inertial Measurement Unit (IMU) is the accelerometer and gyroscope, attached to the occupant, capturing movement and posture, unaffected by environmental conditions, but prone to sensor drift (Mayagoitia et al., 2002; Magalhaes et al., 2015) and very limited in accuracy (Peter et al., 2010).

Indoor positioning and tracking technologies can use various sensors to acquire and utilize the location information of occupants (Mendoza-Silva et al., 2019). Depending on whether the positioning object needs to carry equipment, indoor positioning is divided into equipment-free and equipment-based positioning. Equipment-free methods such as infrared imaging in optics, multi-camera target recognition in computer vision, and ultrasonic positioning in acoustics, all use external sensors to measure location (Want et al., 1992; Tariq et al., 2017; Deng et al., 2021). The advantages of these methods are that they do not rely on the active participation of the object to be located, but the disadvantages are that they require the deployment of a large number of external sensors, which are costly and affected by the indoor environment, resulting in lower accuracy and stability. Equipment-based methods require occupants to carry mobile devices, such as smartphones, wristbands, etc., and obtain their location information through the signal interaction between the devices and external sensors or networks. Methods such as Visible Light Communication (VLC) in optics (Hassan et al., 2015), geomagnetic field sensing in magnetic field methods (Davidson and Piché, 2017), WIFI fingerprint recognition (Brena et al., 2017), Bluetooth Low Energy (BLE) with higher precision, Bluetooth based on iBeacon, UWB, NFC, RFID (Ortakci et al., 2016), NFC (Sakpere et al., 2017), and Location Based Service (LBS) (Huixian and Shaoping, 2016; Huixian and Shaoping, 2018) have been widely applied. The advantage of these methods is that they do not require the deployment of a large number of external sensors, and utilize the active participation of the object being located, which improves accuracy and stability. The disadvantages are that they require the cooperation of the positioning object with the device, high device power consumption, and high cost. Short-range wireless technologies like Radio Frequency Identification (RFID) and Ultra-Wide Band (UWB) can track the status and location of pedestrians in real-time (Meadati et al., 2010; Li et al., 2017b). These technologies can be combined with WSN to achieve efficient data transmission using WSN technology (Liu et al.,2019; Inoue et al., 2008). Among them, RFID technology can be used for static information interconnection in WSN (Ma and Wu, 2020), while UWB technology can serve as a wireless connection technology for WSN, providing accurate distance estimation for sensor nodes (Tomasi et al., 2015). In emergency evacuation scenarios, computer vision methods without equipment, as well as WIFI, Bluetooth, and UWB technologies based on smartphones, have shown good applicability.

6.1.2 Sensing methods based on video surveillance

Video tracking is an essential tool for crowd monitoring and pedestrian dynamics research. It employs surveillance footage and tracking software to extract pedestrian movement trajectories, aiding in the determination of crowd density, speed, and flow for pedestrian model studies (Hoogendoorn et al., 2003). But faces challenges such as limited recording range, manual tracking, and algorithm performance issues (Johansson et al., 2008). The complexity of occupant movement, influenced by factors like clothing and lighting, makes body detection and dynamic tracking challenging (Ibrahim et al., 2016; Han et al., 2024).

Advancements in computer vision and deep neural network technologies have significantly enhanced the level of image recognition and video information extraction. Convolutional Neural Networks (CNN) and Recursive Neural Networks (RNN) are two commonly used methods in video tracking, where CNN extracts image data features and RNN focuses on time series data. Models usually combine CNN and RNN, exemplified by the YOLO model (Chen et al., 2020). Deep learning technology combined with pre-training methods have improved the accuracy and processing speed of video recognition, and become a main research direction of video tracking (Ciaparrone et al., 2020). Video tracking is applicable to the analysis of crowd characteristics in emergency evacuation, and supports decision-making, but due to the high computational complexity, the real-time performance is limited.

6.1.3 Sensing other features of occupants

In the event of a disaster, it is essential to quickly determine the spatial location of individuals and capture their physiological characteristics. At present, spatial positioning technology is quite mature, and as for the capture of physiological characteristics, sensors and other biometrics can be relied on (Liu et al., 2020). Key technologies include infrared sensing, Doppler microwave sensing, and millimeter wave radar.

Infrared sensing, using Pyroelectric technology, captures infrared radiation from the human body to sense body temperature and motion (Zhang et al., 2018). It is sensitive to human motion and can resist interference from ambient light, but it is susceptible to environmental temperature influences. Doppler microwave sensing is based on the Doppler principle, detecting distance and vital signs by recognizing changes in radar waveforms. It can accurately detect the movement of arms and legs, establish gesture recognition systems, and monitor vital signs such as breathing and heartbeat (Pu et al., 2013; Ballal et al., 2012). However, it can only sense moving people, which may lead to significant errors. Millimeter wave radar can detect subtle movements and resist environmental interference, used for monitoring the movement, breathing, and heartbeat of occupants, and accurately tracking multiple pedestrians in 3D space (Anitori et al., 2009; Adib et al., 2015). However, its high cost makes it challenging to be widely adopted.

Although we can rely on previously collected user information for some level of analysis (Ma and Wu, 2020), the application of motion capture, voice, respiration, and heart rate, among other biometric features, remains relatively underutilized.

6.2 Modeling and simulation of human behavior based on digital twin

In recent decades, numerous mathematical physics models have been established by researchers to simulate the evacuation processes of occupants. Based on these models, several computer simulation software has been developed, enabling the assessment of the efficacy of evacuation strategies and guidance measures. The following is an overview of various mathematical physics modeling methods and corresponding computer simulation software commonly used in emergency evacuation simulation.

6.2.1 Mathematical physical model

The existing simulation models for emergency evacuation in buildings can be divided into three categories: macro model, micro model, and meso model (Jiang et al., 2016). Some literatures also refer to the macro model and meso model together as the macro model for consideration (X. Li et al., 2019). The macro model regards a group of pedestrians as a whole and pays more attention to the collective phenomenon of the occupant (Hamacher and Tjandra, 2001), including the network flow model (Xiao and Li, 2021) and hydrodynamics model (Cao et al., 2020). The micro models focus on modeling individual behavior or interactions among individuals (Hamacher and Tjandra, 2001), including the social force model, ABM (Agent-Based Modeling), cellular automata model (Ding et al., 2017; Cao et al., 2020), etc. The meso model amalgamates the features of macro and micro models, primarily adopting the form of a macro model while considering individual behavior during algorithm design. The model retains the impact of certain individual motion characteristics on the system, such as game theory and dynamics models that integrate social force theory. (Jiang et al., 2016).

(1) Macro model

Macro evacuation models include the network flow and hydrodynamics models. Network flow models represent building layouts as network diagrams, and use algorithms like Floyd and Dijkstra, to determine the optimal path using objectives like minimum cost flow, fastest path, and maximum flow (Peng et al., 2019; Taneja et al., 2016; B. Liu et al., 2018b; Taneja and Bolia, 2018). They incorporate pedestrian panic through game theory and neural networks to optimize the evacuation path (Helbing et al., 2000; Li et al., 2015; B. Liu et al., 2018b; Peng et al., 2019). However, there is a lack of consideration of the real-time impact of disasters on the traffic capacity of network sections.

The hydrodynamic model proposed by Henderson uses nonlinear partial differential equations for pedestrian flow, focusing on group behavior. It is extensively utilized for simulating the macroscopic movement and behavior of large-scale crowds (Henderson, 1971; Hughes, 2000; Hughes, 2002). These models are categorized into reactivity dynamic models, where paths are chosen based on current conditions (Xiong et al., 2011), and predictive dynamic models, where paths are selected based on predicted situations (Du et al., 2013; Jiang et al., 2016). However, the solution of the model is more complicated and will consume a lot of computing costs.

(2) Micro model

Different from the macro model considering the overall flow of pedestrians, the micro model focuses more on individual behavior, in which individuals can perceive information and make independent decisions according to their own behavior rules (B. Liu et al., 2018a).

Typical micro continuous models in evacuation studies are mechanical, force-based models like the social force and centrifugal force models (Yu et al., 2005), among which the social force model is more widely used (Arteaga and Park, 2020; Fang et al., 2024). Initially proposed by Dirk Helbing based on social psychology (Helbing and Molnar, 1995), it has undergone several improvements (Helbing et al., 2000). The model simulates phenomena like arch blocking and herding under panic but faces issues like high computational complexity and limited factor consideration (Parisi et al., 2009). Enhancements to the social force model include improved collision modes (Zanlungo et al., 2011), self-stopping mechanisms (Parisi et al., 2009), leadership behavior (Hou et al., 2014), and kin behavior (Moussaïd et al., 2009). It is often applied in conjunction with computer vision technology (Mehran et al., 2009).

The discrete model for evacuation divides space into grids, with the major types being velocity-based models and cellular automata. The velocity-based model (van den Berg et al., 2008) uses discrete time and space steps, while cellular automata define evacuation spaces as cells evolving by local rules (X. Li et al., 2019). Cellular automata, initially used for pedestrian evacuation modeling in 1997 (Blue et al., 1997), are useful in studying self-organization in statistical mechanics. They can simulate the phenomena of incoherence, aggregation, backtracking, and waiting in evacuation, and realize the pedestrian movement simulation with a 3D visualization effect (Chu, 2009). Variants include Lattice-Gas Automata, calculating individual movement probabilities (Muramatsu et al., 1999; Guo and Huang, 2008), floor field models incorporating static and dynamic fields to simulate crowd behavior (Kirchner and Schadschneider, 2002), and other field models like potential field (Guo and Huang, 2011), electrostatic-induced potential field (Georgoudas et al., 2010), and cost potential field models (Zhang et al., 2012). In general, the above methods consider the evacuation environment to be relatively simple. Combining the above two models or combining models with experiments can better reflect the actual evacuation situation (Yang et al., 2005; Fang et al., 2010; H. Liu et al., 2018a).

ABM is the most widely used method, which has been used to study the influence of leadership behavior on the evacuation process (Pelechano and Badler, 2006), the evacuation of deep-buried subway stations (Zhong et al., 2008), the operation inside mines and fire evacuation (Huang et al., 2010), the evacuation process of office buildings (Lin et al., 2010), and even evacuation simulation of large cities (Wijerathne et al., 2013). This method can be extended to a variety of complex evacuation scenarios (Dimakis et al., 2010). Integrated 3D GIS, BIM, and routing technology (Uno and Kashiyama, 2008; Shi and Liu, 2014; Marzouk and Daour, 2018; Sun and Turkan, 2019) to improve the simulation effect. Agent-based evacuation models, constructed using bottom-up methods, treat individuals as autonomous agents making independent decisions based on physical and psychological parameters, simulating interpersonal and inter-group relationships and behaviors (Wooldridge and Jennings, 1995; Almeida et al., 2013; Kaur and Kaur, 2022). These models are categorized into individual decision models based on functional relations, rule-based models, and combinations of both (Young and Aguirre, 2021). Integration with GIS systems enhances modeling and visualization (Uno and Kashiyama, 2008), and the social force model can be incorporated to consider pedestrian interaction (Kaur and Kaur, 2022). Additionally, game theory (Li et al., 2015), genetic algorithms, and neural networks are employed to refine decision-making processes in agent-based models (Yuksel, 2018). In addition, The rule-based model (Reynolds, 1987) and the optimal step model (Seitz and Köster, 2012) can also define pedestrian rules and simulate the movement of pedestrians in space. However, methods based on ABM are usually based on specific assumptions, and the results obtained are difficult to verify.

(3) Meso model

In the meso model, the state of a crowd is determined by individual positions and speeds, represented probabilistically. This model simulates both the crowd as a whole and individuals (Jiang et al., 2016). Key meso models are the gas dynamics model and the game theory-based model. The gas dynamics model, differing from fluid dynamics, treats the crowd as compressible gas, using statistical models to describe individual positions and population velocity distributions (Bellomo and Dogbe, 2011; Bellomo et al., 2013). However, the microscopic evacuation characteristics cannot be considered. Game theory, integrated with fluid dynamics, creates models that consider individual behavior within macro dynamics. These models balance physical precision and computational efficiency (Degond et al., 2013) and use game theory to model pedestrian interactions, considering both macro and micro evacuation characteristics (Agnelli et al., 2015). However, this model is only suitable for large-scale simulation and the computational complexity is extremely high.

Combined with the disaster information and the above model, the dynamic development of disasters and pedestrian movement can be comprehensively considered, so as to realize dynamic simulation(Zarboutis and Marmaras, 2007; Tan et al., 2015; Cheng et al., 2018). The characteristics of various models are shown in Figure 6.

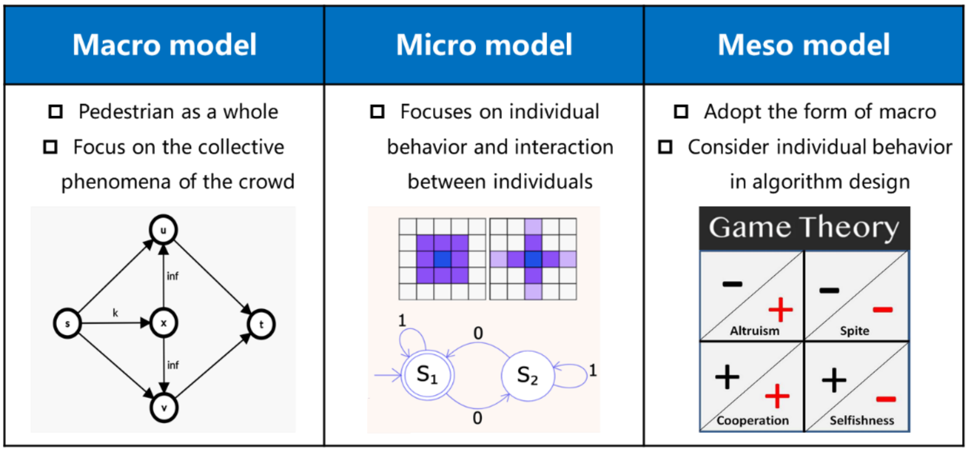

Figure 6 The characteristics of various models

Other models have been used. Yuan et al. (Yuan et al., 2009) proposed an evacuation simulation method that integrates a refined network method and a rough network model, which can effectively save calculation resources. Boje and Li (Boje and Li, 2018) proposed a knowledge mining method based on crowd simulation, which represented the information model, designer knowledge, and design process as the semantic web ontology, providing a more automated process of analyzing building performance through reasoning and data linking. Aleksandrov et al. (Aleksandrov et al., 2019) adopted the Mixed Integer Linear Programming (MILP) method to establish the equation simulating the movement time of office workers and realized the selection of the optimal evacuation strategy for high-rise buildings. Li et al. (X. Li et al., 2019) used a standard genetic algorithm and heuristic method to design a building evacuation network and evacuation plan. Gao et al. (Gao et al., 2020) used the constraint-based design method to optimize the evacuation time of a building. However, these methods are not yet mature, and the application cases are relatively simple.

6.2.2 Computer simulation software

The common commercial or free emergency evacuation computer simulation software on the market is investigated. According to the adopted mathematical physical model, it can be divided into three categories: network model software, grid model software, and agent model software.

In the network model software, the space is represented as a network of nodes and arcs, and the macro network flow method is adopted for modeling and solving. This model has high computational efficiency, but the solution results are rough. Common network model software includes EXIT89(Fahy, 1996; Adams and Galea, 2011), EvacSim (Drager et al., 1992), EVACNET+ (Kisko and Francis, 1985; Radianti et al., 2013), EvacAgent (Ying et al., 2017), etc.

The grid model software adopts the cellular automata and other micro discrete model methods for modeling and solving, allowing the individual state to be expressed, with more detailed solution results than the network model. But it is also built on more assumptions. Common grid model software includes STEPS (Ronchi and Nilsson, 2013), GridFlow (Bensilum and Purser, 2002), etc.

The agent model software can adopt a more refined method to simulate and solve the individual motion, and can easily establish the rules freely. However, due to the diversity of agent-based models, it is difficult to develop a common approach and the environment needs to be built from scratch. Common software includes FDS+Evac (Adams and Galea, 2011), Pathfinder (H.R. Wang et al., 2014; Long et al., 2017), buildingEXODUS (Oven and Cakici, 2009; Gwynne et al., 2005;

Adams and Galea, 2011; Sagun et al., 2011; Xing and Tang, 2012), PyroSim (Long et al., 2017), SIMULEX (Thompson and Marchant, 1995a; Thompson and Marchant, 1995b), AnyLogic (Avdeeva et al., 2020), etc.

In addition, according to the software functions, common emergency evacuation software can be classified into two types: those that emphasize movement (such as Simulex, Evacant, Pathfinder, etc.) and those that emphasize behavior (such as Exit89, Egress, Exodus, etc.) (Ketchell et al., 1993; Radianti et al., 2013).

6.3 Immersive interaction and training based on occupant digital twin

By combining building and occupant information, the actual decision-making of the emergency evacuation process of the occupant can be made, which mainly focuses on evacuation training and evacuation guidance.

6.3.1 Evacuation training

BIM and GIS technologies enable evacuation scenario models for serious games, while XR technology enhances visualization and simulation for more efficient evacuation training. XR-based immersive environments are now widely used in evacuation training (Ren et al., 2008; Rüppel and Abolghasemzadeh, 2010). *Research focuses on two main factors influencing evacuation: the external environment and human cognition. Pedestrians simulate escape in disaster scenarios, providing insights into behavior, emotions, and reactions* (Kinateder et al., 2014). *This approach supports both emergency personnel training and enhances occupant safety awareness* (Lorusso et al., 2022). Immersive VR serious games are becoming increasingly popular for behavior analysis and training in scenarios like building fires (Meng and Zhang, 2014; Feng et al., 2018), tunnel fires (Cosma et al., 2016), and earthquakes (Li et al., 2017a). *The Unity 3D engine plays a key role in collecting human behavior and emergency response data in VR environments* (Sharma et al., 2014). *Recent advances combine deep neural networks* (Chen et al., 2020) *and path planning algorithms* (B. Wang et al., 2014) *for more accurate evacuation behavior simulation, improving system flexibility and training effectiveness* (Catal et al., 2020). However, existing studies still face challenges such as insufficient model accuracy and a lack of immersive real-time interaction between users and virtual environments. Additionally, how to improve computational efficiency remains an important issue that current research needs to address (Dang et al., 2021).

6.3.2 Evacuation guidance

Based on building spatial data and occupant sensing technology, real-time crowd density and motion can be tracked, and this information can be combined with pedestrian evacuation models, which helps to estimate human behavior and congestion, and combined with path planning algorithms that comprehensively consider occupant and environment factors (Jindal et al., 2021), and also consider potential fire points, evacuation starting points and indoor positioning information (Deng et al., 2022), evacuation rescue schemes can be optimized (Fu and Liu, 2019; Pu and Zlatanova, 2005; J. Gao et al., 2020). Evacuation path selection prompts can be realized by technologies such as IoT devices, drones, evacuation guidance sign systems, artificial intelligence technology, Multi-UAVs, etc. (Lin et al., 2013; Chu and Yeh, 2012; H. Wang et al., 2019; Katayama et al., 2018; Gorbil et al., 2011).

Evacuation information can be released through SEIB and smartphones. SEIB, as an emergency notification system, can quickly and comprehensively disseminate evacuation guidance information (Chen, 2009). Smartphone-based evacuation guidance applications are more widespread. In 2008, autonomous navigation services for emergency evacuation applicable to mobile phones appeared (Inoue et al., 2008). With the development of a navigation system, guidance instructions can be dynamically sent to occupant smartphones to achieve evacuation guidance (Chen and Liu, 2018; Ortakci et al., 2016; Ma and Wu, 2020; Zheng and Chen, 2019; Wehbe and Shahrour, 2021). Users can also specify their position in the virtual environment for evacuation navigation (Burigat and Chittaro, 2016). However, the design of disaster type and environment in the above research is relatively simple, and the design other than interactive voice and other visual cues is lacking, which has certain limitations in the actual evacuation process.

By integrating the above sensing, simulation, and interaction methods, a complete occupant digital twin system can be formed. Specifically, indoor positioning, video surveillance identification, and other occupant sensing technologies are used to obtain occupants' location and behavior information in the building for refined crowd evacuation simulation. The obtained crowd evacuation condition information evaluates and optimizes the evacuation plan to provide occupants with evacuation training and path guidance. Table 4 shows the key technologies of each part.

Table *4* Summary of literature related to occupant digital twin

Key components	Application scenarios	Methods	Advantages	Disadvantages
Sensing and creation	Motion capture	Optical motion capture	The uncalibrated type is well-suited for XR systems	Susceptible to environment
		IMU	Not affected by the environment	Very limited accuracy
	Indoor positioning	equipment-free positioning	A large number of external sensors need to be deployed	Low accuracy and stability
		equipment-based positioning	High accuracy and stability	High power consumption and cost
	Video tracking	Pedestrian motion path extraction	Parameters such as population density and flow rate are determined	Limited record range Algorithm underperformance
		Applications of computer vision and deep neural networks	High accuracy Fast processing speed	High computational complexity Lack of real-time
	Sensing other features	Infrared sensing	Sensitive to human movement Not disturbed by ambient light	Easily affected by ambient temperature
		Doppler microwave sensing	High accuracy Wide monitoring range	Can only sense people in motion
		millimeter wave radar	High accuracy	High cost
Modeling and Simulation	Mathematical Physical model	macro model	Simulate large-scale pedestrian movement	High computational complexity Ignoring the influence of individual behavior
		micro model	The influence of individual behavior is considered	The evacuation environment considered is relatively simple The results obtained are difficult to verify
		meso model	Some micro evacuation	It can only be used for large-scale simulation

			characteristics are considered	High computational complexity
	Computer Simulation Software	The network model software	High computational efficiency	Rough solution
		The grid model software	The solution results are more detailed	Based on more assumptions
		The agent model software	Create simulation rules easily and freely	It is difficult to develop a common approach
Immersive interaction and training	Evacuation training	Application of XR technology	Efficient and reliable	Lack of model accuracy Lack of immersive real-time interaction
	Evacuation guidance	path selection information dissemination	Take into account occupants and environmental factors	The design of disaster type and environment is relatively simple Interactive voice prompts are missing

7. Application scenarios of building and occupant digital twin

The following section summarizes the typical applications of various technologies in the fields of building digital twin and occupant digital twin, as discussed in Sections 5 and 6. These applications span the entire digital twin lifecycle of sensing, updating, simulation, and decision-making. The primary application scenarios are categorized into three main areas: behavior collection and training, disaster risk assessment, and pre-disaster monitoring and early warning. The distribution of literature by year and field is shown in Figure 7. Applications in disaster risk assessment are the most mature, while those in pre-disaster monitoring and early warning are less common, with publications volume concentrated between 2016 and 2021.

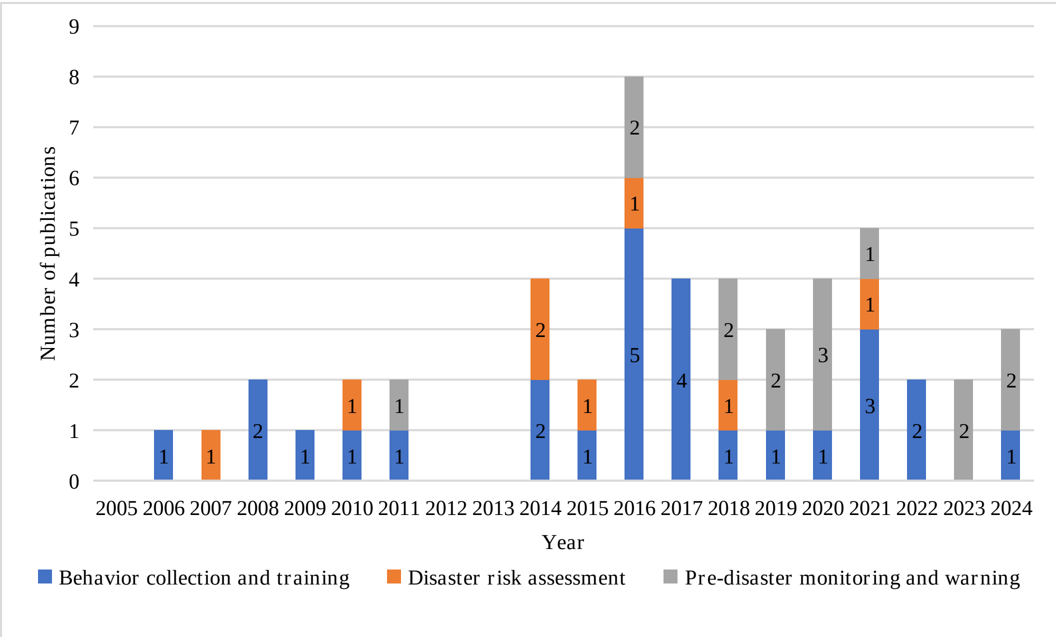

Figure 7 Literature field and year distribution of application scenarios

7.1 Behavior collection and training

Emergency evacuation using digital twin technology creates a simulated environment that offers accurate spatial layouts and environmental data, providing a realistic evacuation experience through XR technology. The digital twin of occupants tracks behaviors and decision-making, based on continuous information exchange between the building and occupant models. This interaction enhances training scenarios, helping to understand the complex dynamics between people and the environment during emergencies, thus improving safety awareness.

In the event of urgent disasters such as fires, sensing technologies can monitor the conditions of pedestrians and environmental factors like smoke, temperature, humidity, external weather, and terrain. This provides a basis for the collection and training of evacuation behaviors. In terms of environmental sensing, the combination of network cameras, IoT (Cheng et al., 2017) , laser measurement (Pu and Vosselman, 2006; Rottensteiner, 2003), and photogrammetry (Guarnieri et al., 2004; Sun et al., 2017; Xu et al., 2022) allows for dynamic consideration of disaster situations. For occupant sensing, positioning technologies such as LBS (Huixian and Shaoping, 2016), RFID (Ortakci et al., 2016), Bluetooth positioning, and computer vision (Deng et al., 2021) can determine the location and behavior of occupants. Optical motion capture (Eichelberger et al., 2016; Aurand et al., 2017; Colyer et al., 2018), IMU, and other technologies can capture the movement and posture of pedestrians. Based on WSN and UWB technologies, information transmission can be achieved (Inoue et al., 2008; Chen, 2009; Cheng et al., 2016; Wang et al., 2016； Wehbe and Shahrour, 2021), combined with real-time updates of platform models such as BIM and GIS (Dimyadi et al., 2017; Cheng et al., 2017; Ma and Wu, 2020; Wehbe and Shahrour, 2021; Lotfi et al., 2021). *Despite progress, challenges include cost, environmental conditions, sensor accuracy, and disruptions in sensor networks that affect stability and accuracy during evacuations. Moreover, processing large data volumes requires substantial computational power.*

Utilizing XR technology, immersive evacuation environments can be constructed to collect human behavior and conduct evacuation training. Many researchers have established BIM-based immersive gaming environments to collect and study human behavior data during the evacuation process (Rüppel and Schatz, 2011; Liu et al., 2014; Zhang and Issa, 2015). The technology for creating immersive virtual environments based on XR technology is relatively mature and has been widely applied in evacuation training (Ren et al., 2008; Rüppel and Abolghasemzadeh, 2010; Huang et al., 2024) . Combining the virtual environment with omnidirectional treadmills (Lorusso et al., 2022) and path planning algorithms (B. Wang et al., 2014) based on BIM and the Unity 3D game engine further enhances simulation accuracy. However, challenges in real-time performance and computational complexity remain.

7.2 Disaster risk assessment

Emergency evacuation using digital twin technology simulates emergency scenarios, combining building and occupant digital twins. The building twin models spatial layouts and environmental data, while the occupant twin simulates people's movements and reactions during disasters. This integration enables dynamic risk assessments, optimizing evacuation plans and response strategies(Kim et al., 2024). Simulations test the performance of designs under evacuation conditions, helping improve building layouts and plans.

Using digital twin technology, emergency evacuation can build simulation environments and develop applications of various models based on the comprehensive sensing of complex building spaces and human behavior, more accurately simulating the evacuation process during emergencies. These models are divided into macro, micro, and meso models (Jiang et al., 2016). Macro models deal with group behavior, micro models examine interactions between individuals, and meso models consider both macro and micro features. Combined with emergency evacuation software, environmental modeling can be performed, along with the simulation of disaster development and evacuation behavior (Zarboutis and Marmaras, 2007; Ma et al, 2012; Tan et al., 2015; Cheng et al., 2018; Ma et al, 2020). Moreover, information obtained from information platforms like BIM and GIS, as well as sensor information, can be input into evacuation software such as FDS(Papinigis et al., 2010; Jiang et al., 2014), AnyLogic (Liao et al., 2014), and Pathfinder (Rahman et al., 2021) to simulate the evacuation process.

Despite progress, challenges remain in evacuation simulation: high computational complexity of crowd movement, oversimplified models that may not reflect real scenarios, and difficulties in model integration and data merging.

7.3 Pre-disaster monitoring and warning

Utilizing digital twin technology for emergency evacuation integrates into a comprehensive early warning network. It combines real-time building monitoring, meteorological, geological, hydrological, and air quality data to support command centers with data for early warning and disaster response. Big data and machine learning algorithms develop predictive models and an emergency command management system, enabling proactive event dispatching. During emergencies, combining the occupant digital twin allows for dynamic simulation and visualization of planning and command, aiding resource deployment, path planning, information dissemination, and target identification. This enhances emergency response accuracy and efficiency.

Digital twin technology can support risk assessment and early warning by integrating and monitoring multiple data sources such as meteorological and geological information in real-time (Costa et. al., 2023) to realize pre-disaster monitoring and early warning. Early warning systems typically integrate IoT sensors, BIM models, and artificial intelligence algorithms to achieve real-time environmental monitoring, predictive analysis, and visual decision support. These systems are capable of promptly identifying potential risks, predicting trends, and providing intelligent control recommendations, thereby ensuring safety while optimizing resource utilization efficiency. The application scenarios of the digital twin framework are extensive, and it holds significant value in the field of emergency management. In evacuation applications, by integrating building structural data, real-time information, and crowd behavior models, the system can simulate the effectiveness of different evacuation strategies and provide decision-makers with the best options (Li et. al., 2023; Zhang et. al., 2024a; Wen et. al., 2024). Additionally, it can visually display the evacuation process through the digital twin interface, coordinate resources from all parties, and enhance the efficiency and accuracy of emergency response. Specifically, sensing technology can monitor crowd density and movement in real-time, and BIM and GIS technology can obtain 3D data and topological information for indoor and outdoor spaces. Based on this, various path planning algorithms, classic graph-based shortest path algorithms such as Dijkstra (Cheng et al., 2016; Ma and Wu, 2020), and heuristic algorithms such as A* (Roan et al., 2011; Kim and Lee, 2019; Zhou et al., 2020), Genetic Algorithm (GA) (Nahum et al., 2020), artificial colony algorithm (H. Liu et al., 2018b) and other improved algorithms. Smartphone applications, IoT devices, and other tools can provide evacuation guidance and information dissemination (Chen and Liu, 2018; Ortakci et al., 2016; Ma and Wu, 2020; Zheng and Chen, 2019; Wehbe and Shahrour, 2021).

Table 5 highlights sensing and modeling technologies used in typical applications. Despite advances in monitoring, early warning, and evacuation planning, challenges remain: (1) Static Data and Dynamic Complexity: Evacuation models often rely on static data and overlook evolving disasters and human behavior, requiring adaptive path optimization through AI and advanced sensing. (2) Data Accuracy and Automation Gaps: Real-time monitoring depends on data precision and processing speed, with manual or semi-automatic data transmission hindering automation. Efficient warning dissemination and cross-domain integration are needed to avoid errors and guide evacuations.

Table 5 Main technologies used in sensing and modeling

	Building		Occupant		Data link
	Sensing	Spatial modeling	Sensing	Behavior Modeling	
Behavior collection and training		BIM (7) GIS (7)		BIM (10) GIS (10)	Manual (7) Semi-automatic (21)
Disaster risk assessment	network cameras (3) IoT (5) Laser measurement (2) Photogrammetry (5) WSN (5)	BIM (12) GIS (12) FDS (2) AnyLogic (1) Pathfinder (1) Navisworks (1)	LBS (1) RFID (1) Bluetooth (1) Computer vision (3) Optical motion capture (4) IMU (3) Infrared sensing (1) Doppler microwave sensing (2) millimeter wave radar (2) XR (11) omnidirectional treadmill (1) WSN (3)	Macro models (10) Micro models (45) Meso models (5) STEPS (3) GridFlow (1) buildingEXODUS (5) EVACNET+ (3) AnyLogic (1)	Manual (60) Semi-automatic (12)
Pre-disaster monitoring and warning		BIM (3) GIS (3)		BIM (3) GIS (3)	Semi-automatic (6)

Note: The number of techniques used in typical scenarios is shown in parentheses.

8. Trends and discussions

8.1 Summary of the development trends of the digital twin in building and occupant

Through the reading and analysis of the full text by two researchers, the application cases of digital twin emergency evacuation for buildings and occupants involved in Sections 5-7 are divided into 6 categories from L0 to L5 (Tao et al., 2022). *The classification criteria and case descriptions are as follows:* L0 virtual imitate reality: *offline simulation mainly based on manual interaction, relying on preset parameters and static models, without real-time data access. For example, early pure algorithm simulation studies based on the social force model only simulated by manually setting evacuation paths and crowd behavior rules.* L1 virtual mapping actual: *realizes one-way data mapping from the physical space to the virtual space, supporting dynamic visualization but lacking a feedback mechanism. For example, using RFID or Bluetooth positioning technology to obtain personnel locations and dynamically display the evacuation process in the evacuation model.* L2 virtual adjust reality: *establishes a two-way data closed loop between the physical and virtual* *spaces, where the virtual model can dynamically adjust evacuation strategies according to real-time perception data. For example, using smoke concentration and temperature monitored by sensors to update disaster data in real time and optimize paths.* L3 virtual preview reality: *introduces time-dimensional analysis, generating previews of future scenarios based on historical data or prediction algorithms to support pre-disaster assessment and trend prediction. For example, based on a fire evacuation simulation framework, predicting the evacuation efficiency of different schemes in advance.* L4 virtual optimize reality: *realizes intelligent decision-making and automated evaluation with the help of artificial intelligence algorithms, and dynamically generates the optimal evacuation strategy. For example, it predicts crowd behavior and optimizes paths through deep learning.* L5 virtual and reality coexistence: *requires the virtual system to have autonomous cognitive ability, which can dynamically reconstruct models according to unknown scenarios and achieve real-time collaboration with the physical world. Due to the current level of technological development, there is no application of L5 digital twin emergency evacuation yet, while the usage trends and proportions of L0-L4 are shown in Figure 8.*

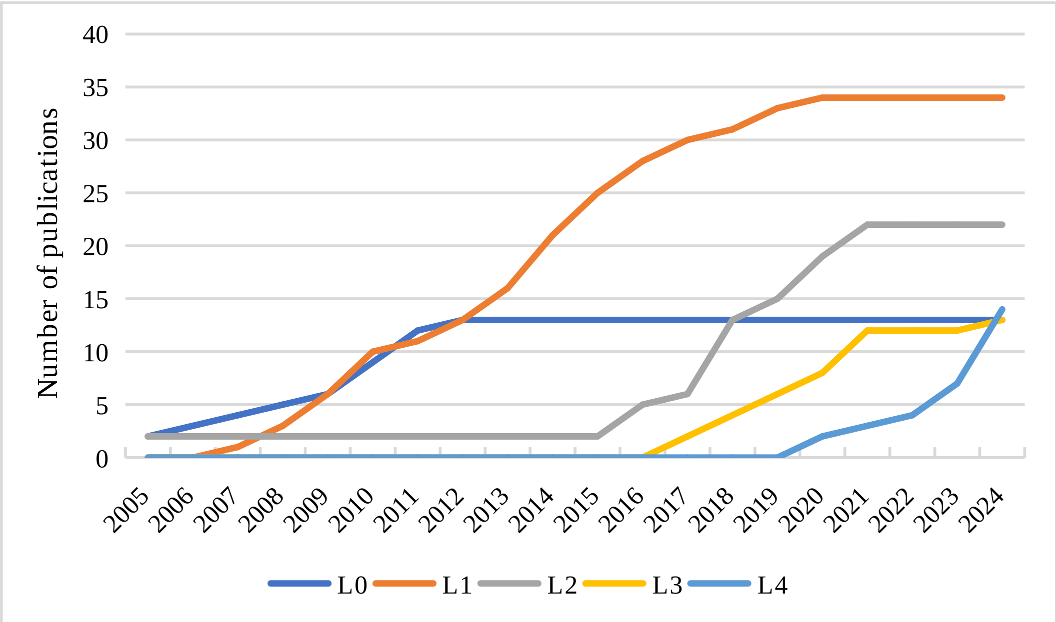

Figure 8 The application trend of L0~L4

As can be seen from Figure 4, 5, 7, 8, the concept of digital twin for emergency evacuation has exhibited continuous growth since 2005. In the initial phase, research predominantly focused on modeling and simulating macroscopic and microscopic pedestrian behaviors from a sociological perspective, with occupant digital twin research occupying a dominant position and applications primarily concentrated at L0 and L1 maturity levels. A significant paradigm shift occurred post-2011, characterized by the plateauing of L0 growth and a redirected research emphasis toward L1 implementations for enhanced real-world mapping capabilities. Building digital twin research demonstrated substantial expansion from 2014 onward. The past quinquennium has witnessed significant advancements in computer vision, including video image analysis, depth sensing, and multi-view imaging technologies, coupled with IoT device integration, facilitating accurate acquisition, analysis, and simulation of crowd behavior at both macro and micro scales. Consequently, exploration of L2 and L3 levels has progressed expeditiously, albeit their proportional representation remains lower than L0 and L1 levels.

The limited exploration of L4 and L5 maturity levels can be attributed to several critical factors: (1) Substantial challenges in real-time data acquisition and synchronization, with current methodologies predominantly relying on semi-automated and manual approaches, lacking automated data processing capabilities; (2) Systemic challenges in multi-source heterogeneous data integration, with existing frameworks lacking comprehensive architectures for tool integration; (3) Inherent contradictions between computational complexity and real-time response requirements, as high-fidelity models demand substantial computational resources, conflicting with the immediacy required in emergency scenarios; (4) Insufficient comprehensive modeling of psychological and social factors, failing to adequately capture panic behavior and group dynamics in emergency situations. These challenges collectively constitute the primary impediments to implementing advanced intelligent evacuation systems, elucidating why current research remains concentrated at L0 to L2 levels. Future research necessitates breakthroughs in high-precision sensing, multi-scale modeling, real-time updating, and dynamic risk assessment to realize cognitive digital twin and adaptive decision-making systems.

8.2 Discussions

Unlike other digital twin-related reviews that focus on specific applications in the manufacturing sector (Cimino et al., 2019; Holler et al., 2016; Kritzinger et al., 2018; Negri et al., 2017; Tao et al., 2018; Deng et al., 2021; Sepasgozar, 2021), this study, for the first time, integrates the two dimensions of the building environment and human behavior to construct a complete digital twin closed loop and applies it to emergency evacuation scenarios. It summarizes key theories, methods, models, and tools, and integrates previous research results that focused on isolated elements. It can serve as an overview and guide on how to accurately model and analyze the building environment and human behavior for emergency evacuation, covering the full cycle of perception, updating, simulation, and decision-making of digital twin at different scales in emergency evacuation.

In addition, by classifying existing application scenarios into different maturity levels, this study provides a clear pathway for the future development of fully autonomous cognitive evacuation systems. Although this paper attempts to provide a comprehensive review of the application of digital twin in emergency evacuation for buildings and occupants, limitations in scope and workload mean that the initial research only used the Scopus database. Although the snowball method was employed to increase the number of references, some important studies may still have been overlooked. Future literature reviews could expand the time span and database sources of the literature search, for example, by including the Web of Science, to obtain a more comprehensive literature sample. Furthermore, in conducting quantitative analysis, this paper mainly adopts descriptive statistical methods. In the future, more econometric perspectives and methods could be introduced to provide stronger data support for the review's conclusions.

8.2.1 Research status and challenges

(1) Building digital twin: sensing, reconstruction, simulation, and decision-making

For building digital twin, it mainly includes key technologies such as sensing, reconstruction, simulation, and decision-making. While building digital twin have made progress in areas like BIM-based modeling and GIS integration, significant challenges remain in achieving high-fidelity modeling (Su et al., 2023). High-precision physical models often require substantial computational resources, which conflicts with the need for real-time responses in emergency situations, especially when simulating complex physical processes such as fire spread and smoke dispersion. Simplified models may fail to accurately reflect real-world conditions. Additionally, the coverage, power supply methods, and anti-interference capabilities of sensors can also impact the reliability of data collection. Moreover, the current application of BIM technology in emergency evacuation is mostly experimental (Deng et al., 2021). In the research, the design of disaster types and environments is relatively simple and there is still a certain distance for its wide application. In particular, it is worth noting that the integration of multi-source heterogeneous data faces systemic challenges. The implementation of various technologies under the current digital twin emergency evacuation framework is fragmented, and there is no complete framework to integrate multiple tools into an integrated system, resulting in difficulties in data sensing and data exchange among different platforms(Park et al., 2024)， especially when combining real-time sensor data with static building information models. In addition, semantic interoperability between different data formats and standards also poses an important challenge (Guo et al., 2023).

(2) Occupant digital twin: sensing, modeling, simulation, and interaction

For occupant digital twin, it mainly includes key technologies such as sensing, modeling, simulation, and interaction. The key technology is the crew model and simulation methods, as well as their combination. At present, spatial positioning technology has been relatively mature in the research, and behavior collection and training can be realized based on interactive technology(Paes et al., 2024). However there has been relatively little research on motion capture and other biometric features such as voice, breathing, and heart rate. The traditional evacuation model is not well combined with the new sensing technology, and the computational complexity is high, there is a lack of effective methods for updating indoor road networks and dynamically planning evacuation paths (Deng et al., 2021). In terms of human behavior prediction and analysis, current methods have significant limitations. Although statistical methods based on historical data analysis perform reliably under stable conditions, they cannot effectively capture panic behavior in emergency situations. Individual differences in stress responses can lead to significant deviations from predicted evacuation patterns. Moreover, the complex interactions between psychological states and group behavioral effects introduce additional uncertainty, and existing models struggle to adequately address these challenges (Aleksandrov et al., 2019). The high computational complexity of large-scale crowd simulations also poses a significant challenge. The computational demand increases exponentially with the number of evacuations, especially when simulating complex interactions between individuals (Chen and Chu, 2016). The need for real-time response in emergency situations often requires a tradeoff between solution optimality and computational speed (Chen and Huang, 2015).

(3) Application scenarios: From basic analysis to intelligent risk control

For application scenarios, digital twin technology can analyze the optimal evacuation paths and plans under different conditions, providing the scientific basis and decision-making support for emergency management. Through analyzing the maturity levels (L0-L4) of current applications, clear development patterns and limitations emerge. Current implementations predominantly cluster at L0 to L2 levels, focusing on basic virtual modeling and one-way data mapping. These applications successfully demonstrate fundamental evacuation path optimization and simple scenario planning but lack real-time adaptability. There is a lack of research on intelligent risk assessment, planning, decision-making, and cognitive twin in the evacuation process. Several critical limitations impede progress toward higher maturity levels. First of all, in the entire digital twin framework, data transmission relies mainly on semi-automatic and manual methods and lacks automated integration. The limited real-time synchronization between physical and virtual environments and insufficient mechanisms for handling multi-source heterogeneous data pose significant challenges(Kim et al., 2024). Secondly, in the process of modeling, simulation and decision-making, there is a lack of comprehensive consideration of the building environment and human behavior. Insufficient modeling of psychological and social factors in evacuation behavior, as well as a lack of refined and complex environmental modeling, further exacerbate the aforementioned challenges(Rahman et al., 2021). Finally, the interaction process primarily relies on visual feedback mechanisms, lacking the development of other sensory cues, which presents certain limitations in practical applications. The challenge in achieving dynamic adaptive risk control during the evacuation process lies in integrating precise sensing technologies with emerging artificial intelligence technologies to develop reliable decision support and evacuation guidance systems. More importantly, despite the significant potential of digital twin technology in emergency evacuation, its actual deployment still faces multiple technical and computational constraints. First, the deployment of high-precision sensing systems is costly, especially for large buildings and complex environments, requiring numerous sensors and communication devices to achieve comprehensive perception, which not only increases initial investment but also brings subsequent maintenance challenges. Second, the real-time requirements for data processing and transmission are extremely high. In emergency situations, the system must respond and process large amounts of heterogeneous data quickly, while current network infrastructure and edge computing capabilities may struggle to meet this requirement in practical applications (M. Wang et al., 2019). Third, the significant customization requirements for different buildings and scenarios, coupled with the lack of standardized implementation methods and interfaces, increase the difficulty of system integration. Furthermore, system robustness and reliability in emergency situations are crucial. Sensor failures, network interruptions, or power supply issues may lead to system failure, while designing redundancy mechanisms further increases implementation complexity. Finally, large-scale evacuation simulations have enormous computational demands, especially when integrating various disaster models and crowd behavior models, which may require high-performance computing resources, constituting an important limitation in resource-constrained practical application scenarios. Addressing these constraints requires coordinated advancement of technological innovation, standard formulation, and cost-effectiveness analysis to achieve widespread application of digital twin in the field of emergency evacuation.

8.2.2 Future research

According to the above conclusions, the future research trends can be summarized as the following:

(1) Data integration, system integration, and advanced evacuation simulation

One of the key directions for future research is to promote the deep integration of BIM, ABM, and traditional evacuation algorithms. BIM provides spatial layout and facility location information of buildings, which is a critical foundation for disaster simulation and evacuation path planning. When combined with IoT technology, real-time disaster sensing and 3D evacuation path navigation can be realized. Additionally, ABM can simulate human behavior in emergencies, and when integrated with classic algorithms like Dijkstra's, it enables dynamic and complex evacuation simulations.

Future research should focus on the deep integration of disaster simulation, human behavior models, and BIM, establishing a more comprehensive disaster perception, personnel tracking, and emergency response system, while optimizing data transmission and real-time updates of simulation parameters. Furthermore, standardized system interfaces and data formats are crucial for seamless integration across different technologies and platforms. Therefore, research on standardization and system integration should proceed in parallel with the development of other technologies to ensure that digital twin technology can be widely applied in various building and emergency scenarios.

(2) High-precision sensing, real-time guidance, and collaborative evacuation

Accurate sensing technologies will play a crucial role in future emergency evacuations. Currently, devices like smartphones are well-developed in location sensing, but there are still limitations in real-time sensing of personnel position changes, dynamic environmental changes, and decision-making behaviors. Future research should strengthen the integration of multi-source sensing technologies, including radar, surveillance cameras, environmental sensors, and mobile terminals, to achieve more comprehensive and precise environmental perception and personnel positioning.

Simultaneously, real-time guidance during emergency evacuations needs to be dynamically adaptable, capable of adjusting instructions and paths in response to sudden changes. Future research could focus on the integration of multi-source data and the development of adaptive evacuation algorithms to address dynamic factors such as building structural changes, personnel behavior variations, and disaster spread, thereby improving evacuation efficiency and safety.

(3) Intelligent monitoring, simulation, and decision support

Artificial intelligence technologies, especially deep learning and pattern recognition, will be key to enhancing the perception, simulation, and decision-making capabilities of digital twin systems. Although current disaster and personnel sensing technologies have gathered vast amounts of data, real-time analysis and dynamic decision-making remain significant challenges. Future research should actively incorporate artificial intelligence technologies to process complex and dynamic data, thereby optimizing the evacuation process.

By combining big data analysis and quantitative modeling, large-scale evacuation simulations, disaster scenario drills, and situation predictions can be achieved, helping to form dynamic simulation and visualization decision support systems. For example, neural networks can be used to process video and sensor data, optimizing evacuation path planning algorithms; simultaneously, knowledge graph technologies can integrate emergency evacuation data with expert knowledge, creating a knowledge-based building disaster response and crowd evacuation system.

It should be noted that the collection of personnel behavior and physiological data will inevitably raise ethical, legal, and privacy concerns. Currently, research in the field of emergency evacuation mainly focuses on technological implementation, lacking in-depth discussions of ethical and privacy issues. Future research needs to focus on how to protect user privacy, data security, and legal compliance while ensuring functional implementation. In particular, when collecting behavioral data through video surveillance and sensors, anonymization and privacy protection measures should be enhanced. Furthermore, relevant laws and regulations need to be improved, with clear data usage standards and ethical guidelines formulated to prevent technology misuse and ensure fair and transparent application.

(4) Computational efficiency optimization and system robustness enhancement

Large-scale evacuation simulations require substantial computational resources, especially when real-time processing of multi-source data and high-precision models is necessary, which significantly increases computational pressure. Future research should focus on algorithm optimization and computational resource scheduling, developing lightweight models that improve computational efficiency while ensuring adequate precision, to meet the high real-time response demands of emergency evacuations. At the same time, the robustness of digital twin evacuation systems is also critical. Future research should explore the design of redundancy mechanisms to ensure that the system can continue to operate normally even in the event of sensor failure, network interruption, or power instability. Improving system reliability and fault tolerance is a prerequisite for the practical deployment and application of this technology.

9. Conclusions

Emergency evacuation is a crucial method to ensure occupant safety and minimize losses. Digital twin technology offers new possibilities for emergency evacuation. Therefore, this paper systematically reviews the application and development trends of digital twin technology in building and personnel emergency evacuation scenarios. By integrating two key dimensions, the built environment and human behavior, a comprehensive digital twin closed-loop framework is established, encompassing the theoretical foundations, key technologies, models, and tools. Through the classification of maturity levels (L0-L5), a clear path for the development of future autonomous cognitive evacuation systems is provided.

The review results indicate that current research mainly focuses on maturity levels from L0 to L2, achieving results in basic virtual modeling, one-way data mapping, and preliminary bidirectional interaction. While significant progress has been made in simulating occupant behavior, building environment, and optimizing evacuation paths, real-time adaptability, intelligent decision-making, and cognitive-level integration (L4-L5) remain major challenges. The main barriers include: (1) difficulties in real-time data collection and synchronization; (2) systematic challenges in integrating multi-source heterogeneous data; (3) the contradiction between high-fidelity simulation demands and computational resource constraints; and (4) the lack of comprehensive psychosocial behavior modeling in emergency situations.

Since the emergency evacuation process involves complex interactions of multiple factors and is constrained by technical or computational limitations in practical deployment, efficient data processing, high-precision model construction, and high-performance computing capabilities are required to achieve dynamic simulations. The future development of digital twin-based emergency evacuation systems requires breakthroughs in multi-disciplinary collaboration. First, continuous optimization and improvement of underlying mechanisms should be promoted to facilitate data integration, system integration, and advanced evacuation simulation. Second, sensor accuracy should be enhanced, and adaptive evacuation algorithms developed. Third, emerging artificial intelligence technologies should be adopted, with attention to data ethics. Finally, computational efficiency should be optimized to enhance system robustness.

In conclusion, this study not only consolidates the fragmented knowledge in the field but also provides a systematic framework and development roadmap for future research and practical applications. Future research could expand the time span and database sources of literature retrieval and introduce more econometric perspectives and methods for quantitative analysis to further refine the conclusions.

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Appendix

An open repository has been established on GitHub, containing the classification of research *questions, main contents, and research limitations for all literatures. The URL is:* https://github.com/wokeayo/List-of-References