buildings

Article

Digital-Twin-Based Fire Safety Management Framework for Smart Buildings

Manea Almatared [1,2], Hexu Liu [1,*], Osama Abudayyeh [1], Obaidullah Hakim [1] and Mohammed Sulaiman [3]

1 Civil and Construction Engineering Department, Western Michigan University, Kalamazoo, MI 49008, USA; maneamohammeds.almatared@wmich.edu (M.A.); osama.abudayyeh@wmich.edu (O.A.); obaidullah.hakimi@wmich.edu (O.H.)
2 Civil Engineering Department, College of Engineering, Najran University, Najran 55461, Saudi Arabia
3 Civil Engineering Department, Faculty of Engineering, Al-Baha University, Al-Baha 65779, Saudi Arabia; msulaiman@bu.edu.sa
* Correspondence: hexu.liu@wmich.edu

Abstract: In recent years, the implementation of digital twin (DT) technology has gained significant attention in various industries. However, the fire safety management (FSM) sector has been relatively slow in adopting this technology compared to other major industries. Therefore, this study aims to explore the limitations, opportunities, and challenges associated with adopting DT technology in the FSM sector and further develop a DT-based FSM framework towards smart facility management (FM). To achieve this objective, this research started by reviewing several promising DTs for FSM, including building information modeling (BIM), the Internet of Things (IoT), artificial intelligence (AI), and augmented reality (AR). On this basis, a conceptual framework was synthesized in consideration of the benefits of each technology. A questionnaire was conducted for FM professionals to evaluate the proposed framework and identify the challenges of adopting DT in the FSM sector. The survey results reveal that the proposed framework can assist decision makers in obtaining comprehensive information about facilities' communication among stakeholders. The survey results validate the potential of the adoption of DTs toward smart FM practices in FSM. The survey results provide insights into the perception of DT technology among FM practitioners and identify the current state of DT technology in the FSM sector, its expected benefits, and its potential challenges. The main barriers to adopting DTs in FSM are a lack of knowledge about DTs, their initial costs, user acceptance, difficulties in systems integration, education training costs, a lack of competence, development complexity, difficulties in data management, and a lack of trust in data security.

Keywords: digital twin; facility management; fire safety evacuation; fire safety equipment; BIM; Internet of Things; artificial intelligence; augmented reality; smart decision making

Citation: Almatared, M.; Liu, H.; Abudayyeh, O.; Hakim, O.; Sulaiman, M. Digital-Twin-Based Fire Safety Management Framework for Smart Buildings. *Buildings* **2024**, *14*, 4. https://doi.org/10.3390/buildings14010004

Academic Editor: Chyi Lin Lee

Received: 14 October 2023
Revised: 13 December 2023
Accepted: 17 December 2023
Published: 19 December 2023

1. Introduction

The field of fire safety in buildings is of utmost importance due to the potential risks fires pose to occupants. Fires in buildings can potentially cause serious injuries, fatalities, and significant financial losses. In 2021, the National Fire Protection Association (NFPA) reported 1,353,500 fires in the United States, resulting in 3800 deaths, 14,700 injuries, and a financial loss of $15.9 billion USD [1]. The primary concern for a building's safety in a fire is our ability to ensure the safe evacuation of all occupants [2]. Therefore, it is crucial to develop effective strategies and technologies to enhance fire safety, including fire evacuation and fire safety equipment (FSE) maintenance.

In recent years, the digitization and computerization of the 21st century have paved the way for applying information technologies in facility management (FM) to improve fire emergency practices. However, several challenges need to be addressed to ensure optimal fire safety management (FSM) in buildings. In the initial stages of a fire incident, occupants typically have to rely on themselves, assuming that the fire safety facilities within the building, such as fire extinguishers, are capable of adequately responding to the fire [3,4]. However, in practice, the measures mandated by design codes do not always yield the expected results [5], often due to insufficient facility maintenance or a lack of operational skills among occupants [4,6]. Currently, the diagnostics of FSE rely on routine inspections conducted by facility staff, which are not conducted in real time and are subjective, making them prone to human errors. This can lead to faulty equipment or inadequate maintenance, compromising the effectiveness of fire safety measures. Another challenge is the inefficiency of traditional methods used for information retrieval in FSE. Traditional methods of searching for information, such as using two-dimensional (2D) drawings [7] and relying on paper documents for facility maintenance, operations, and management, have become inefficient and costly as buildings have become larger and more complex [8].

In the context of fire evacuations, firefighters often rely on 2D evacuation handbooks and paper-based documents to gather information during emergency situations [9,10]. However, these traditional methods have limitations in comprehensively understanding the building layout and evacuation routes. Moreover, users often face challenges in quickly interpreting drawings, understanding their precise location within a building, and selecting appropriate evacuation routes [11,12]. Furthermore, research has shown that a significant proportion of emergency casualties can be attributed to delayed evacuation services [13], which can be caused by a lack of real-time information updates [14]. For instance, during emergencies, building users may not have access to real-time location-based evacuation routes [14]. Therefore, to mitigate injuries and fatalities resulting from fire accidents in FM, it is crucial to develop safety evacuation tools that rely on real-time information [15]. Such tools can improve the decision-making process and provide real-time access to information, enabling occupants to evacuate promptly from hazardous locations. Moreover, a lack of information about the scene of the fire and its spatial configuration can lead to incorrect decision making when choosing an escape route [16–18]. This gap in knowledge can hinder occupants from making informed decisions about the safest path to take during an emergency. Additionally, the ambiguity of changes in the scene of a fire can cause occupants to spend an excessive amount of time trying to escape [16,19,20]. Uncertainty and a lack of clarity in an evolving fire situation can delay evacuation efforts and potentially put occupants at greater risk. Furthermore, the lack of integration between FSM and building information hinders comprehensive safety analyses, leading to information gaps, poor connections, and inefficient decision making [21]. Therefore, it is imperative to establish integration and interactions between buildings and safety systems focusing on FSE and fire evacuation.

To overcome these challenges, it is essential to prepare intelligent FSM based on real-time information to improve the decision-making process and provide real-time access to information for FSE maintenance and safe fire evacuation. The development of digital twin (DT) technologies with real-time data acquisition and integration support is crucial in achieving this goal. The rapid development of information technologies, particularly the emergence of new generation information technologies, such as building information modeling (BIM), the Internet of Things (IoT), artificial intelligence (AI), and augmented reality (AR), has significantly accelerated the process of digitalization.

Recently, researchers have made significant progress in the development of DT technologies and tools for fire safety [22–24]. For instance, Jiang et al. [23] proposed a system that combines DT technology, semantic web technologies, and IoT data to enable the dynamic monitoring and predictive operation of fire protection systems. This system integrates domain knowledge, BIM information, and IoT data to enhance the effectiveness of building fire protection measures. Khajavi et al. [22] proposed a framework for implementing DT throughout a building's lifecycle. They utilized sensor packages, 3D visualization, and AI techniques to detect and predict potential fire threats in buildings.

Zhang et al. [24] proposed Artificial Intelligence Digital Fire (AID-Fire), a framework for the real-time identification of the evolution of fires in buildings using artificial intelligence (AI) and DT technology. The system consists of an IoT sensor network, cloud server, AI engine, and user interface. It provides detailed information on the development and spread of fires, supporting smart firefighting practices and contributing to fire-resilient smart cities.

Cheng et al. [25] proposed an intelligent system that combines BIM, Bluetooth sensors, and a mobile application to predict indoor fires and support disaster relief efforts. By leveraging real-time data on indoor environments, the system can identify potential fire hazards and determine the best evacuation routes. The mobile application enhances the system's usability by providing crucial information to both evacuees and firefighters.

Choi et al. [26] developed a BIM-based evacuation regulation checking system for high-rise and complex buildings. The system utilized BIM technology to analyze evacuation routes and safety features, providing a comprehensive tool for assessing the compliance and effectiveness of evacuation plans. Their study highlighted the potential of BIM in enhancing safety and regulatory compliance in building design and construction.

Wehbe and Shahrour [27] employed a BIM-based smart system for fire evacuation. Their study aimed to develop a system that provides early fire detection, evaluates environmental data, identifies the best evacuation path, and provides occupants with information about the optimal evacuation routes. The system was implemented and tested in a research building at Lille University in France. Their results demonstrate the capabilities and benefits of the system, particularly in terms of identifying the most effective evacuation paths.

Chen et al. [8] applied a BIM-based AR system for the inspection and maintenance of FSE. The researchers aimed to enhance the efficiency and effectiveness of these tasks by integrating BIM and AR technologies. The system allowed for the visualization of FSE in a virtual environment, enabling inspectors to access relevant information and perform maintenance tasks using AR interfaces. Their study demonstrated the potential of BIM-based AR systems in improving the inspection and maintenance processes of FSE. Despite significant advancements in fire emergency management through the application of DT technologies, BIM, IoT, and AI, there remains a critical gap in our understanding of the state of practice in the FM industry.

Although there is agreement about the potential applicability and benefits of DTs in the FM industry and some pioneering FM organizations are pushing for the use of DTs in this context, the level of industry interest in DT adoption is still unclear. The uniqueness of this study lies in its targeted approach towards fire safety, a critical aspect of FM that has not yet fully explored the vast potential of DT technology. By concentrating on fire evacuation and FSE maintenance, two key areas on which the application of DT can have a profound impact, this research addresses a vital gap in the current research. Additionally, this study stands out in its effort to gauge industry readiness and interest, a perspective often overlooked in technological adoption studies. This approach provides valuable insights into current industry trends and readiness and guides the development of practical DT solutions tailored to the specific needs of the FM industry. The aim of this paper is to understand the industry's interest in implementing DTs in buildings' fire evacuation and FSE maintenance operations and identify potential application areas for DTs. To achieve this, this study provides an overview of the current implementation status of DTs in FSM within the FM industry and outlines the opportunities and challenges associated with its use in fire safety practices.

To gather insights, this study presents various industries' responses to a questionnaire seeking to identify the potential challenges and barriers FM organizations may encounter in fully adopting DT technology. The findings of our research will serve as a foundation for future investigations in this field. The findings of this study analyze the data gathered and insights gained from the literature review and the questionnaire survey results. This study extracted the main challenges and barriers hindering DT adoption, including technical, economic, and stakeholder-related barriers. Future research should explore economically viable solutions for addressing technical barriers and ensure stakeholder engagement to ensure inclusiveness, validity, and effective decision making.

The subsequent sections of this paper will describe the literature review, the materials and methods used to establish the framework for DT-enabled FM, the results of the survey conducted, and the ensuing discussion. These sections will outline the current status of DT implementation in FSM within the FM industry and introduce the application areas in which DTs can be leveraged in FM.

Despite the attention this topic has received in academia and the private consulting industry, there need to be more studies that can drive industry stakeholders toward the faster adoption of DTs in FM. While rapid advancements in DT technologies offer new opportunities to enhance fire emergency management in the FM industry, the industry-wide adoption of DTs has yet to occur. One of the primary motivators for stakeholders in FM is the potential for direct operational gains and benefits. Therefore, our understanding of the benefits of DTs in fire safety practices, the challenges involved, and their expected value is limited.

This study aims to provide an overview of the current implementation status of DTs in fire safety, outline the opportunities and challenges for their use in fire safety practices, and identify potential application areas for DTs. This study attempts to address this gap by presenting the following research questions:

- What is the current state of DT adoption for fire emergencies in the FM industry?
- What are the core DT drivers and challenges for a fire emergency?

These DTs are required for the enhancement of decision-making quality in FM activities. The following specific research objectives are pursued to meet the overall goal of this study:

1. Explore the current status of DT implementation in FSE and fire evacuation;
2. Develop a DT-based FSM framework towards smart FM;
3. Explore the current state of DT adoption for fire emergencies through a survey;
4. Explore the technical challenges encountered during DT implementation through a survey.

2. Literature Review

This study consists of a narrative or traditional literature review that provides a broad, qualitative, and interpretive overview of the literature of FM systems and their challenges. This descriptive and comprehensive approach summarizes findings and identifies thematic patterns, particularly regarding FM's integration of emerging technologies like DT. The review provides a contextual and theoretical framework for empirical research by collating and analyzing many academic and professional sources. This approach meets the goals of a traditional literature review by providing a comprehensive, synthesized overview, identifying gaps in the literature, and preparing for further research.

2.1. Current Systems-Based FM

There are currently a variety of commercial systems designed for FM that are used to manage the data of a high-performance building and provide the information required to support decision making on the operation and maintenance of the building [28–32]. These current advanced technologies, software, and systems at FM serve a wide range of needs in facilities, including computerized maintenance management systems (CMMS), computer-aided FM systems (CAFM), building management or automation systems (BMS or BAS), and firefighting alarm systems (FAS). FM systems have several uses, with each system serving specific purposes for FM.

CMMSs primarily focus on maintenance-related tasks such as managing work orders, historical maintenance information, and equipment management [28]. CMMSs are also utilized by facility maintenance organizations for record keeping, management, and communication, allowing for data collection from multiple sources and linking the compiled data to other systems [33,34]. Additionally, CMMSs can be deployed for asset management, inventory control, service request generation, and tracking the time and costs of services and materials used to complete work orders [35]. CAFM systems integrate computer-aided design (CAD), graphics modules, and relational database software to provide various FM capabilities, including space management [36]. CAFM solutions provide facility managers with the means to organize, execute, and monitor workspace management, asset management, reactive and preventative maintenance services, room reservations, and other FM administrative support activities. BMSs are control systems that monitor and manage mechanical and electrical services within a facility, including lighting, power, heating, ventilation, air conditioning (HVAC), elevators, and fire control [37–39]. FASs are used to prevent fire disasters by equipping high-rise, large-scale buildings with sensors and monitors [40].

Despite the advantages of these current systems, FM teams face several challenges when utilizing them. Many FM information systems are prone to failure as a result of (1) the lack of interoperability between different FM information systems; or (2) the inability of FM personnel to access accurate information [7]. Moreover, current FM systems are unable to capture and retrieve detailed information and knowledge generated from building maintenance or operations [41]. For example, CMMSs cannot provide automatic maintenance work order scheduling, and FM staff are unable to access accurate information [7]. Moreover, FASs utilize only two-dimensional (2D) images to represent the inner spaces of complex buildings, which lack information about fire scenes and their spatial configuration [16,42]. Moreover, most FM systems cannot share information with each other to support comprehensive decision making; instead, information must be extracted and processed by individual systems. As a result, FM teams face difficulties in making informed decisions about facility maintenance tasks and cannot optimize their workflows [33,34]. Moreover, there is a lack of data integration and communication in current FM practices [43–45].

To address the challenges of the lack of information sharing, data integration, and communication in current fire safety practices in the FM industry, the implementation of a DT framework can provide a potential solution. DTs act as a virtual representation of a physical building, capturing real-time data and enabling the seamless integration of FM systems. By leveraging DTs, FM personnel can access accurate and up-to-date information from multiple sources, facilitating comprehensive decision making and the optimization of workflows. Additionally, the DT framework allows for the simulation and analysis of fire evacuations, enhancing FSE maintenance and emergency response capabilities in buildings.

2.2. Digital Twin (DT)

The National Aeronautics and Space Administration (NASA) utilized the DT concept in the 1960s as a "twin" within the Apollo spaceship program, which built two identical space vehicles so that the space vehicle on Earth could mirror, simulate, and predict the conditions of the vehicle in space [46]. DTs were first introduced in Michael Grieves's product lifecycle management (PLM) model in 2002 [47]. The origin of DTs can be traced back to a presentation of Michael Grieves at the University of Michigan in 2002, which proposed the creation of a Product Lifecycle Management (PLM) center and already included all the essential elements of DTs, such as real spaces, virtual spaces, a data link from real spaces to virtual spaces, an information link from virtual spaces to real spaces, and virtual subspaces [47]. Currently, there are various definitions of DTs, but the two most widely accepted definitions were provided by NASA and Grieves. DTs are defined by NASA as follows: "A digital twin is an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin". Grieves and Vickers [47] defined a DT as "a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin".

DTs are a technology that collects data in real time from physical assets and uses these data to create a virtual model of the physical asset to facilitate smart decision making.

DTs use AI and data analytics to generate digital simulation models that can learn from and update based on multiple sources, as well as represent and predict the current and future conditions of their physical counterparts [48]. Deng et al. [20] proposed a DT evolved from BIM in a series of four developmental stages in which it was integrated with other technologies, such as simulations, sensors, and AI, operating at different levels. Furthermore, DTs utilize AI tools, such as machine learning (ML) and deep learning (DL), to organize and analyze data effectively in real time. This enables various functionalities, including condition monitoring, environmental learning, system failure prediction, real-time feedback, and bi-directional information integration throughout the entire lifecycle of the asset [21,22].

Figure 1 explains how DTs integrate the virtual–physical system for real-time monitoring, analyses, prediction, automatic control feedback, optimization, and visualization. It incorporates three main components to create a practical loop: a physical entity, a virtual entity, and a data link which can assist stakeholders in decision making for FM practices. The framework integrates state-of-the-art technologies such as BIM, the IoT, AI, and AR. This survey aims to evaluate the benefits of the proposed framework and discover the potential challenges of applying DTs in FM.

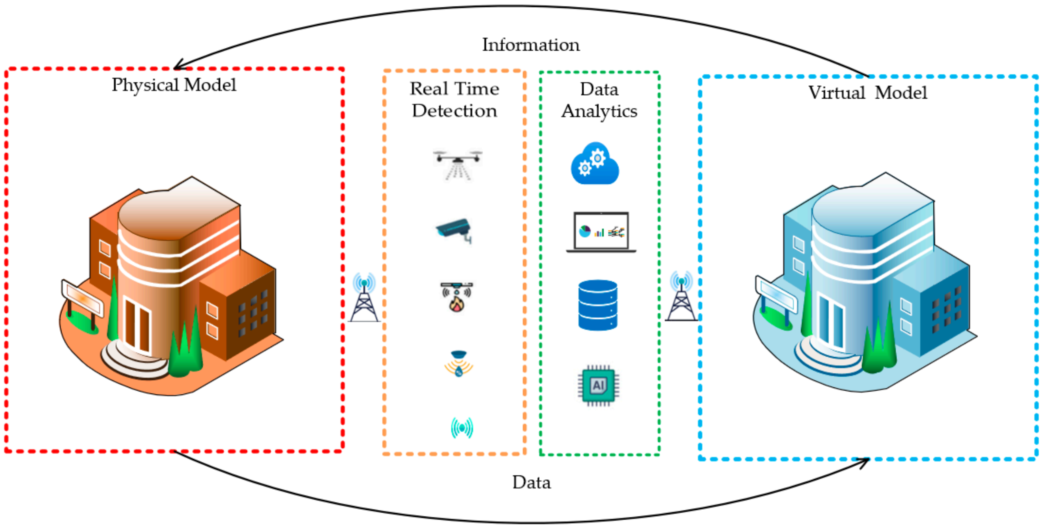

Figure 1. System Architecture.

2.3. DT-Enabling Technologies for Fire Safety Management

2.3.1. Building Information Modeling (BIM)

The definition of BIM by The United States National Institute of Building Sciences (NIBS) is "the digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onwards" [49]. Fire risk management is a critical aspect of building operations, encompassing various elements such as fire protection design, the limitation of fire/smoke spread, fire extinguishment, and the escape probability [50]. Several factors, including the characteristics of the occupants, the building facilities, and the features of a fire, influence efficiency in fire risk management. To manage these factors effectively, an integrated environment capable of collecting and analyzing relevant data should be established [51,52]. BIM has emerged as a promising solution for fire risk management, as it improves safety by visualizations, fire simulations, fire warnings, and planning escape routes [23,53]. Furthermore, the informatization capabilities of BIM, such as information storage, extraction, and retrieval, can be effectively utilized as a comprehensive database for managing fire safety information in a BIM-based system [23,31]. For instance, Wang et al. [54] created a BIM-based model for FSM, consisting of evacuation assessments, escape route planning, safety education, and equipment maintenance modules. The model integrated BIM with a fire dynamics simulator (FDS) for evaluating evacuation capabilities and utilized BIM for acceptable escape route distances. Safety education was enhanced through 3D presentations, while equipment maintenance was supported through a web-based prototype. Ma and Wu [55] developed a fire emergency management system using the BIM platform. Their proposed system includes a database management module and four functional modules: intelligence monitoring, a warning, a response, and a treatment. The system can monitor building fires and provide users with visual guidance towards escape routes. The proposed system has the capability to acquire fire information, determine the status of a fire, and make decisions for individuals who may be trapped. However, BIM itself is typically limited to providing the static data of the built environment and lacks the capability to automatically update real-time information in the models without additional data sources [56]. The emergence of IoT has made it possible to integrate real-time sensing data with the static information provided by BIM models. This integration can be an effective tool in disaster and emergency response, both at the building and urban scale [56]. The integration of BIM and IoT has laid the foundation for the emergence of DTs [48]. It is crucial to emphasize that DTs are a prominent technological advancement that facilitate the instantaneous bidirectional integration of cyber–physical systems and empower intelligent decision making.

2.3.2. Internet of Things (IoT)

The IoT is defined as "an ecosystem that contains smart objects equipped with sensors, networking, and processing technologies integrating and working together to provide an environment in which smart services are taken to the end-users" [57]. Researchers have employed the integration of BIM and IoT devices for various purposes. They have used these technologies to detect the indoor location of trapped victims and display their positions within BIM models [16,58]. Furthermore, they have utilized BIM models, real-time building information, and location data from sensors or victims' mobile devices to calculate the shortest evacuation path [59,60]. Moreover, researchers have focused on creating mobile guidance for evacuation by integrating BIM tool APIs with mobile devices [25]. Furthermore, researchers employed advanced sensor networks to analyze real-time data on the smoke concentration, temperature, and surrounding environment in a cost-effective manner [61]. The integration of BIM and IoT sensors presents a novel approach to fire monitoring and decision making in evacuations [9,62]. However, it is important to note that improving situational awareness for firefighters requires not only an accurate and intuitive display of fire information but also the ability to make correct decisions in compromised visibility. While BIM integrated with sensor data has been extensively used in fire monitoring, the BIM platform itself lacks the immersive environment necessary for effective rescue decision making. Therefore, AR technology serves as a solution tool that can enhance our visualization and perception of an environment, allowing stakeholders to make more informed decisions. Moreover, to obtain more real-time information on human fire evacuation behaviors for faster and safer evacuations and to enhance the predictive maintenance of FSE, we need a more intelligent monitoring system based on AI.

2.3.3. Artificial Intelligence (AI)

AI is the science and engineering of creating intelligent machines with the ability to reason, learn, acquire knowledge, communicate, perceive, plan, and move and operate objects [63,64]. In recent years, AI has played a significant role in fire FSM, driving the development of smart firefighting [65,66]. One notable application of AI in fire safety is the development of a hybrid artificial neural network (ANN) model for fire scenario identification. This model utilizes temperature data to evaluate the distribution of temperatures within a compartment fire [66,67]. Computer vision methods, specifically those based on convolutional neural networks (CNNs), have also been employed to identify the fire heat release rate (HRR) by extracting features from flame and smoke images. These techniques enable the accurate and efficient detection of fire characteristics, aiding in assessing and managing incidents [68,69]. For fire prediction, ML techniques combined with zone models have been proposed to recover missing data in cases in which sensors are destroyed during fires [70,71]. Moreover, AI has been applied for fire source locations [24,72]. For instance, Wu et al. [72] applied AI and big data to predict the location and size of a fire source in a tunnel. They construct a database of numerical simulations and use temperature data from multiple sensors to train a recurrent neural network.

2.3.4. Augmented Reality (AR)

Delgado et al. [73] defined AR as a technology that enables the overlay of digital objects and information onto real objects to augment or improve the real environment in real time and with the correct spatial positioning. AR technology enables the overlay of digital information, such as 3D models, images, and animations, onto the real world, facilitating natural interactions between users and their environment [74]. This technology plays a crucial role in helping workers and staff better understand information by providing visual and interactive representations [11]. Recent studies have focused on integrating AR and BIM to improve the visualization of 3D models and context-specific information [75,76]. For instance, Chen et al. [8] developed a BIM/AR-based system for the inspection and maintenance of FSE, enabling fire safety engineers to access visualized inspection information on a cloud database using a mobile device, overcoming the limitations of interpreting 2D paper-based information. However, their study also noted that the system required experts with a large amount of experience to analyze and determine specific data requirements for different operations. Kanangkaew et al. [11] proposed a real-time fire evacuation system that combines BIM and AR, and this system utilizes real-time data from sensors to detect and monitor fire incidents, which are then integrated into the BIM model. During emergencies, the AR component overlays evacuation routes and personalized instructions onto the user's view of the physical space, improving the efficiency and accuracy of fire evacuation procedures [11]. The proposed integrated DT framework can be utilized to combine technologies such as AR for an immersive experience and AI capabilities for better connections, insights, and analytics [77]. The integration of AR within the proposed DT framework can provide a more intuitive and interactive environment for stakeholders, enhancing their understanding and decision-making processes. Additionally, AI capabilities can enable advanced data analyses and predictive modeling to monitor, recognize, evaluate, and predict potential risks in terms of safety, quality, efficiency, and costs across teams and work areas, even under a high level of uncertainty [78]. By leveraging the combined potential of AR, the IoT, and AI within the DT framework, the challenges identified in this study can be overcome, leading to more efficient and effective operations throughout the building life cycle.

2.4. DT Technologies for Smart Building Applications

DT technologies have been applied to various aspects of buildings, including healthcare, residential, commercial, and infrastructure management. In the healthcare sector, Song and Li [79] explored the implementation of a DT system architecture within Shanghai Tongji Hospital to enhance healthcare facility management (HFM). The proposed DT framework integrates five key layers—data acquisition, transmission, an integrated middle platform, services, and targeting to streamline decision-making processes and improve healthcare delivery. Similarly, Peng et al. [80] developed a DT-based system with real-time visual management and artificial intelligent diagnosis modules to visually manage a hospital's status and receive timely facility diagnoses and operation suggestions that are automatically sent from the digital building to reality. The system can save energy use, prevent facility issues, reduce repair requests, and improve the quality of daily maintenance work.

In the context of occupant comfort in the residential sector, Hosamo et al. [81] developed a DT framework for automated fault source detection and prediction, targeting comfort performance evaluations in existing non-residential Norwegian buildings. Their study focused on utilizing DT technology to improve building performance by identifying and addressing issues related to occupant comfort. This approach offers a more efficient way of managing facility comfort levels and ensuring a satisfactory indoor environment for occupants. In the context of energy performance, Jafari et al. [82] employed a simulation approach to evaluate the application of DT technology in various building types, including offices, residences, schools, and restaurants. The researchers integrated the established asset management theory with building simulation technology to enhance both the buildings' energy efficiency and asset performance by utilizing DT technology. The authors used building assets' IoT data to compare the assets' performance and energy use to their condition. In the context of improving building indoor safety management in the commercial sector, Liu et al. [21] proposed a framework for an indoor safety management system based on DT technology for building the bobsleigh and sled stadium for the Beijing Winter Olympics. The proposed framework exploits BIM, the IoT, and AI techniques to improve the level of intelligence for building indoor safety management and evaluate the types and levels of danger by processing the data in their system. Other studies have utilized DT technology in school buildings to develop integrated building- and city-level solutions. Lu et al. [48] developed a dynamic DT at the building and city levels, focusing on a case study of the West Cambridge Campus to integrate heterogeneous data sources, support effective data querying and analyses, support O&M management decision making, and bridge human relationships with buildings/cities. The authors utilized BIM and IoT technologies to create a comprehensive digital model that can simulate the building's performance and provide real-time monitoring and control of the building systems. Their study demonstrated the potential of DTs in improving the efficiency and sustainability of building operation and maintenance.

Table 1 states that DT technologies for smart building applications present opportunities for improving real-time monitoring, automated decision making, optimization for predictive maintenance, the emergency tracking of evacuees, and indoor safety in buildings. The table highlights their diverse barriers and technological opportunities. For instance, the integration of digital technologies can address specific needs and provide solutions for fire safety in various contexts, contributing to the overall safety and well-being of occupants. Much research has focused on smart DT application technologies for predictive maintenance, energy management, and asset management. However, there is a lack of studies focusing on DT technology applications for fire safety emergency management.

Table 1. Applications of, technologies utilized in, and barriers of studied DTs for smart buildings.

Paper	Title	Applications	Technologies	Sector	Barriers
[21]	A framework for an indoor safety management system based on digital twin	Indoor safety management system (ISMS) using DT technology for real-time safety monitoring, danger assessments, and management within buildings.	BIM, IoT, ML	Stadium	BIM and IoT integration and independent safety management systems
[24]	Building artificial-intelligence digital fire (AID-Fire) system: A real-scale demonstration	The AID-Fire system's application encompasses fire detection, firefighting strategy enhancement, evacuation guidance, risk assessments, data-driven emergency responses, and ongoing safety monitoring and maintenance.	AI, IoT, DL, CV, data fusion	University campus	Sensor reliability, AI performance, real-time processing, system integration, data preprocessing, fire dynamics complexity, user interface design, and privacy concerns

Table 1. *Cont.*

Paper	Title	Applications	Technologies	Sector	Barriers
[48]	Developing a digital twin at building and city levels: case study of west Cambridge campus.	Collaboration, visualization, and O&M management of buildings and a city.	AI, BIM, ICTs, ML, IoT, IFC	University campus	Data integration and synchronization, big data management, and data quality.
[80]	Digital twin hospital buildings: an exemplary case study through continuous lifecycle integration	Develop a DT for complex infrastructures, enhance clash detection using VR/AR, optimize building energy management, and advance predictive maintenance for performance forecasting	BIM + IoT + ML + VR/AR	Hospital	Complex DT model creation, interoperability issues, data security concerns, and high amount of long-term data latency.
[83]	Developing a web-based BIM asset and facility management system of building digital twins.	Integrating building assets throughout its lifecycle.	BIM, Unreal Engine, web in real time.	AECO/FM	Data sharing issues and unreliable operation data.
[84]	Federated data modeling for built environment digital twins.	Real-time monitoring and data-driven decision tools for buildings.	IoT, robotics, AR, MR, VR, AI, BIM, IFC.	University campus	Information/process clarity, fragmented data, and interoperability
[85]	Toward smart-building digital twins: BIM and IoT data integration.	DTs for real-time building monitoring and visualization.	BIM, IoT	University campus	Semantic interoperability and real-time building data validation.
[86]	CLOI: An automated benchmark framework for generating geometric digital twins of industrial facilities.	Generate automatic as-built models from point cloud data.	Point Cloud + ML/computer vision	Industrial buildings	Limited what-if scenario analysis and slow asset updating due to extensive point cloud data preparation
[87]	Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms	Predictive maintenance using BIM and IoT.	BIM, IoT, ML	University campus	Algorithm selection, prediction methods, and model training.
[88]	A digital twin predictive maintenance framework of air handling units based on automatic fault detection and diagnostics	DT predictive maintenance framework for air handling unit (AHU)	BIM, IoT, IFC, ML, AR	University campus	Algorithm selection and prediction methods
[89]	Towards an occupancy-oriented digital twin for facility management: test campaign and sensors assessment	Optimization of a building's operational stage through advanced monitoring techniques and data analytics	BIM, IoT, ML	University campus	Monitoring issue in detecting more users, network security, and reliable data storage
[90]	Digital twin–based health care facilities management	Developing a DT for real-time, efficient management of healthcare facility systems and equipment	BIM, IoT, ML	Healthcare facility management	Data accuracy, sensor's reliability, user privacy integration, And high initial costs
[91]	Intelligent emergency digital twin system for monitoring building fire evacuation	Developed a DT system based on AI and computer vision to track evacuees in building fire.	BIM, IoT, AI, CV, YOLO	University campus	Detection accuracy in crowds and privacy issues

2.5. Summary of the Literature Review

The literature review highlights several challenges in current FM systems that hinder effective data exchange, integration, and decision making. These include issues with interoperability between different FM information systems, leading to frequent system failures and inefficiencies in FM operations [7]. Additionally, there is a significant problem in accessing accurate and timely information, which is crucial for effective maintenance and operation [7]. The systems, such as CMMSs, often fall short of capturing and retrieving comprehensive details from building maintenance activities [41]. FASs are limited to using 2D images to represent building interiors, which inadequately convey critical information like fire scenes and spatial configurations [16,42]. A common issue across most FM systems is their inability to share information effectively, which complicates informed decision making and workflow optimization [33,34]. This is further compounded by a general lack of data integration and communication within current FM practices [43]. Moreover, BIM, while useful, is often constrained to static data, lacking the capability for automatic real-time updates, a gap that is starting to be addressed through the integration of IoT and BIM, laying the foundation for the development of DTs [56]. These challenges highlight the need for more integrated and dynamic systems in FM, pointing towards the potential of technologies like DTs to revolutionize FM processes. The literature review also highlights the applications, technologies utilized, and barriers of studied DTs for smart buildings, as shown in Table 1. It suggests that there is a lack of focus on DT technology applications for FSM.

3. Methodology

This paper aims to develop a conceptual framework for the evaluation of the facility manager's level of acceptance of using DTs in FSM and to identify potential application areas for DTs. The research methodology is illustrated in Figure 2. The methodology started with a comprehensive review of the existing challenges in FM systems. This review explores the DT concept and its origins, highlighting its significance in FSM. Furthermore, it aids in investigating the potential advantages of DT in FM. The effectiveness of the DT-based FSM framework towards smart FM, such as BIM, the IoT, AI, and AR, is explored based on existing studies [92–94]. These technologies are recognized for their potential to enhance FSM systems and improve decision making [95,96]. From the insights of the review, a DT-based FSM framework for smart FM is proposed. This framework is designed to achieve smart FSM practices with improved information and communication. Afterward, a survey-based approach was implemented to collect data from FM professionals. This approach was crucial in creating a comprehensive understanding and capturing perceptions and opinions of DT adoption in the FM industry [97]. A questionnaire was subsequently developed based on the findings of the literature review. The questionnaire survey method was adopted for its ability to ensure participant anonymity and freedom, as well as to maintain the uniformity of responses [98]. Additionally, the adoption of a questionnaire survey in this study was motivated by its advantage in gathering empirical information from a broad range of respondents [99]. Furthermore, the survey aimed to assess participants' comprehension of adopting DTs in FSE maintenance and fire evacuation practices and to identify potential issues that could be addressed early in the design phase [97].

The survey questionnaire is distributed to FM professionals, especially those from the Western Michigan University (WMU) FM department and International Facility Management Association (IFMA), to validate the proposed framework and to investigate deeper into the challenges faced during the adoption of DT in FSM. Our data collection, analysis, and a detailed discussion of the challenges of adopting DTs are then presented. The next sections outline the logical connection between the framework, the main challenges of DTs, and the evaluation for their adoption in the industry. The framework is shown to enhance decision making in FSM significantly. Moreover, the discussion of the challenges of DT applications in FM offers avenues for further academic research to address these challenges.

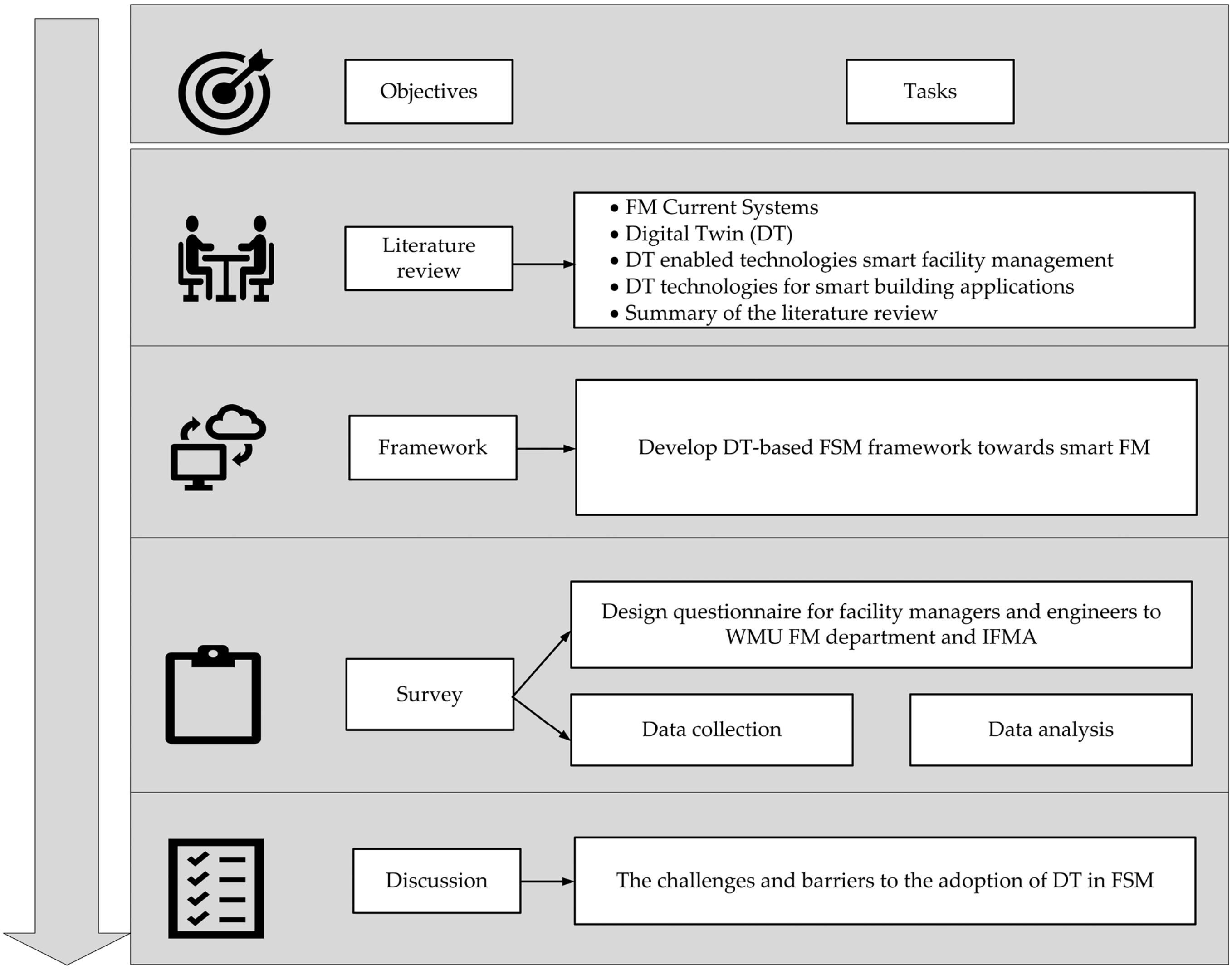

Figure 2. Research methodology.

3.1. Literature Selection

The selection of Scopus as the preferred scientific abstract and indexing database was based on its well-established reputation in the academic community [94,100]. In comparison to other similar databases, Scopus is renowned for its extensive collection of literature, making it a valuable resource for researchers and scholars alike [94,100]. A search was conducted in the Scopus database using keywords related to DTs and FSM. The search was performed using two primary search strings of DTs and FSM, which were searched using article titles, abstracts, and keywords. The DT search string included the following various keywords: "Digital Twin" OR "Digital Twins" OR "Digital-twin" OR "Digital Twinning" OR "Virtual Twin" OR "Digital Replica" OR "Virtual Replica" OR "Virtual Counterpart" OR "Virtual Representation" were used. In the second part of the search string, the keywords "Facility Management" OR "Facilities Management" OR "Asset Management" OR "Facility Lifecycle Management" OR "Building Facility" OR "Operation and Maintenance" OR "O&M" OR "Smart Building" OR "fire safety management" OR "fire evacuation" OR "fire safety equipment" OR "Fire safety equipment maintenance" OR "fire rescue" OR "firefighting" OR " fire emergency response". The search was integrated with DTs using the AND command for comprehensiveness.

The literature search process involved identifying relevant keywords and performing a thorough query-based search to locate potential papers. To ensure the systematic review's integrity and provide a detailed explanation of the literature search process, the authors employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 flow diagram. This flow diagram provides a clear visual representation of the systematic review stages, making it easier for readers to track the decision-making process and how the initial literature search led to the final set of selected studies [100,101]. The literature search period was set from January 2012 to May 2023, as this was when DTs emerged as a significant technology and attracted substantial research interest. The initial search yielded 730 papers from Scopus, which were then filtered using automation to limit the language to English, the source type to journals and conference proceedings, and the subject area to engineering, computer science, energy, decision science, and environmental science. The entire literature retrieval process is summarized in Figure 3.

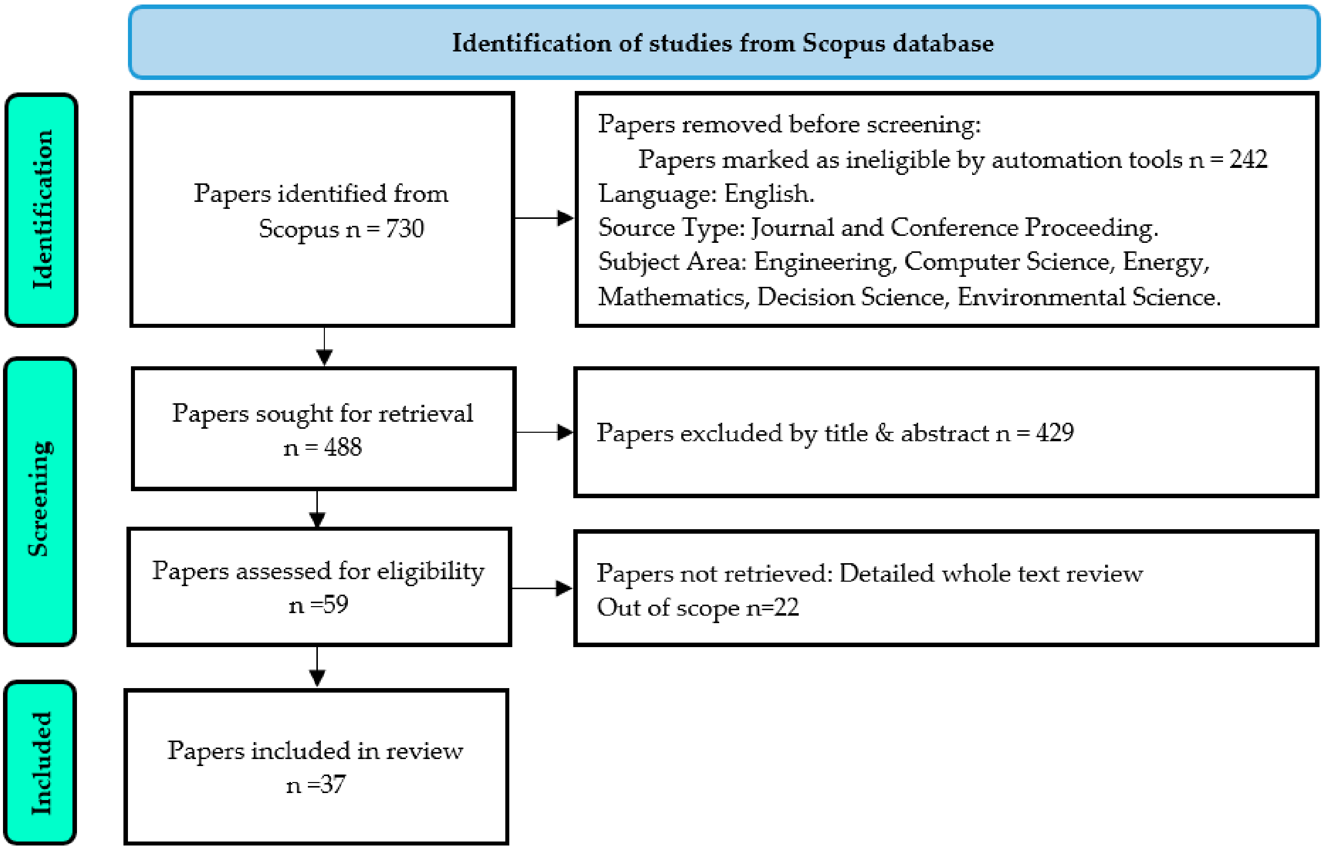

Figure 3. Literature retrieval flowchart based on PRISMA 2020 flow of a systematic review.

3.2. Literature Characteristics

Studies on the use of DT in fire safety management and evacuation have been gaining momentum, with a significant increase in the number of research studies conducted recently. Figure 4 shows a clear trend in the publication distribution, with a remarkable increase in publications on DTs in FSM and fire evacuation in the past three years, highlighting growing interest in and the immense potential of intelligent FSM. Figure 5a indicates that most publications on DTs in FSM and fire evacuation belong to the fields of engineering and computer science, emphasizing the role of machines and computer-aided tools in advancing intelligent engineering solutions. Meanwhile, based on the type of document source, Figure 5b categorizes academic publications on DTs in FSM and fire evacuation from January 2012 to May 2023, revealing that 39% of the publications from this study are journal articles, while 61% are from conference proceedings.

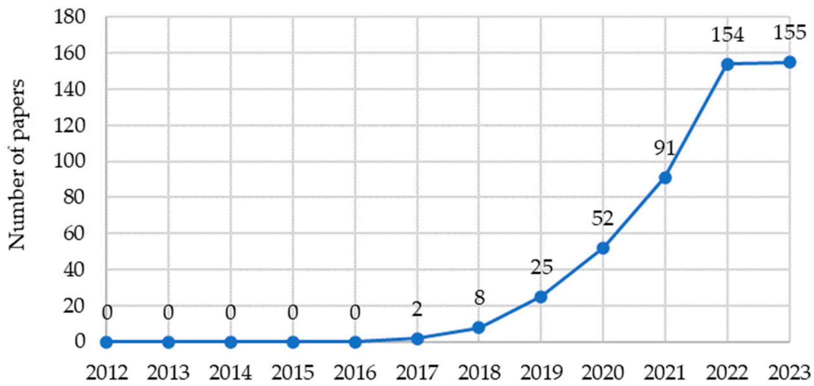

Figure 4. Number of papers published yearly on the topic of DTs in FSM and fire evacuation (January 2012–May 2023).

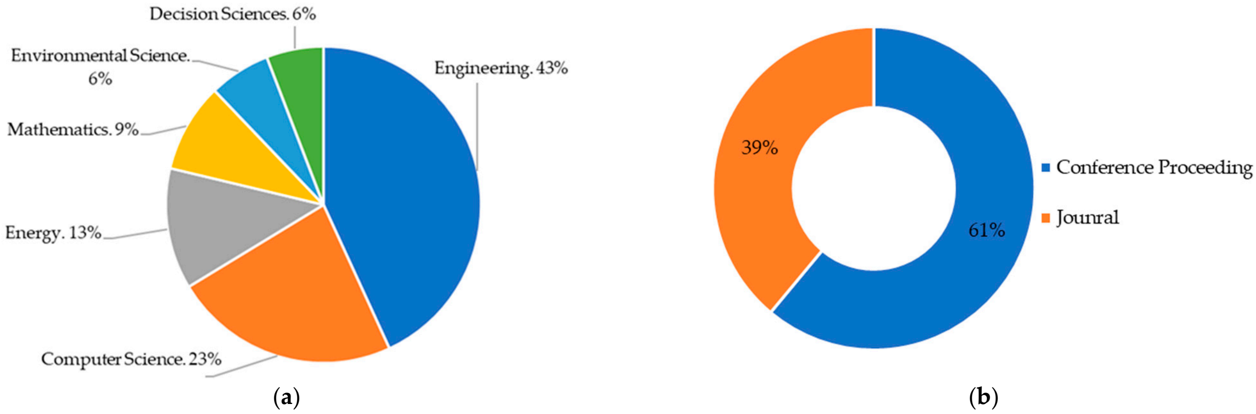

Figure 5. Distribution of publications on DTs in FSM: (**a**) publications in various research fields; (**b**) document source type.

3.3. Development of DT-Based FSM Framework toward Smart FM

This paper presents a conceptual framework aimed at identifying potential application areas and requirements for DTs in FSM. The framework underwent a rigorous validation process, which involved the distribution of a survey questionnaire among FM professionals. Following a comprehensive second round of refinement, the framework presented in this study was updated. This enhancement is based on a detailed analysis of the challenges identified in the literature review and valuable insights derived from the survey results. The framework effectively tackles key issues such as missing information, the need for integrating virtual and real-time data, and the necessity of dynamic monitoring and predictive operations in FSE maintenance and fire evacuation. The framework is designed to enhance FM practices, particularly in FSM. Traditional building fire management systems often pose critical challenges during fire emergencies, particularly regarding data interoperability and the integration of BIM and IoT technologies [23,56]. DTs have emerged as a promising solution to address these challenges. DTs facilitate the integration of virtual representation with real-time data, enabling the dynamic monitoring and predictive operation of fire protection systems [91,102].

This paper outlines an intelligent framework, as illustrated in Figure 6, that offers a high degree of flexibility and adaptability, catering to two distinct applications that center on FSE and fire evacuation practices. The proposed DT building FSM involves layers: a physical layer, a monitoring layer, a DT data layer from IoT and BIM data, a smart platform FSE maintenance and fire evacuation layer, and a fire warning control layer. The proposed framework is structured into four layers: the physical building layer, the virtual building layer, the application layer, and the user interaction layer. It operates through a centralized physical building layer, which acts as the primary source for real-time data collected from fire sensors, indoor localization systems, and IoT devices. These data are then processed and analyzed within the virtual building layer, utilizing predictive algorithms for fire spread and evacuation simulations. Additionally, the framework enables multi-tiered data fusion. In the virtual building layer, data-level fusion integrates real-time sensor data with predictive algorithms for decision making. Meanwhile, decision-level fusion takes place in the application layer, where functionalities such as fire detection, evacuation path planning, and occupant tracking are synthesized to optimize emergency responses. The user interaction layer utilizes AR technology to provide an interactive visualization of the building and its safety features to users, such as facility managers, firefighters, and occupants. By leveraging AR, the virtual building layer can seamlessly integrate with the application layer, enabling users to make informed modeling decisions that are presented in a visually engaging format within the user interaction layer. In the physical building layer, data are collected through sensing technologies and transferred through a wireless network to the virtual building layer. In the virtual building layer, the data (FSE data, BIM data, and IoT data) are processed using AI tools. Additionally, data fusion techniques are employed to integrate data from various sources, and blockchain is utilized to ensure data security and privacy. Decisions made in the virtual building layer are transferred to an application layer to provide services and also to be integrated back with the physical building layer for automatic control and operation optimization [48]. In order to integrate end users, the decisions from the application layer are visualized using AR and other smart technologies. The decisions made are checked and confirmed by FM professional users before being implemented to ensure humans are kept in the loop.

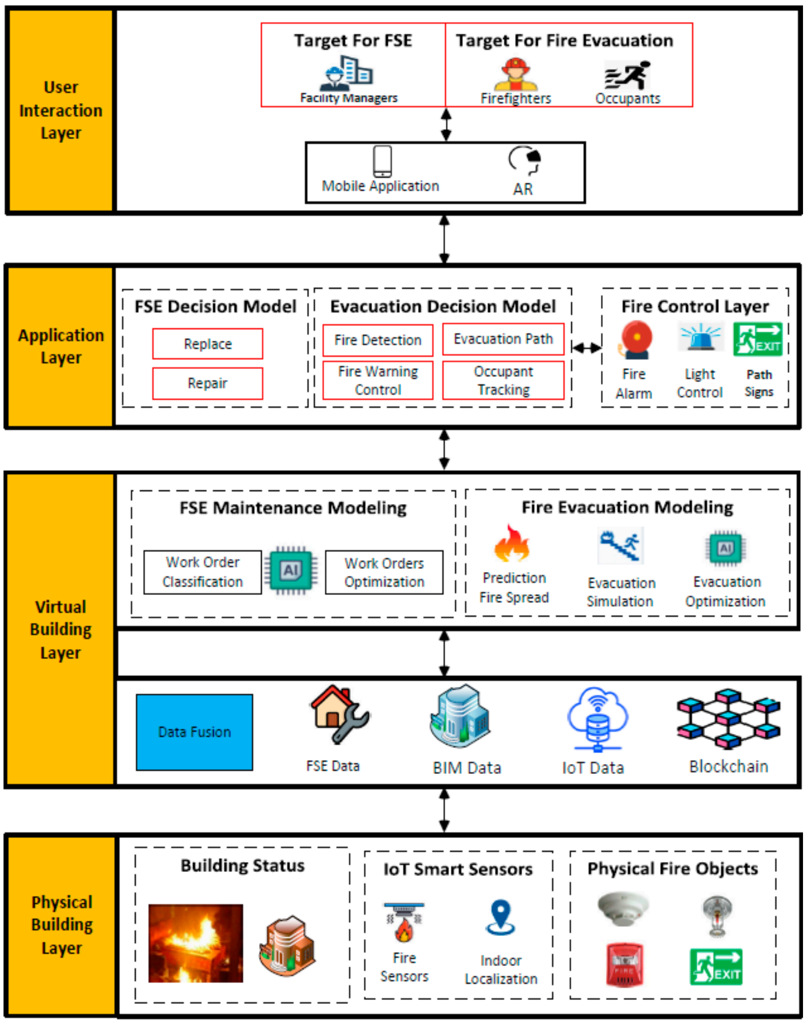

Figure 6. Smart fire safety framework.

3.3.1. Physical Building Layer

The most crucial component of DTs is real-time data acquisition, which occurs in the physical building layer. This layer provides dynamic monitoring information to the virtual building layer in real time [23,90]. The physical building layer integrates physical fire objects and IoT smart sensors, including fire sensors, extinguishers, alarms, and emergency exit signs. IoT technologies facilitate data connections, enabling a two-way flow of information between physical and virtual building layers. These data from IoT technologies are used to monitor the current conditions of a building, such as its temperature, smoke, and carbon dioxide (CO2) levels. For example, Wehbe and Shahrour [27] employed smart sensors specifically for building supervision and fire evacuation management. They used sensors that measure temperature, smoke, and CO2, strategically placing them in critical locations to transmit real-time data to their smart system. The successful integration of the physical layer with the virtual layer completes the DT framework in terms of real-time updates and bidirectional information flow.

3.3.2. Virtual Building Layer

This layer integrates different data resources according to a set data structure. In this layer, a 3D geometric model is created based on BIM to provide information on building components (e.g., the architectural layout, geometric dimensions, and spatial locations). These geometric data take into account various obstacles, such as walls, columns, and furniture, as well as doors. They also include essential functions for managing data and models, such as storage, analysis, integration, and processing. Furthermore, they provide AI-enhanced learning capabilities to support decision making [102]. One of the data resources is BIM databases that include information related to digital models and historical FSE maintenance, design and construction data, as-built data, geometric information, physical information, and spatial information.

Blockchain technology is employed in the framework to ensure the quality and accuracy of BIM data. The integration of blockchain in our framework goes beyond traditional data security; it is crucial for verifying data and maintaining privacy at the database level, especially in IoT-based systems [100]. As highlighted by Sadri et al. [103], integrating blockchain with IoT facilitates the decentralized processing of data, enhancing system resilience and reducing the risks associated with centralized systems. This approach not only ensures secure and reliable data transfer but also significantly improves the robustness and response efficiency of the FSE system.

Blockchain is a crucial enabler for facilitating robust security and transparency in recording emergency response activities [104]. Additionally, blockchain can facilitate the distribution of emergency resources and enable the efficient tracking of their utilization [105–107]. Our framework utilizes indoor localization, which could pose privacy and location security concerns. Using blockchain technology in our system addresses these privacy and security concerns associated with user localization and the vulnerability of our IoT sensing system to hacker attacks. Research has demonstrated that blockchain can protect IoT devices and users' location privacy, ensuring secure and private location information sharing. This integration is crucial for maintaining the integrity and reliability of our fire safety and evacuation framework [108]. Additionally, blockchain has been effectively used in FSE maintenance. For instance, Khan et al. [109] used blockchain's application in portable firefighting equipment (PFE) maintenance, ensuring record integrity, automating inspections, and ensuring compliance with safety standards, aligning with our framework's objectives. This approach further underscores the role of blockchain in bolstering the efficiency and reliability of fire safety and evacuation systems.

Hence, blockchain's role in our framework is integral for advancing the reliability and effectiveness of modern FSE practices. BIM-FSE data can be stored in blockchain, which leads to various levels of BIM–blockchain integration to improve BIM-based data sharing and trust in BIM collaborations while enhancing the security and transparency of BIM data [110]. For example, Zheng et al. [111] introduced the concept of a blockchain

BIM (bcBIM) system. This system was designed with the specific purpose of conducting audits on BIM modifications and regulating access within the mobile cloud environment. Suliyanti and Sari [112] have explored the use of blockchain technology to enable secure and comprehensive BIM information exchange among multiple stakeholders throughout the entire building lifecycle. In this virtual layer, blockchain enhances BIM data management and improves the security and reliability of the data collected from IoT sensors. The collected data from the IoT sensors is wirelessly sent in real time to a cloud-based IoT database. Blockchain offers secure and reliable data access, transactions, and storage, thereby enhancing the integrity of the data collected from IoT sensors [110]. For example, Siountri et al. [113] highlighted the use of BIM, the IoT, and blockchain to enhance building security during the operation stage. The framework provides data fusion technology that can combine BIM data and FSE data with real-time IoT data that captures dynamic sensor-generated information.

Data fusion is crucial for decision making, predictive analytics, and system optimization within the context of smart FM. Data fusion serves as a bridge that links BIM data, FSE data, and IoT data, aiding in better real-time tracking and smarter decision making in FSE maintenance and fire evacuation planning. For example, Xiongwei et al. [114] propose a framework for systematically fusing BIM and IoT data, highlighting the importance of data fusion in enhancing real-time decision making in the AEC industry. Data fusion enhances BIM–IoT integration to collect the data gathered in the physical building layer, leverage the value of the data in the virtual building layer, and enhance decision making in the physical building layer.

In this layer, FSE maintenance modeling utilizes AI techniques such as ML and DL to perform data analysis for the classification and optimization of the work order of FSE maintenance. For example, McArthur et al. [115] and Raghubar et al. [116] both discuss the development and application of supervised machine learning models to classify maintenance requests and work orders. They achieve prediction accuracies ranging from 46.6% to 90% for problem-type classification. Collectively, these papers demonstrate the potential of AI techniques in improving maintenance issue classification and data collection in FM. Moreover, AI techniques are used to predict fire spread, simulation, and optimization in modeling fire evacuations. For example, Wang [117] proposed a fire evacuation routing model called "Bee-Fire" that uses artificial bee colony optimization to find optimal evacuation routes, reducing both the clearance time and total evacuation time. In the fire spread prediction, Chetehouna et al. [118] developed an artificial neural network (ANN) to predict the physical and geometrical parameters of a forest fire front, such as the rate of its spread and flame height. They found that the ANN model provided accurate results. DTs provide facility managers the advantage of accessing real-time, reliable, and immutable records of asset data [119].

3.3.3. Application Layer

The objective of this layer is also to store, analyze, integrate, and visualize data in platforms and models using AI technologies, machine learning, and simulations [120]. By utilizing all available data and model resources generated from the virtual layer, it can perform various functions and contribute to advanced decision making. These functions include replacing or repairing the equipment based on the FSE decision model. Moreover, it can provide a fire evacuation model decision that offers functionalities such as fire detection, evacuation path planning, fire warning control, and occupant tracking. This layer also provides fire alerts based on IoT sensors and data analyses to activate fire emergencies. Additionally, the system implements actions for fire defenses, such as closing doors, turning off equipment, initiating automatic fire suppression, or controlling smoke systems. In simpler terms, adequate measures are taken by the system concerning locks, lighting, and critical equipment control to restrict the spread of the fire and associated damage. Light and voice path signalization are also provided.

3.3.4. User Interaction Layer

The user interaction layer represents the highest realization level within the proposed DT framework, facilitating interactions between individuals, such as facility managers, firefighters, and occupants, and digital environments. It assists firefighters in guiding occupants along the optimal safe fire evacuation path to the exit. Moreover, it helps facility managers visualize and check information related to FSE in a building by utilizing AR technology. The primary interfaces for implementing comprehensive fire safety management and interactions involve AR technology, bridging the gap between physical spaces and virtual spaces [121]. This layer primarily provides a range of services in two key applications: FSE management and fire evacuation. These services include tasks like locating and predicting optimal fire evacuation routes, as well as enhancing information and communication between stakeholders. AR-based experiments have been used not only to study evacuation behavior but also to improve emergency management systems. In emergency situations, the use of AR technology assists responders in getting a better view of the danger and surroundings, enabling them to make well-informed decisions and take necessary actions [104]. Yoo et al. [122] developed a machine learning and augmented-reality-based indoor navigation and emergency evacuation system that guides users toward optimal escape paths. This system has the potential to enhance safety during emergency situations and improve navigation in indoor environments. Similarly, Chen et al. [123] used AR to implement a fast flow control algorithm in a real evacuation system at a university. Tsai and Yau [124] used AR, route planning, and three-dimensional graphics to provide guidance for an escape route in the event of a radioactive accident. The adoption of AR in the framework is a crucial enabler for enhancing performance in real-time communication between stakeholders. AR technology is utilized to enhance decision making by providing a visual representation and the integration of decisions in a real-world environment. It offers interactive engagement and remote control, such as in emergency situations like fire evacuations, for which AR can guide occupants to safety by displaying the most efficient route [100,125]. Chen et al. [8] utilized an AR system based on BIM to inspect and maintain FSE. The objective of their study was to integrate BIM and AR technologies to improve the efficiency and effectiveness of these tasks.

In brief, the DT framework provides a comprehensive view of the components and interactions of a system that uses advanced technologies to enhance FSE maintenance and fire evacuations. The DT framework leverages BIM, IoT technologies, data fusion, blockchain, cloud computing, AI, and AR to improve FSM.

3.4. Survey of FM Professionals

In this research study, a survey was conducted to validate the presented framework for future FM (FM) practice. The objective of this survey is to understand the perception of the FM team on adopting DT applications in facility maintenance for FSE and fire evacuation practices. Specifically, this survey could measure whether practitioners accept DTs in FM, evaluate the proposed framework, and discover the challenges of applying DTs in FM practices. The information collected from the survey would significantly impact the development of the knowledge base for the DT framework in FM. The survey was designed using the Qualtrics platform, facilitating the creation of online questionnaires for ease of use. The survey was distributed to FMs and facility engineers using three different methods: (1) through the department of FM at Western Michigan University from 9 September 2022 to 26 January 2023; (2) through LinkedIn groups related to FM; and (3) through the International FM Association (IFMA). A total of 66 responses were received, of which 28 were complete. The survey targeted FMs and engineers from various FM domains to collect data from diverse perspectives and ensure the suitability of DT applications in different FM practices.

The survey started by introducing the aim of the study and the purpose of the survey. Before each question, a description was provided to ensure that the participants understood each question, reducing the sampling bias. The questionnaire began with demographic questions, such as their age, education level, work experience, and position. The questionnaires also included questions regarding current FM practices, issues, reasoning, and suggested solutions to improve FM practices with DTs. The participants were also asked about their experience with DTs, BIM, the IoT, AI, and AR [43,126]. The survey also asked about the impact of missing information on their decision making and solicited suggestions for enhancing the DT framework [43,127–129]. The survey included questions about participants' familiarity and understanding of DT technologies in FM [126,129–131], the frequency of data collection for FSE maintenance [43,126], the expected benefits from DT technologies in FM [126–129], and the evaluation of DT technologies in FSE and fire evacuations [126,129,132].

Our initial survey was specifically designed to gather insights from FM professionals, focusing on the integration and management aspects of DT technologies in FSM. We recognize, in hindsight, that including firefighters as key end users of the proposed framework would have enriched our understanding of its practical applications. Future research will address this gap by involving firefighters to ensure the framework is not only technologically sound but also practically applicable and user-centric.

4. Results

The questionnaire was utilized in this study to gather demographic information, such as the age, gender, and education level of the participants. The subsequent section aimed to gather information about the current methods used by the participants to access necessary maintenance and emergency data, as well as the electronic format they use for maintenance information and communication. Furthermore, the survey sought to understand the preferred means of communication for the participants when engaging with stakeholders. The next section of the questionnaire explored the opinions of the participants on the types of technology that can improve the performance of FM. This included questions on the technologies that the participants believe will be necessary for FM practices in the next decade, their familiarity with the proposed technologies, their understanding of DT technologies in FM practices, and their experience with the proposed technologies. The following section of the questionnaire aimed to collect data on the use of the proposed technologies in FM departments, including the areas that may benefit from the implementation of DT applications. Additionally, the questionnaire investigated the impact of missing information on decision making, as well as the effect of the proposed technology on the efficiency and cost of FM performance and decision making. The final section of the questionnaire delved into the challenges of applying DTs in FM, asking the participants for their opinions on the proposed framework of applications, any additional challenges they foresee that may impact the adoption of DT applications, and their suggestions on how to improve the proposed framework to enhance our research.

4.1. Literature Review Findings

This section presents the findings from a thematic analysis of 37 studies on the enablers and main barriers of DT adoption for FSM. First, the barriers and enablers were extracted through 37 selected papers. Each of the 37 papers included in the study was analyzed in detail. Every barrier and enabler was recorded in an Excel worksheet, together with the title of the article mentioning it. All the barriers were clustered into nine groups, and the total number of papers mentioning each factor was computed, while the enablers were clustered into six groups. Based on an analysis of the 37 papers, the identified barriers and enablers are presented and ranked according to their respective frequency of occurrence.

4.1.1. Barriers

Based on an analysis of 37 studies about DT technologies for FSM, Table 2 summarizes the nine identified barriers, presented and ranked according to their frequency of occurrence.

Table 2. The occurrences DT barriers from analysis of barriers in 37 studies.

Rank Barriers	Barriers	Occurrences
B1	Difficulties in systems integration	30
B2	Difficulty in performance in real-time communication	24
B3	Lack of DT knowledge	16
B4	Lack of trust in data security	15
B5	Initial costs	8
B6	User acceptance	5
B7	Difficulties in data management	4
B8	Lack of competence	3
B9	Education training costs	2

Difficulties in systems integration were the most prominent theme with 30 occurrences, highlighting the challenges and complexities of integrating heterogeneous data sources, especially from different sensors, photogrammetry technologies, and conventional sources. Difficulties in performance in real-time communication, with 24 occurrences, show the challenges concerning the processing of the massive amount of data generated in real-time communication, and this presents a significant challenge in adopting DT [129]. Lack of DT knowledge, with 16 occurrences, shows that the knowledge and skill gap is a significant factor complicating effective DT implementation in FSM in the FM industry. Proper training, expertise, and efficient knowledge transfer are vital. The lack of trust in data security, with 15 occurrences, underscores challenges related to data privacy, security, and ethical considerations in the digital system. Initial costs, with 8 occurrences, emphasize the need to evaluate the costs/benefits of DT implementation for FSM and prove its long-term impact and business value. User acceptance, with five occurrences, addresses that the lack of knowledge and understanding of emerging technology has the potential to provide resistance to its acceptance and adoption [133,134]. Difficulties in data management emerged as the most prominent barrier, with four occurrences related to data collection, data quality, and efficient management. This barrier highlights areas that need further research and development. Lack of competence, with three occurrences, shows that developing demanding skills is critically important for the emerging DT paradigm [135]. Lastly, education training costs, with two occurrences, emphasize the need for investments from companies for education training and for evaluations of the costs/benefits of DT implementation for FSM.

Figure 7 elaborates on the main barriers that hinder the successful implementation of DT initiatives. The findings indicate that the most significant barrier is difficulties in system integration, which accounts for 28% of the total barriers. The second most significant barrier is the difficulty in achieving real-time communication performance, which accounts for 22% of the total barriers, followed by a lack of DT knowledge, lack of trust in data security, and high initial costs. On the other hand, the barriers that are least significant include education training costs, which account for 2%, followed by a lack of competence, difficulties in data management, and user acceptance. It is noteworthy that researchers and academic scholars have paid relatively less attention to these barriers.

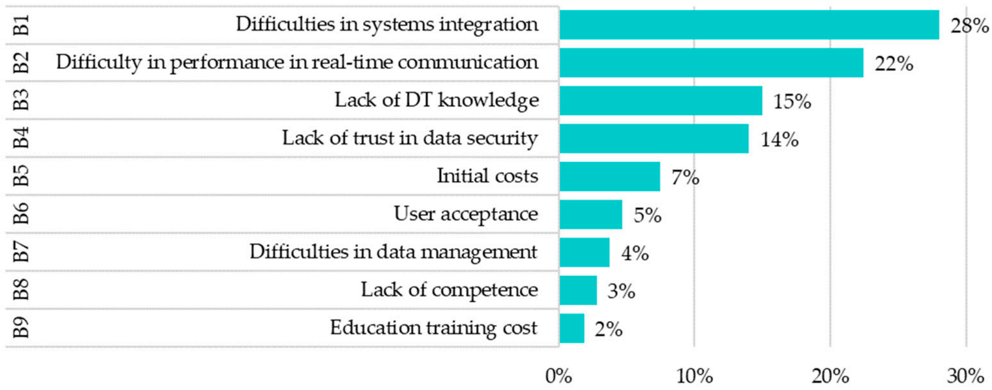

Figure 7. Barriers of adopting DTs in FSE maintenance and fire evacuation from literature review.

4.1.2. Enablers

Based on an analysis of 37 studies on DT technologies for FSM, six main enablers for DT implementation in FSM were identified and ranked based on their frequency of occurrence, as illustrated in Table 3. The literature findings revealed that AI was identified as the most prominent enabler with 27 occurrences, emphasizing the importance of ML, DL, data processing, cloud computing, edge computing, data mining, and pattern recognition in extracting insights from the vast amount of data collected from various sources. The IoT stands out as the second most critical enabler, with 23 occurrences, indicating the significant reliance on sensor technology and the IoT for various DT applications. BIM holds a crucial position with 20 occurrences, as BIM models provide rich information about assets, including geometric information, spatial relationships, quantities, cost estimates, material inventories, and schedules. Additionally, BIM aids in visualization, fabrication/shop drawings, construction sequencing, conflict/collision detection, and forensic analyses [100,136]. AR and VR were highlighted with eight occurrences for their potential in visualizing, simulating, and interacting with 3D models in real time to enhance FSE maintenance and fire evacuations. Blockchain is a crucial enabler, with five occurrences, facilitating robust security, and it is used at the database level for data verification and privacy control. Lastly, GIS is the least-frequent enabler with two occurrences and can integrate with the BIM model for visualization and information querying in a spatial context to enhance fire emergency evacuation planning [137].

Table 3. The occurrences of DT enablers from analysis of enablers in 37 studies.

Code	Enabler	Occurrences
E1	AI	27
E2	IoT	23
E3	BIM	20
E4	AR/VR	8
E5	Blockchain	5
E6	GIS	2

Figure 8 indicates that AI is the most significant enabler for DT adoption in FSM, representing 32% of mentions in the literature. The IoT follows closely at 27%, underscoring its critical role in real-time data acquisition and connectivity. BIM, with 24%, is also a key enabler, integral for creating detailed digital representations of physical spaces. The least significant is GIS, with 2%, which, while still necessary, needs to be more emphasized in the literature for implementing DT in this context.

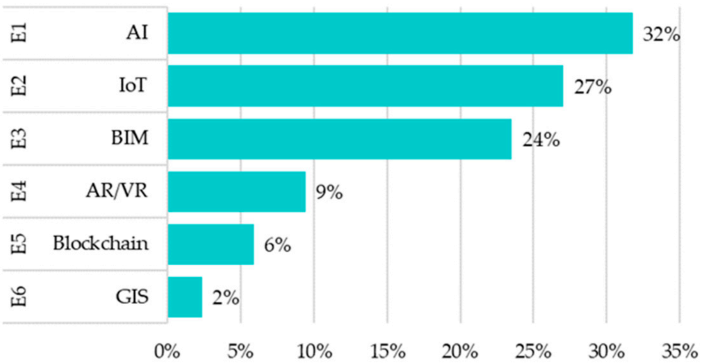

Figure 8. Enablers of adopting DTs in FSE maintenance and fire evacuations from literature review.

4.2. Survey Results

4.2.1. Demographic Distribution

As shown in Figure 9, the survey results indicate that the majority of participants are male (80%), with a smaller percentage of female respondents (10%) and an equal percentage (10%) preferring not to reveal their gender. Figure 9 also shows that the age distribution demonstrates that the largest group of respondents is aged between 55 and 64 years old (38%), followed by those between 45 and 54 years old (28%).

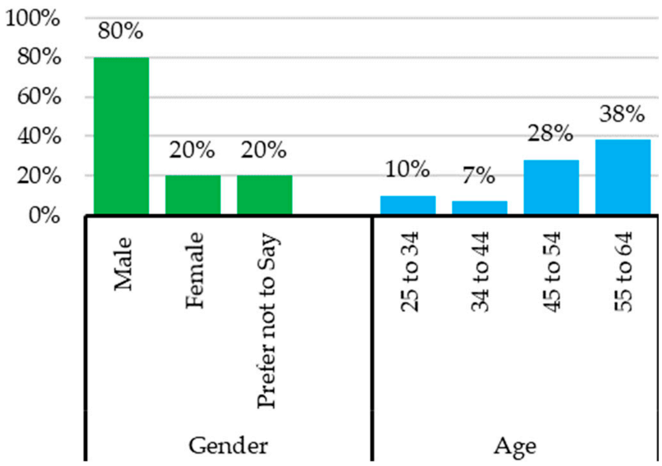

Figure 9. Demographic distribution.

In terms of education levels, as shown in Figure 10, the data reveal that 55% of the participants hold a Master's degree, 28% have a Bachelor's degree, 7% possess a high school diploma, and 10% have obtained a Ph.D. or higher qualification. Figure 10 also shows that the respondents' roles within FM are diverse, with facility managers and engineers both representing the largest groups at 21% each, followed by directors (9%), supervisors (12%), and administration (12%). The "other" category, which accounts for 24% of the participants, includes various professionals such as FM consultants, mechanical engineering managers, consultants, project managers, faculty members, and FM service providers, all of whom work within the FM industry.

Overall, the survey results present a well-rounded demographic profile of FM professionals, encompassing their education and work experience. The data suggest that most participants are male, aged between 45 and 64 years old, hold a Master's degree, and have diverse roles in the FM industry. This varied group of respondents facilitates a comprehensive evaluation of the perceptions of and potential challenges surrounding the adoption of DT applications for FSE maintenance and fire evacuations.

Regarding work experience in Figure 10, the majority of the respondents (80%) have 10 years or more of experience in the field, while 10% have between 1 and 3 years, and another 10% have between 5 and 10 years of experience. No respondents reported having less than 1 year or 3 to 5 years of experience.

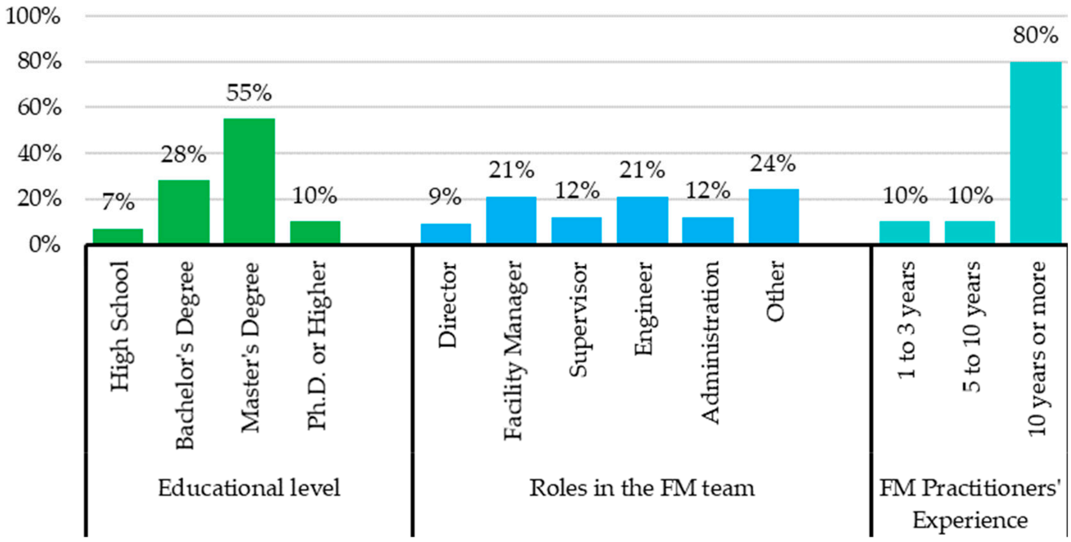

Figure 10. Educational level, roles in the FM team, and FM practitioners' experience.

4.2.2. Level of Familiarity and Understanding with DT Technologies in FM

Figure 11 shows valuable insights into FM professionals' skills, experience, and familiarity with various DT technologies. These insights suggest that the integration of DTs in FM is an area that requires further investigation and understanding. While a proportion of respondents have experience with DTs and related technologies, the data imply that there is still substantial room for growth in the adoption and application of DTs within the FM sector. A notable 19% of respondents have experience with DTs, highlighting that some participants are familiar with the technology's potential in integrating virtual–physical systems, real-time monitoring, analyses, and optimization. However, as the adoption of DTs in FM is still in its early stages, there is a need to further investigate the benefits, challenges, and best practices for its effective implementation.

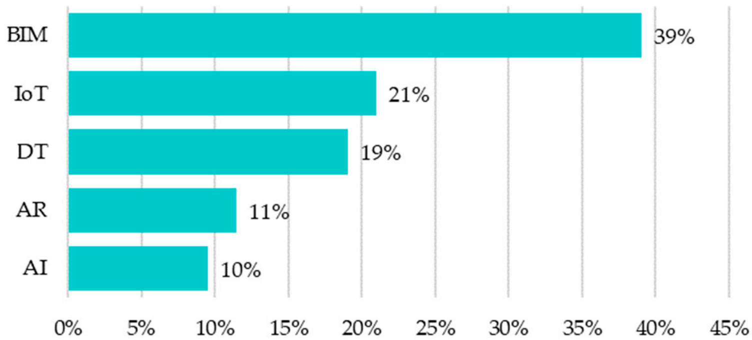

Figure 11. Participants' familiarity and understanding with DT technologies in FM.

Figure 11 also illustrates that 39% of participants are familiar with BIM and 21% with IoT technology. Both BIM and the IoT are key components of the proposed DT framework, and their integration is essential to realizing the full potential of DTs in FM. This indicates the necessity of further exploring how to effectively integrate these technologies within the DT context to enhance FM practices, especially in terms of FSE maintenance and fire evacuations. With only 10% and 11% of respondents familiar with AI and AR, respectively, it is evident that these technologies are not yet widely adopted in the FM sector. As AI can be employed for data analyses, predictions, and decision making in a DT-based FM system, and AR can enhance the visualization of and interaction with digital representations of facilities, it is crucial to investigate how these technologies can be integrated into the DT framework to maximize its benefits.

According to the results in Figure 12, only 38% of FM professionals are familiar with DT technology and understand how it differs from BIM. In contrast, 62% of the respondents either have limited knowledge about DTs and their differences from BIM or are completely unfamiliar with the concept. These results emphasize the need for further exploration and exploitation of DTs' potential in the FM industry. The limited familiarity with DTs among industry professionals highlights the importance of promoting awareness, conducting in-depth research, and providing educational initiatives that emphasize the benefits of DTs in FM practices, such as improved maintenance, fire safety, and emergency response measures. By addressing the gaps in knowledge and understanding, industry professionals can better appreciate the potential advantages of implementing DTs in FM. This will ultimately help the FM industry adopt and implement more efficient and effective solutions for FSE maintenance and fire evacuation practices. The aforementioned findings indicate that there have been many discussions related to the concept of a DT without a clear understanding of DT technology and its potential. Many industry practitioners and researchers hold misconceptions about DTs, with some drawing comparisons to BIM due to their shared characteristics [138]. Hence, a lack of consensus exists pertaining to the capabilities of digital twins within the industry.

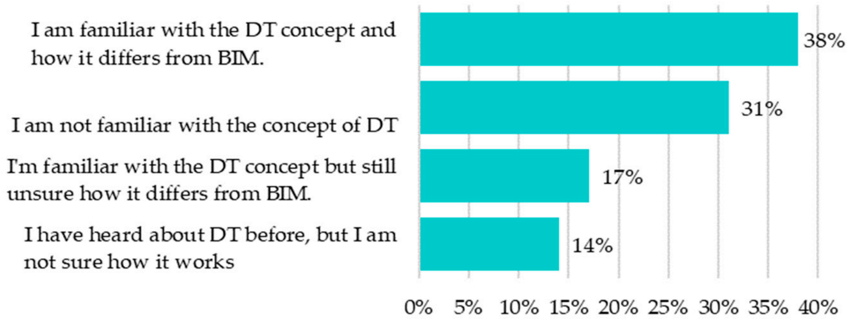

Figure 12. Participants' familiarity with the DT concept.

The results in Figure 13 highlight a diverse range of perspectives when it comes to implementing DT technologies within FM departments. The results revealed that 14% of participants reported that their department is currently in the development stage of implementing DTs. Only 7% indicated that DT implementation would be considered within a year or two, while 36% mentioned that they would potentially implement DT technologies three or more years from now. Interestingly, 43% of the respondents stated that their FM department has no plans for implementing DT technologies anytime soon. These results highlight the importance of raising awareness about the potential benefits of DT technologies in FM practices and of addressing the challenges that may be inhibiting its widespread adoption. By addressing these issues, the industry can move towards a more efficient and effective approach to FM, with DT technologies playing a central role in FSE maintenance and emergency response measures.

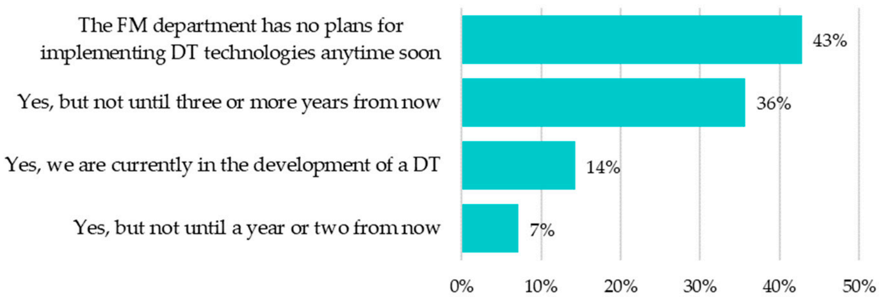

Figure 13. Participants' consideration of DT implementation for future FM practices.

4.2.3. DTs for FSE Maintenance and Fire Evacuation Benefits

The survey also sought to understand the frequency of data collection for FSE maintenance within facilities. According to the responses in Figure 14, 55% of the participants collect data weekly, 40% collect data daily, and only 5% collect data hourly. These results suggest that data collection practices for FSE maintenance in FM vary significantly. While some organizations prioritize frequent data collection, others may not see the need for such regular monitoring. This presents an opportunity to explore the potential advantages of more frequent data collection through DT technologies. By leveraging DT technologies, FM teams can access real-time data for FSE, enabling more efficient and proactive maintenance strategies. Incorporating DT technologies in FM practices can facilitate more informed decision making and help organizations better understand their FSE's condition. This, in turn, can lead to improved FSE and emergency response measures, such as fire evacuation planning, ultimately contributing to safer environments for occupants and staff alike. The survey results emphasize the need for further investigations into and education on the potential benefits of adopting DT technologies in FM, particularly in the realm of FSE maintenance.

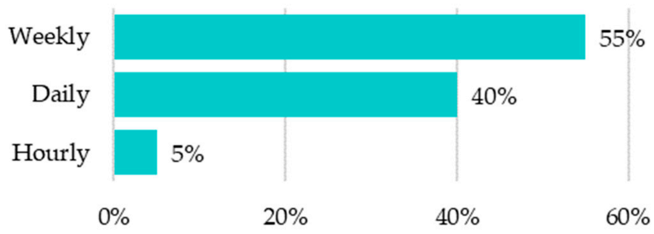

Figure 14. Frequency of data collection for FSE maintenance.

Figure 15 shows that 26% of FM professionals perceive missing maintenance information for FSE and communication difficulties as having a significant impact on decision making, while another 26% believe it has a moderate impact. In total, 52% of respondents consider the issue to be impactful. This highlights the potential benefits of implementing DT technologies in FM to enhance decision-making processes, minimize information gaps, and improve fire safety and emergency preparedness. The adoption of DT technologies could address these concerns by providing a real-time understanding of the status of FSE and facilitating improved communication among stakeholders.

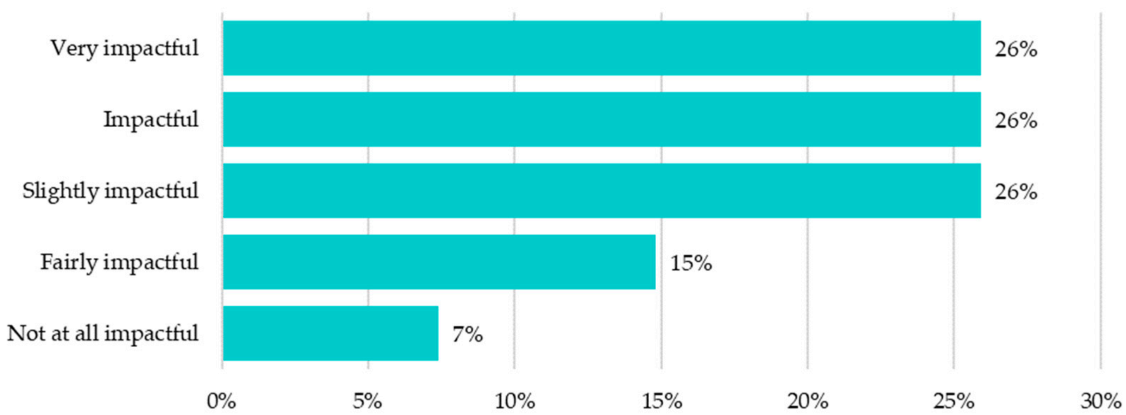

Figure 15. Impacts of missing maintenance information on FSE.

In Figure 16, using a Likert scale, the survey results indicate that most FM professionals perceive potential benefits in implementing DTs for FSE and fire evacuations. The survey results reveal a positive attitude toward the potential advantages of DT technology for enhancing operational responsiveness in real-time decision making. Specifically, 15% of the respondents strongly agree and 40% agree with this anticipated benefit. Additionally, a significant percentage of the professionals (30% strongly agree and 55% agree) acknowledge the potential of DT technology in determining optimal fire evacuation routes in real time, reflecting confidence in the technology's proficiency in fire emergency management.

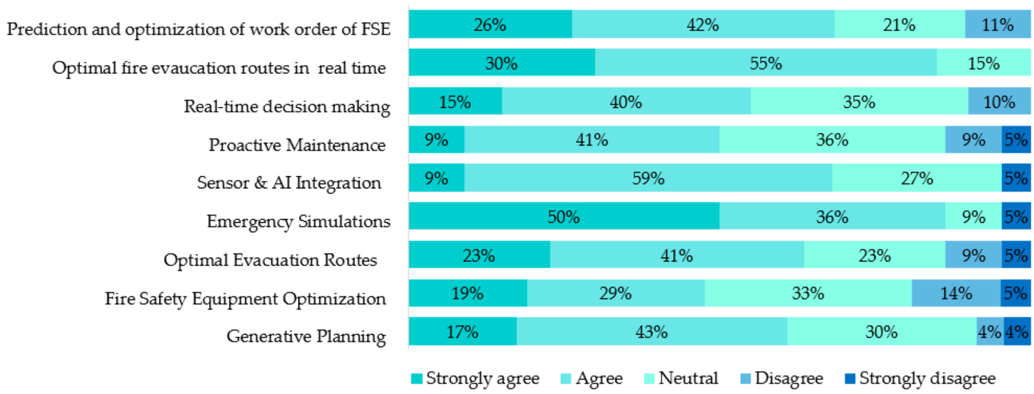

Figure 16. Participants' expected benefits from DT technologies in FM.

The study also shows that DT technology has a positive impact on proactive maintenance, with 9% strongly agreeing and 41% agreeing that a proactive approach to maintenance activities is beneficial when augmented by DTs. The integration of sensors and AI in DT systems receives the highest combined agreement, with 9% strongly agreeing and 59% agreeing. This consensus underscores the industry's trust in DTs' ability to enhance the interplay between physical assets and their digital counterparts through real-time data and machine learning. Emergency simulations are also highly regarded, with 50% agreeing and 36% strongly agreeing on the benefits of DTs, indicating a widespread belief in its effectiveness for emergency preparedness and response training. Meanwhile, views on DTs' role in generating optimal evacuation routes are supportive, with 23% strongly agreeing and 41% agreeing, indicating a strong endorsement of DTs' application in safety route planning during emergencies.

For FSE optimization, the results present a more moderate but still positive reception, with 19% strongly agreeing and 29% agreeing, suggesting a cautious yet optimistic attitude towards the technology's role in optimizing equipment deployment. Lastly, generative planning through DTs was supported by the respondents, with 17% strongly agreeing and 43% agreeing, reflecting an acknowledgment of the innovative potential DTs hold for strategic and operational planning in FSE.

These findings collectively suggest that DTs are perceived as a valuable asset across various aspects of FSE maintenance and fire evacuations, with the greatest confidence in their data integration and simulation capabilities. This indicates a forward-looking perspective among FM professionals who are open to technological advancements that promise to improve efficiency, safety, and decision making in fire safety operations.

4.2.4. Participants' Evaluation of DT Framework in FM

In Figure 17, the findings indicate that a majority of individuals hold the belief that the utilization of DTs has the potential to enhance FSE maintenance practices and optimize fire evacuations. A significant proportion of the responders (75%) hold the belief that the implementation of DTs may enhance the performance of FSE maintenance. Furthermore, a substantial majority (89%) supports the use of DTs to provide 3D models with related real-time information by using BIM-IoT integration to enhance FSE maintenance and fire evaluations. Additionally, a considerable percentage (70%) believe that DTs can contribute to improving decision making by using AI techniques to conduct work order classifications and optimize FSE. Moreover, 69% of the respondents indicate that applying DTs will improve data management and enhance decision making in FM practices. Furthermore, 66% of the responses indicate that DT implementation can provide assistance to firefighters to evacuate occupants during fire evacuations. However, only 6% indicate a strong opposing viewpoint. Similarly, 58% of the responses indicate that DTs use AR to improve real-time visualization and communication for FSE maintenance. This suggests a growing interest in immersive technologies as tools for enhancing the clarity and immediacy of information dissemination. The proposition that DT technology can contribute to improving the intelligence level of indoor safety management is supported by 60% of the respondents, indicating an expectation that DTs will bring a higher level of smart automation and analytics to safety protocols inside buildings. Furthermore, 69% of the participants believe that DTs can improve data management and provide better decision making during emergency evacuations, reflecting the crucial role of DTs in managing complex data streams and enhancing the quality of decisions.

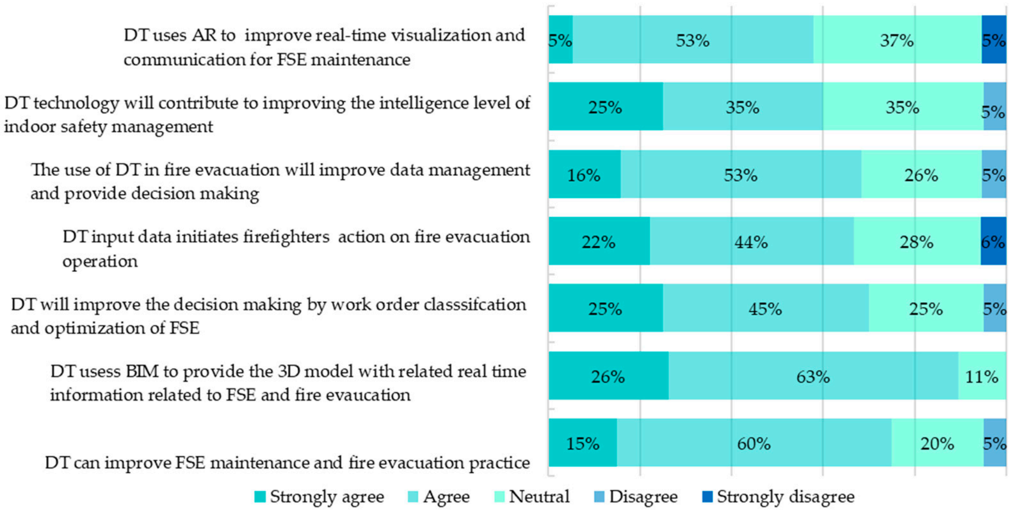

Figure 17. Evaluating DT technologies in FSE and fire evacuations.

DTs' role in providing actionable insights to first responders is evident by the positive reception of DT input data initiating firefighters' actions during fire evacuation operations, with 66% of the respondents agreeing or strongly agreeing. Additionally, 70% of the respondents expressed confidence in DTs' ability to improve decision making through work order classifications and the optimization of FSE, suggesting that DTs can enhance operational efficiency and resource allocation.

The integration of BIM into the DT system can provide 3D models enriched with real-time information for FSE, and fire evacuation is the most strongly supported use case, with 89% of the respondents agreeing or strongly agreeing. This reflects a broad consensus on the value of combining BIM with DTs to create dynamic, informative models that can significantly impact FSE and evacuation planning.

The data indicate that 75% of the respondents believe in DTs' potential to improve FSE maintenance and fire evacuation practices, indicating a strong belief in DTs' overall benefits for fire safety and evacuation. While there may be reservations or a need for more evidence of DTs' effectiveness, the analysis suggests that DT technology holds considerable promise for revolutionizing FSE and fire evacuation practices. The data reflect a forward-looking stance within the industry, with professionals willing to embrace DTs' advanced capabilities for better safety outcomes.

In Figure 18, the participants were asked to evaluate the clarity and data security of the proposed DT framework for fire evacuation planning and FSE maintenance. Based on a Likert scale, the results revealed that 76% of the respondents agreed or strongly agreed that the proposed DT framework clearly described the potential use of fire evacuation planning and the FSE of facilities based on DT applications. Additionally, 24% of the participants remained neutral, while no participants disagreed or strongly disagreed. Regarding data workflow security in the proposed DT framework, 58% of the respondents agreed or strongly agreed that the data workflow is secure. Meanwhile, 33% remained neutral, and only 9% disagreed or strongly disagreed with this statement. This indicates that the majority of the participants found the proposed DT framework clear and secure in the context of facility fire evacuations and FSE maintenance.

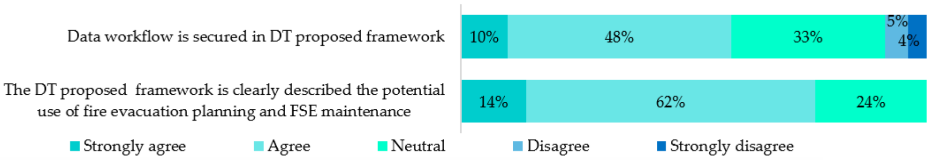

Figure 18. Participants' evaluation of proposed DT framework in FM.

5. Discussion

This section provides a detailed overview of the current implementation status of DTs in the FM industry and tries to outline opportunities and challenges for the use of DT technologies in FM practices based on the feedback gathered from current FM practitioners. Introducing the potential uses of DT technologies to current FM practitioners will give them a chance to consider the idea of adopting DT technologies to reduce errors resulting from the lack of integration between fire safety systems and BIM in real time and to enhance real-time information guidance during fire evacuations. In this section, we focused on the challenges that prevent the adoption of DTs in the FM industry. As introduced previously, DT technologies provide a solution for the current system that improves upon current FM practices. Moreover, each type of DT technology has the potential to play a significant role in improving FSE maintenance and fire evacuations. Therefore, the questionnaires were designed to investigate the potential use of each type of DT technology in FM departments' daily work to discover their needs, along with the possibility of improving decision making. The lack of integration between systems and missing information and communication have shown how DT can help FM managers make the right decision, as shown by the survey results. A total of 90% of respondents agreed that DT technologies improved decision making. As the responses supported the application of DTs in the FM industry, we need to discuss the challenges that may slow the implementation of DTs in FSE maintenance and fire evacuations.

5.1. Main Challenges

The extracted barriers from the literature review were sent to professionals in the FM industry to scale the barriers from practitioners' perspectives. Figure 19 highlights the findings from FM professionals in the industry and represents the lack of DT knowledge as the most significant barrier, cited by 15% of the respondents on DT adoption from industry perspectives. Following this, initial costs and user acceptance emerge as subsequent concerns. At the same time, difficulties in data management and data security trust are perceived as the least significant, each accounting for 8% of the responses.

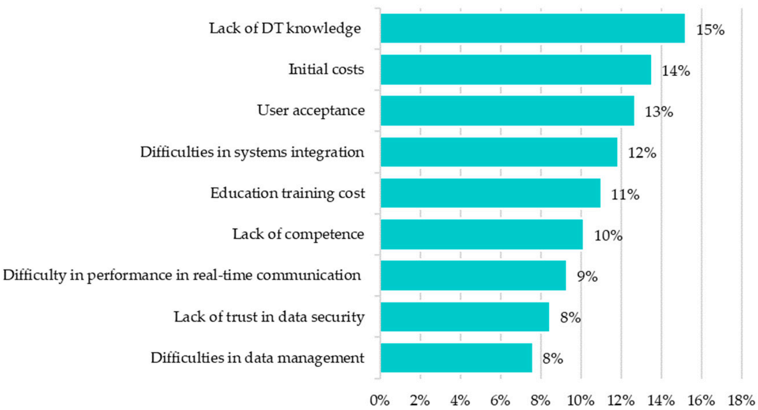

Figure 19. Challenges of adopting DTs in FSE maintenance and fire evacuations.

The barriers to adopting DTs in FSM are identified and presented in Table 4. These barriers have been grouped into three categories, namely stakeholder-oriented, economic, and technical barriers. This categorization has been made to provide better clarity and simplify the understanding of the barriers identified through the survey.

Table 4. Classification of adopting DT barriers in FSE maintenance and fire evacuations.

Category	Barriers
Stakeholder-oriented barriers	Lack of DT knowledge Lack of competence User acceptance
Economic barriers	Initial costs Education training costs
Technical barriers	Difficulties in systems integration Difficulty in performance in real-time communication Lack of trust in data security Difficulties in data management

5.1.1. Stakeholder-Oriented Barriers

The adoption and application of DT technology in the FM industry are heavily reliant on the industry's stakeholders. In order to achieve effective implementation, it is imperative that stakeholders possess a comprehensive knowledge of the DT concept. Nevertheless, the DT concept is subject to ambiguity, as stakeholders and professionals hold divergent perspectives on its effectiveness in the context of buildings and FM. This ambiguity with the DT concept has been recognized by several studies [138–140]. There are several obstacles that impede the adoption of DTs in FM, as shown in Figure 19. The first highest barrier to adopting DTs encompasses a lack of DT knowledge, representing 15% of the participants. This highlights the need for further education and awareness initiatives to disseminate knowledge about DTs and their potential applications in FM. These findings also agree with prominent gaps found by several studies [127,129,141]. The authors of [128] highlighted a lack of educational programs at universities that especially focus on addressing DTs. They argue that this lack of education negatively affects organizations' capacity to make appropriate decisions regarding the implementation of DTs. Furthermore, there are misconceptions about how advanced technologies such as DTs, BIM, blockchain, and similar innovations can be used to address problems in the industry, and this causes a lack of DT knowledge [142]. Some studies just use BIM models with integrated IoT data to represent a DT, with no bidirectional communication between the real and virtual layers. This further proves the lack of knowledge of the DT concept [129]. This barrier causes a lack of competence that prevents the adoption of emerging digital twins, such as DTs in FM, which represents 10% of the participants. Saporiti et al. [143] emphasize the need to address the lack of competence to implement DTs, and this challenge varies by organization and environment. The issue is underrepresented in the literature despite its criticality. To address this, FM professionals should receive targeted training to improve their skills. This is essential for FM–DT integration, which is considered an issue in technical barriers. However, a lack of knowledge and understanding of DT technology causes resistance to its acceptance and adoption [134,144]. This barrier is confirmed in the findings since user acceptance represents 13% of the participants, and this suggests that organizations should invest in comprehensive training programs to enhance the understanding and acceptance of this technology among their staff. Since users play a pivotal role in driving technology's progress and adoption, their acceptance of DT technology is crucial for an organization's decision to adopt it [144].

5.1.2. Economic Barriers

The second highest barrier to adopting DTs is their initial cost, with 14% of the respondents, indicating that organizations may need to explore various funding options and develop cost-effective strategies to implement DT technology successfully. These findings also agree with prominent gaps found by several studies stating that high-cost implementation causes a major challenge to DT adoption [129,143,145].

The implementation of DT systems requires the acquisition of costly sensors, software modules, and data acquisition and storage systems, owing to the large volume of data and complex processes involved [128,146–148]. The education training cost is another challenge of DT technology's adoption, which totals 11% of the participants. The budget is an essential factor in the FM industry, which needs to plan ahead or DT. Dixit et al. [98] stated that it is very important to prepare a sufficient amount of time and human resources to train employees to use this technology and suggested that adopting this technology would help solve education and training cost issues in the long term.

5.1.3. Technical Barriers

The final category of barriers to adopting DTs in the FM industry is technical barriers. This category includes difficulties in systems integration, performance in real-time communication, data management, and the lack of trust in data security. Difficulties in systems integration are another challenge of DT technology's adoption, which is cited by 12% of the participants. Lu et al. [48] stated that data interoperability causes difficulties in system integration because these systems may use different data formats, structures, or standards, making it challenging to exchange and integrate data seamlessly. Moreover, safety management systems are often independent and not fully integrated with building information. This lack of integration hinders the comprehensive analysis of safety information and the automatic processing of danger [21]. Difficulty in performance in real-time communication is another challenge of technical barriers, representing 9% of the participants. This challenge arises due to limitations in hardware and software resources that affect the efficient data flow between the two systems [128]. The difficulty in achieving efficient real-time communication is a significant challenge in adopting DT technology in the FM industry. DT technology relies on bidirectional mapping and real-time data interaction between physical entities and their digital models [149]. This real-time communication is crucial for monitoring and simulating the performance of facilities in real time. However, DT technology has the potential to revolutionize fire safety management by enabling real-time dynamic planning and risk management. For example, a DT model can be developed to simulate fire safety evacuations and dynamically plan evacuation routes based on the fire's development [130,131]. This allows for more effective and efficient evacuation strategies. The lack of trust in data security presents a significant barrier to adopting DT technology for 8% of the participants. Concerns about data privacy, integrity, and unauthorized access have become paramount [138]. The implementation of DT involves collecting and analyzing vast amounts of data, making it crucial to establish robust security measures to protect sensitive information. Blockchain technology offers a potential solution to address the lack of security data by ensuring information security through encryption [112]. By using blockchain, stakeholders can securely access, process, and share quality information, inspection records, and safety information [150]. Integrating blockchain with advanced sensing technologies, such as reality capture and the IoT, can further enhance data security [110]. Difficulties in data management are another barrier, which represents 8% of the participants. In FSM, data management plays a crucial role in the effectiveness of DT applications. Fire safety data, such as sensor readings, building information, and evacuation plans, must be collected, stored, and analyzed in real time to enable dynamic decision making [151]. However, the complexity and volume of data generated in fire safety scenarios pose challenges in terms of data storage, processing, and analysis [151]. Advancements in data management technologies are necessary to address these challenges. This includes the development of data standardization protocols, interoperability frameworks, and efficient data storage and processing systems [152–155]. Additionally, the integration of AI and ML techniques can enhance data management capabilities by automating data analyses and decision-making processes [151].

From technical barriers, the integration of DT technologies in FM is a crucial area for future research. As emphasized in the proposed framework, while we demonstrate the potential of integrating current technologies like BIM and the IoT for FSM, we acknowledge the complexity and challenges accompanying such an integration. Supporting this viewpoint, Hakimi et al. [94] state that the challenges of DT implementation include the integration of physical entities with the BIM model, interoperability issues, and managing big data throughout a facility's lifecycle. These aspects are critical and must be the subject of thorough investigation in future studies. Our framework aims to lay a foundation for this ongoing research, highlighting areas that require further exploration and development to realize the potential of DTs in FM fully.

The survey focused on the potential benefits of using DTs and related technologies; we gathered perspectives primarily from FM sector professionals. Recognizing the limitations of this approach, we propose an expanded scope for future research. This research will use a Delphi method to conduct a more robust study of DTs' benefits for the FM sector. It will include a panel of diverse professionals—not only FM experts but also IT specialists, architects, building designers, and other relevant stakeholders. These professionals provide the data necessary to implement DT effectively, as outlined in our proposed framework. By engaging a broader spectrum of expertise, we aim to gain a comprehensive understanding of the practical aspects of technology integration and its multidisciplinary implications, thereby enriching the depth and applicability of our research.

To sum up, the findings from our literature review and survey results offer insights into the perceived barriers to DT technology's adoption in FSM. Both identify 'difficulties in systems integration' and the 'lack of DT knowledge' as significant obstacles, though they differ in priority; the former is most emphasized in the literature, while the latter is highlighted in survey responses. 'Initial costs' also appear as a common concern in both sources.

Significant differences emerge in the emphasis on 'user acceptance' and 'education training cost,' which are more pronounced in the survey results, reflecting the practical concerns of those in the field. Conversely, the literature review places a greater weight on the 'lack of trust in data security' and 'difficulty in performance in real-time communication,' suggesting an academic focus on DT systems' technical and security aspects.

While there is concordance on certain barriers, our literature review leans towards the technical and theoretical, whereas our survey responses lean towards practical implementation and operational concerns.

6. Conclusions

This paper aims to investigate the impact of DTs in FM, provide an overview of the DT concept, and briefly identify potential application areas and requirements for DTs in FSM. Our research began by conducting a literature review on current FM practices and the potential use of DT applications in FSM. The review revealed that various DT technologies, including BIM, the IoT, AI, and AR, have unique characteristics that can be useful in FSE maintenance and fire emergency responses. A framework was proposed to explore further the potential use of DT technologies in FM and the integration of these technologies with current FSM systems. The framework highlighted the potential benefits of adopting DT technologies in terms of improved FSM performance and efficiency. However, our research also identified several barriers to adopting DTs in FM through a survey conducted at the FM of Western Michigan University and the IFMA organization. The survey involved facility managers and engineers, who provided feedback on the potential adoption of DT technology in FSM, its impact on FSM performance, and the associated challenges. The survey findings indicated that the respondents agreed with the potential adoption of DT technology in future FM practices. However, they also identified several barriers to its adoption, grouped into thematic categories such as stakeholder-oriented, economic, and technical barriers. These barriers included a lack of DT knowledge, initial costs, user acceptance, difficulties in systems integration, education and training costs, a lack of competence, development complexity, difficulties in data management, and a lack of trust in data security. Although there is agreement on some obstacles, the research papers tend to focus more on technical and theoretical barriers, while the feedback obtained from surveys highlights practical implementation and operational issues. Despite some progress in adopting DT solutions in FSM, our survey results suggest that much work is still needed to integrate this technology fully into the FM industry. Our paper emphasizes that the overall success of DT implementation in FM will require collaboration among the government, industry, academia, and society. This collaboration will facilitate the process of industry standardization and simplify the adoption of DT technologies in FM. This paper provides valuable insights into the potential impact of DT technologies in FM and highlights the barriers that need to be addressed for their successful adoption.

Author Contributions: Conceptualization, M.A. and H.L.; methodology, M.A. and H.L.; software, M.A.; validation, M.A., H.L. and O.A.; formal analysis, M.A.; investigation, M.A.; resources, M.A.; data curation, M.A.; writing—original draft preparation, M.A.; writing—review and editing, M.A., H.L., O.A., O.H. and M.S.; visualization, M.A.; supervision, H.L. and O.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy protection of de-identified individual data, as per WMU IRB guidelines.

References

1. US Fire Administration. U.S. Fire Statistics. Available online: https://www.usfa.fema.gov/statistics/ (accessed on 9 November 2022).
2. Deak, G.; Curran, K.; Condell, J. A survey of active and passive indoor localisation systems. *Comput. Commun.* **2012**, *35*, 1939–1954. [CrossRef]
3. Kobes, M.; Helsloot, I.; De Vries, B.; Post, J.G. Building safety and human behaviour in fire: A literature review. *Fire Saf. J.* **2010**, *45*, 1–11. [CrossRef]
4. Zhang, J.; Guo, J.; Xiong, H.; Liu, X.; Zhang, D. A Framework for an Intelligent and Personalized Fire Evacuation Management System. *Sensors* **2019**, *19*, 3128. [CrossRef] [PubMed]
5. Rubadiri, L.; Ndumu, D.T.; Roberts, J.P. Predicting the evacuation capability of mobility-impaired occupants. *Fire Technol.* **1997**, *33*, 32–53. [CrossRef]
6. Binalhaj, M.; Liu, H.; Sulaiman, M.; Abudayyeh, O. Mobile crowdsourcing-based data collection for user-centered facility maintenance management. *Can. J. Civ. Eng.* **2021**, *48*, 1652–1662. [CrossRef]
7. Chen, W.; Chen, K.; Cheng, J.C.; Wang, Q.; Gan, V.J. BIM-based framework for automatic scheduling of facility maintenance work orders. *Autom. Constr.* **2018**, *91*, 15–30. [CrossRef]
8. Chen, Y.-J.; Lai, Y.-S.; Lin, Y.-H. BIM-based augmented reality inspection and maintenance of fire safety equipment. *Autom. Constr.* **2020**, *110*, 103341. [CrossRef]
9. Chen, H.; Hou, L.; Zhang, G.; Moon, S. Development of BIM, IoT and AR/VR Technologies for Fire Safety and Upskilling. *Autom. Constr.* **2021**, *125*, 103631. [CrossRef]
10. Sulaiman, M.; Liu, H.; Binalhaj, M.; Liou, W.W.; Abudayyeh, O. GIS-Based Automatic Flight Planning of Camera-Equipped UAVs for Fire Emergency Response. In Proceedings of the IEEE International Conference on Electro Information Technology 2020, Chicago, IL, USA, 31 July–1 August 2020. [CrossRef]
11. Kanangkaew, S.; Jokkaw, N.; Tongthong, T. A real-time fire evacuation system based on the integration of building information modeling and augmented reality. *J. Build. Eng.* **2023**, *67*, 105883. [CrossRef]
12. Adjiski, V.; Despodov, Z.; Mirakovski, D.; Mijalkovski, S. Fire risk assessment and computer simulation of fire scenario in underground mines. *Stud. Eng. Technol.* **2015**, *2*, 54. [CrossRef]
13. Wang, B.; Li, H.; Rezgui, Y.; Bradley, A.; Ong, H.N. BIM based virtual environment for fire emergency evacuation. *Sci. World J.* **2014**, *2014*, 589016. [CrossRef] [PubMed]

14. Fahy, R.F.; Proulx, G. Toward Creating a Database on Delay Times to Start Evacuation and Walking Speeds for Use in Evacuation Modeling. In Proceedings of the 2nd International Symposium on Human Behaviour in Fire, Boston, MA, USA, 26–28 March 2001; pp. 175–183.
15. Alsharari, H.; Liou, W.W.; Abudayyeh, O. An Immersive Environment for Building Fire Safety Training. In Proceedings of the CSCE Annual Conference "Growing with youth", Montreal, QC, Canada, 12–15 June 2019.
16. Chen, X.-S.; Liu, C.-C.; Wu, I.-C. A BIM-based visualization and warning system for fire rescue. Adv. *Eng. Inform.* **2018**, *37*, 42–53. [CrossRef]
17. Li, N.; Yang, Z.; Ghahramani, A.; Becerik-Gerber, B.; Soibelman, L. Situational awareness for supporting building fire emergency response: Information needs, information sources and implementation requirements. *Fire Saf. J.* **2014**, *63*, 17–28. [CrossRef]
18. Groner, N.; Jennings, C.; Robinson, A. A Negotiated-Text Method for Assessing Situation Awareness Information Requirements from Emergency Responders. In Proceedings of the 2012 IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support, New Orleans, LA, USA, 6–8 March 2012; IEEE: Piscataway, NJ, USA, 2012; pp. 259–263. [CrossRef]
19. Lurz, F.; Mueller, S.; Lindner, S.; Linz, S.; Gardill, M.; Weigel, R.; Koelpin, A. Smart Communication and Relative Localization System for Firefighters and Rescuers. In Proceedings of the IEEE MTT-S International Microwave Symposium (IMS), Honolulo, HI, USA, 4–9 June 2017. [CrossRef]
20. Harris, M. The Way through the Flames. *IEEE Spectr.* **2013**, *50*, 30–35. [CrossRef]
21. Liu, Z.; Zhang, A.; Wang, W. A framework for an indoor safety management system based on digital twin. *Sensors* **2020**, *20*, 5771. [CrossRef]
22. Khajavi, S.H.; Tetik, M.; Liu, Z.; Korhonen, P.; Holmstrom, J. Digital twin for safety and security: Perspectives on building lifecycle. *IEEE Access* **2023**, *11*, 52339–52356. [CrossRef]
23. Jiang, L.; Shi, J.; Wang, C.; Pan, Z. Intelligent control of building fire protection system using digital twins and semantic web technologies. *Autom. Constr.* **2023**, *147*, 104728. [CrossRef]
24. Zhang, T.; Wang, Z.; Zeng, Y.; Wu, X.; Huang, X. Building artificial-intelligence digital fire (AID-Fire) system: A real-scale demonstration. *J. Build. Eng.* **2022**, *62*, 105363. [CrossRef]
25. Cheng, M.-Y.; Chiu, K.-C.; Hsieh, Y.-M.; Yang, I.T.; Chou, J.-S.; Wu, Y.-W. BIM integrated smart monitoring technique for building fire prevention and disaster relief. *Autom. Constr.* **2017**, *84*, 14–30. [CrossRef]
26. Choi, J.; Choi, J.; Kim, I. Development of BIM-based evacuation regulation checking system for high-rise and complex buildings. *Autom. Constr.* **2014**, *46*, 38–49. [CrossRef]
27. Wehbe, R.; Shahrour, I. A BIM-based smart system for fire evacuation. *Future Internet* **2021**, *13*, 221. [CrossRef]
28. Lewis, A.; Riley, D.; Elmualim, A. Defining high performance buildings for operations and maintenance. *Int. J. Facil. Manag.* **2010**, *1*, 1–16.
29. Alkasisbeh, M.R.; Abudayyeh, O. Building Asset Management System: A Performance Evaluation Approach. In Proceedings of the 2018 IISE Annual Conference, Orlando, FL, USA,, 19–22 May 2018; pp. 2175–2180.
30. Al-Kasisbeh, M.R.; Abudayyeh, O. Municipality Asset Management: Asset Types and Effective Management Decision Using GIS. In Proceedings of the Construction Research Congress 2018, New Orleans, LA, USA, 2–4 April 2018; pp. 273–280.
31. Al-Kasasbeh, M.; Abudayyeh, O.; Liu, H. An integrated decision support system for building asset management based on BIM and Work Breakdown Structure. *J. Build. Eng.* **2021**, *34*, 101959. [CrossRef]
32. Al-Kasasbeh, M.; Abudayyeh, O.; Liu, H. A Unified Work Breakdown Structure-Based Framework for Building Asset Management. *J. Facil. Manag.* **2020**, *18*, 437–450. [CrossRef]
33. Shalabi, F.; Turkan, Y. IFC BIM-based facility management approach to optimize data collection for corrective maintenance. *J. Perform. Constr. Facil.* **2016**, *31*, 04016081. [CrossRef]
34. Wong, J.K.W.; Ge, J.; He, S.X. Digitisation in facilities management: A literature review and future research directions. *Autom. Constr.* **2018**, *92*, 312–326. [CrossRef]
35. Parsanezhad, P.; Dimyadi, J. Effective Facility Management and Operations via a BIM-Based Integrated Information System. In Proceedings of the CIB Facilities Management (CFM) 2014 Conference, Copenhagen, Denmark, 21–23 May 2014; p. 8. Available online: http://www.cfm.dtu.dk/english/CIB-Conference (accessed on 10 November 2016).
36. Sapp, D. Facilities Operations & Maintenance—An Overview. 2017. Available online: https://www.wbdg.org/facilities-operations-maintenance (accessed on 3 November 2022).
37. Villa, V.; Naticchia, B.; Bruno, G.; Aliev, K.; Piantanida, P.; Antonelli, D. Iot Open-Source Architecture for the Maintenance of Building Facilities. *Appl. Sci.* **2021**, *11*, 5374. [CrossRef]
38. Oti, A.; Kurul, E.; Cheung, F.; Tah, J. The utilization of BMS in BIM for facility management. In Proceedings of the CIB World Building Congress, Tampere, Finland, 30 May–3 June 2016. [CrossRef]
39. Yang, R.; Wang, L. Multi-objective optimization for decision-making of energy and comfort management in building automation and control. *Sustain. Cities Soc.* **2012**, *2*, 1–7. [CrossRef]
40. Zhou, X.; Li, H.; Wang, J.; Zhao, J.; Xie, Q.; Li, L.; Liu, J.; Yu, J. CloudFAS: Cloud-based building fire alarm system using Building Information Modelling. *J. Build. Eng.* **2022**, *53*, 104571. [CrossRef]
41. Motamedi, A.; Hammad, A.; Asen, Y. Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management. *Autom. Constr.* **2014**, *43*, 73–83. [CrossRef]

42. Hsu, H.P.; Yu, K.M.; Chine, S.T.; Cheng, S.T.; Lei, M.Y.; Tsai, N. Emergency evacuation base on intelligent digital signage systems. In Proceedings of the 2014 7th International Conference on Ubi-Media Computing and Workshops, Ulaanbaatar, Mongolia, 12–14 July 2014; pp. 243–247. [CrossRef]
43. Sulaiman, M.; Liu, H.; Binalhaj, M.; Al-Kasasbeh, M.; Abudayyeh, O. ICT-based integrated framework for smart facility management: An industry perspective. *J. Facil. Manag.* **2021**, *19*, 652–680. [CrossRef]
44. Sulaiman, M.; Liu, H.; Bin Alhaj, M.; Abudayyeh, O. UAV Applications in the AEC/FM Industry: A Review. In *Canadian Society of Civil Engineering Annual Conference*; Springer: Singapore, 2021; pp. 249–259.
45. Bin Alhaj, M.; Liu, H.; Abudayyeh, O.; Sulaiman, M. Development of a Mobile Application for Occupant-Centric Facility Maintenance Management. In Proceedings of the 2022 IEEE World AI IoT Congress, AIIoT 2022, Seattle, WA, USA, 6–9 June 2022; pp. 323–329. [CrossRef]
46. Liu, M.; Fang, S.; Dong, H.; Xu, C. Review of digital twin about concepts, technologies, and industrial applications. *J. Manuf. Syst.* **2020**, *58*, 346–361. [CrossRef]
47. Grieves, M.; Vickers, J. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In *Transdisciplinary Perspectives on Complex Systems*; Springer: Cham, Switzerland, 2016; pp. 85–113. [CrossRef]
48. Lu, Q.; Parlikad, A.K.; Woodall, P.; Don Ranasinghe, G.; Xie, X.; Liang, Z.; Konstantinou, E.; Heaton, J.; Schooling, J. Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus. *J. Manag. Eng.* **2020**, *36*, 05020004. [CrossRef]
49. National Institute Building Sciences National BIM Guide for Owners. *Nibs* **2017**, *38*, 1–37. Available online: https://www.nibs.org/files/pdfs/NIBS_BIMC_NationalBIMGuide.pdf (accessed on 3 November 2022).
50. Mousharbash, N.; Carbonari, A.; Giretti, A.; Turk, Ž. Current Research, Trends, and Challenges in Building Emergency Management. In Proceedings of the 2022 European Conference on Computing in Construction, Ixia, Rhodes, Greece, 24–26 July 2022. [CrossRef]
51. Shokouhi, M.; Nasiriani, K.; Cheraghi, Z.; Ardalan, A.; Khankeh, H.; Fallahzadeh, H. Preventive measures for fire-related injuries and their risk factors in residential buildings: A systematic review. *J. Inj. Violence Res.* **2019**, *11*, 1–14. [CrossRef] [PubMed]
52. Sabbaghzadeh, M.; Sheikhkhoshkar, M.; Talebi, S.; Rezazadeh, M.; Rastegar Moghaddam, M.; Khanzadi, M. A BIM-Based Solution for the Optimisation of Fire Safety Measures in the Building Design. *Sustainability* **2022**, *14*, 1626. [CrossRef]
53. Yang, Y.; Sun, Y.; Chen, M.; Zhou, Y.; Wang, R.; Liu, Z. Platform development of BIM-based fire safety management system considering the construction site. *Buildings* **2022**, *8*, 1268. [CrossRef]
54. Wang, S.-H.; Wang, W.-C.; Wang, K.-C.; Shih, S.-Y. Applying building information modeling to support fire safety management. *Autom. Constr.* **2015**, *59*, 158–167. [CrossRef]
55. Ma, G.; Wu, Z. BIM-based building fire emergency management: Combining building users' behavior decisions. *Autom. Constr.* **2020**, *109*, 102975. [CrossRef]
56. Tang, S.; Shelden, D.R.; Eastman, C.M.; Pishdad-Bozorgi, P.; Gao, X. A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Autom. Constr.* **2019**, *101*, 127–139. [CrossRef]
57. Asghari, P.; Rahmani, A.M.; Javadi, H.H.S. Internet of Things applications: A systematic review. *Comput. Netw.* **2019**, *148*, 241–261. [CrossRef]
58. Li, N.; Becerik-Gerber, B.; Krishnamachari, B.; Soibelman, L. A BIM Centered Indoor Localization Algorithm to Support Building Fire Emergency Response Operations. *Autom. Constr.* **2014**, *42*, 78–89. [CrossRef]
59. Cho, J.; Lee, G.; Lee, S. An automated direction setting algorithm for a smart exit sign. *Autom. Constr.* **2015**, *59*, 139–148. [CrossRef]
60. Chen, A.Y.; Chu, J.C. TDVRP and BIM integrated approach for in-building emergency rescue routing. *J. Comput. Civ. Eng.* **2016**, *30*, C4015003. [CrossRef]
61. Eftekharirad, R.; Nik-Bakht, M.; Hammad, A. Extending IFC for Fire Emergency Real-Time Management Using Sensors and Occupant Information. In Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC 2018), Berlin, Germany, 20–25 July 2018; pp. 985–992. [CrossRef]
62. Cheung, W.F.; Lin, T.H.; Lin, Y.C. A real-time construction safety monitoring system for hazardous gas integrating wireless sensor network and building information modeling technologies. *Sensors* **2018**, *18*, 436. [CrossRef]
63. McCarthy, J. The inversion of functions defined by turing machines. In *Automata Studies. (AM-34)*; Shannon, C.E., McCarthy, J., Eds.; Annals of Mathematical Studies; Princeton University Press: Princeton, NJ, USA, 1956; Volume 34, pp. 177–181.
64. Darko, A.; Chan, A.P.C.; Adabre, M.A.; Edwards, D.J.; Hosseini, M.R.; Ameyaw, E.E. Artificial intelligence in the AEC industry: Scientometric analysis and visualization of research activities. *Autom. Constr.* **2020**, *112*, 103081. [CrossRef]
65. Naser, M.Z. Mechanistically informed machine learning and artificial intelligence in fire engineering and sciences. *Fire Technol.* **2021**, *57*, 2741–2784. [CrossRef]
66. Huang, X.; Wu, X.; Usmani, A. Perspectives of using artificial intelligence in building fire safety. In *Handbook of Cognitive and Autonomous Systems for Fire Resilient Infrastructures*; Naser, M.Z., Corbett, G., Eds.; Springer: New York, NY, USA, 2022; Volume 34, pp. 139–159.
67. Lee, E.W.M.; Yuen, R.K.K.; Lo, S.M.; Lam, K.C.; Yeoh, G.H. A novel artificial neural network fire model for prediction of thermal interface location in single compartment fire. *Fire Saf. J.* **2004**, *39*, 67–87. [CrossRef]
68. Wang, Z.; Zhang, T.; Wu, X.; Huang, X. Predicting transient building fire based on external smoke images and deep learning. *J. Build. Eng.* **2022**, *47*, 103823. [CrossRef]

69. Wang, Z.; Zhang, T.; Huang, X. Predicting real-time fire heat release rate by flame images and deep learning. *Proc. Combust. Inst.* **2023**, *39*, 4115–4123. [CrossRef]
70. Wang, J.; Tam, W.C.; Jia, Y.; Peacock, R.; Reneke, P.; Fu, E.Y.; Cleary, T. P-flash–a machine learning-based model for flashover prediction using recovered temperature data. *Fire Saf. J.* **2021**, *122*, 103341. [CrossRef] [PubMed]
71. Kou, L.; Wang, X.; Guo, X.; Zhu, J.; Zhang, H. Deep learning based inverse model for building fire source location and intensity estimation. *Fire Saf. J.* **2021**, *121*, 103310. [CrossRef]
72. Wu, X.; Park, Y.; Li, A.; Huang, X.; Xiao, F.; Usmani, A. smart detection of fire source in tunnel based on the numerical database and artificial intelligence. *Fire Technol.* **2021**, *57*, 657–682. [CrossRef]
73. Davila Delgado, J.M.; Oyedele, L.; Beach, T.; Demian, P. Augmented and virtual reality in construction: Drivers and limitations for industry adoption. *J. Constr. Eng. Manag.* **2020**, *146*, 04020079. [CrossRef]
74. Volk, R.; Stengel, J.; Schultmann, F. Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Autom. Constr.* **2014**, *38*, 109–127. [CrossRef]
75. Chen, K.; Chen, W.; Li, C.T.; Cheng, J.C.P. A BIM-based location aware AR collaborative framework for facility maintenance management. *J. Inf. Technol. Constr.* **2019**, *24*, 360–380.
76. Hou, L.; Wang, Y.; Wang, X.; Maynard, N.; Cameron, I.; Zhang, S.; Maynard, Y. Combining photogrammetry and augmented reality towards an integrated facility management system for the oil industry. *Proc. IEEE* **2014**, *102*, 204–220. [CrossRef]
77. Attaran, M.; Celik, B.G. Digital twin: Benefits, use cases, challenges, and opportunities. *Decis. Anal. J.* **2023**, *6*, 100165. [CrossRef]
78. Pan, Y.; Zhang, L. Roles of artificial intelligence in construction engineering and management: A critical review and future trends. *Autom. Constr.* **2020**, *122*, 103517. [CrossRef]
79. Song, Y.; Li, Y. Digital Twin Aided Healthcare Facility Management: A Case Study of Shanghai Tongji Hospital. In *Construction Research Congress 2022*; American Society of Civil Engineers (ASCE): Reston, VA, USA, 2022; pp. 1145–1155.
80. Peng, Y.; Zhang, M.; Yu, F.; Xu, J.; Gao, S. Digital Twin hospital buildings: An exemplary case study through continuous lifecycle integration. *Adv. Civ. Eng.* **2020**, *2020*, 8846667. [CrossRef]
81. Hosamo, H.H.; Nielsen, H.K.; Kraniotis, D.; Svennevig, P.R.; Svidt, K. Digital Twin framework for automated fault source detection and prediction for comfort performance evaluation of existing non-residential Norwegian buildings. *Energy Build.* **2023**, *281*, 112732. [CrossRef]
82. Jafari, M.A.; Zaidan, E.; Ghofrani, A.; Mahani, K.; Farzan, F. Improving building energy footprint and asset performance using digital twin technology. In Proceedings of the Computing in Civil Engineering 2021, Orlando, FL, USA, 12–14 September 2021.
83. Liu, Y.; Jebelli, H. Developing a Web-Based BIM Asset and Facility Management System of Building Digital Twins. In Proceedings of the Computing in Civil Engineering 2021, Orlando, FL, USA, 12–14 September 2021; pp. 811–818.
84. Moretti, N.; Xie, X.; Garcia, J.M.; Chang, J.; Parlikad, A.K. Federated data modeling for built environment digital twins. *J. Comput. Civ. Eng.* **2023**, *37*, 04023013. [CrossRef]
85. Eneyew, D.D.; Capretz, M.A.M.; Bitsuamlak, G.T. Towards smart building digital twins: BIM and IoT data integration. *IEEE Access* **2022**, *10*, 130487–130506. [CrossRef]
86. Agapaki, E.; Brilakis, I. CLOI: An Automated Benchmark Framework for Generating Geometric Digital Twins of Industrial Facilities. *J. Constr. Eng. Manag.* **2021**, *147*, 0002171. [CrossRef]
87. Cheng, J.C.P.; Chen, W.; Chen, K.; Wang, Q. Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. *Autom. Constr.* **2020**, *112*, 103087. [CrossRef]
88. Hosamo, H.H.; Svennevig, P.R.; Svidt, K.; Han, D.; Nielsen, H.K. A Digital Twin predictive maintenance framework of air handling units based on automatic fault detection and diagnostics. *Energy Build.* **2022**, *261*, 111988. [CrossRef]
89. Seghezzi, E.; Locatelli, M.; Pellegrini, L.; Pattini, G.; Giuda, G.M.D.; Tagliabue, L.C.; Boella, G. Towards an occupancy-oriented digital twin for facility management: Test campaign and sensors assessment. *Appl. Sci.* **2021**, *11*, 3108. [CrossRef]
90. Madubuike, O.C.; Anumba, C.J. Digital Twin–based health care facilities management. *J. Comput. Civ. Eng.* **2023**, *37*, 04022057. [CrossRef]
91. Ding, Y.; Zhang, Y.; Huang, X. Intelligent emergency digital twin system for monitoring building fire evacuation. *J. Build. Eng.* **2023**, *77*, 107416. [CrossRef]
92. Almatared, M.; Liu, H.X.; Tang, S.X.; Sulaiman, M.; Lei, Z.; Li, H.X. Digital Twin in the Architecture, Engineering, and Construction Industry: A Bibliometric Review. In Proceedings of the Construction Research Congress 2022: Computer Applications, Automation, and Data Analytics, Arlington, VA, USA, 9–12 March 2022; pp. 670–678. [CrossRef]
93. Siccardi, S.; Villa, V. Trends in Adopting BIM, IoT and DT for Facility Management: A Scientometric Analysis and Keyword Co-Occurrence Network Review. *Buildings* **2022**, *13*, 15. [CrossRef]
94. Hakimi, O.; Liu, H.; Abudayyeh, O. Digital twin-enabled smart facility management: A bibliometric review. *Front. Eng. Manag.* **2023**, 1–18. [CrossRef]
95. Liu, H.; Abudayyeh, O.; Liou, W. BIM-Based Smart Facility Management: A Review of Present Research Status, Challenges, and Future Needs. In Proceedings of the Construction Research Congress 2020, American Society of Civil Engineers, Tempe, AZ, USA, 8–10 March 2020; pp. 1087–1095.
96. Olimat, H.; Liu, H.; Abudayyeh, O. Enabling technologies and recent advancements of smart facility management. *Buildings* **2023**, *13*, 1488. [CrossRef]

97. Liu, R.; Issa, R. Survey: Common knowledge in BIM for facility maintenance. *J. Perform. Constr. Facil.* **2015**, *30*, 04015033. [CrossRef]
98. Dixit, M.K.; Venkatraj, V.; Ostadalimakhmalbaf, M.; Pariafsai, F.; Lavy, S. Integration of facility management and building information modeling (BIM): A review of key issues and challenges. *Facilities* **2019**, *37*, 455–483. [CrossRef]
99. Meng, X.; Minogue, M. Performance measurement models in facility management: A comparative study. *Facilities* **2011**, *29*, 472–484. [CrossRef]
100. Hakimi, O.; Liu, H.; Abudayyeh, O.; Houshyar, A.; Almatared, M.; Alhawiti, A. Data fusion for smart civil infrastructure management: A conceptual digital twin framework. *Buildings* **2023**, *13*, 2725. [CrossRef]
101. Khallaf, R.; Khallaf, L.; Anumba, C.J.; Madubuike, O.C. Review of Digital Twins for Constructed Facilities. *Buildings* **2022**, *12*, 2029. [CrossRef]
102. Lu, Q.; Xie, X.; Parlikad, A.K.; Schooling, J.M. Digital Twin-Enabled Anomaly Detection for Built Asset Monitoring in Operation and Maintenance. *Autom. Constr.* **2020**, *118*, 103277. [CrossRef]
103. Sadri, H.; Yitmen, I.; Tagliabue, L.C.; Westphal, F.; Tezel, A.; Taheri, A.; Sibenik, G. Integration of blockchain and digital twins in the smart built environment adopting disruptive technologies—A systematic review. *Sustainability* **2023**, *15*, 3713. [CrossRef]
104. Damaševičius, R.; Bacanin, N.; Misra, S. From Sensors to Safety: Internet of Emergency Services (IoES) for Emergency Response and Disaster Management. *J. Sens. Actuator Netw.* **2023**, *12*, 41. [CrossRef]
105. Bhawana; Kumar, S.; Rathore, R.S.; Mahmud, M.; Kaiwartya, O.; Lloret, J. BEST—Blockchain-Enabled Secure and Trusted Public Emergency Services for Smart Cities Environment. *Sensors* **2022**, *22*, 5733. [CrossRef] [PubMed]
106. Bhawana; Kumar, S.; Dohare, U.; Kaiwartya, O. FLAME: Trusted Fire Brigade Service and Insurance Claim System Using Blockchain for Enterprises. *IEEE Trans. Ind. Inform.* **2023**, *19*, 7517–7527. [CrossRef]
107. Choo, K.K.R.; Gai, K.; Chiaraviglio, L. Blockchain-Enabled Secure Communications in Smart Cities. *J. Parallel Distrib. Comput.* **2021**, *152*, 125–127. [CrossRef]
108. Li, D.; Hu, Y.; Lan, M. IoT Device Location Information Storage System Based on Blockchain. *Future Gener. Comput. Syst.* **2020**, *109*, 95–102. [CrossRef]
109. Khana, N.; Leea, D.; Alia, A.K.; Parka, C. Artificial Intelligence and Blockchain-based Inspection Data Recording System for Portable Firefighting Equipment. In Proceedings of the International Symposium on Automation and Robotics in Construction, Kitakyushu, Japan, 27–28 October 2020; pp. 941–947.
110. Liu, H.; Han, S.; Zhu, Z. Blockchain Technology toward Smart Construction: Review and Future Directions. *J. Constr. Eng. Manag.* **2023**, *149*, 03123002. [CrossRef]
111. Zheng, R.; Jiang, J.; Hao, X.; Ren, W.; Xiong, F.; Ren, Y. bcBIM: A blockchain-based big data model for BIM modification audit and provenance in mobile cloud. *Math. Probl. Eng.* **2019**, *2019*, 5349538. [CrossRef]
112. Suliyanti, W.N.; Sari, R.F. Blockchain-based implementation of building information modeling information using hyperledger composer. *Sustainability* **2021**, *13*, 321. [CrossRef]
113. Siountri, K.; Skondras, E.; Vergados, D.D. Towards a Smart Museum Using BIM, IoT, Blockchain and Advanced Digital Technologies. In Proceedings of the ACM International Conference Proceeding Series, Association for Computing Machinery, New York, NY, USA, 26–28 August 2019. [CrossRef]
114. Huang, X.; Liu, Y.; Huang, L.; Onstein, E.; Merschbrock, C. BIM and IoT data fusion: The data process model perspective. *Autom Constr.* **2023**, *149*, 104792. [CrossRef]
115. McArthur, J.J.; Shahbazi, N.; Fok, R.; Raghubar, C.; Bortoluzzi, B.; An, A. Machine learning and BIM visualization for maintenance issue classification and enhanced data collection. *Adv. Eng. Inform.* **2018**, *38*, 101–112. [CrossRef]
116. Raghubar, C.; Shahbazi, N.; Bortoluzzi, B.; An, A.; McArthur, J.J. Integrating Visual Analytics and Machine Learning into BIM-Enabled Facilities Management. In Proceedings of the Joint Conference on Computing in Construction (JC3), Heraklion, Greece, 4–7 July 2017; Volume 1, pp. 113–120. [CrossRef]
117. Wang, C.; Wood, L.C.; Li, H.; Aw, Z.; Keshavarzsaleh, A. Applied Artificial Bee Colony Optimization Algorithm in Fire Evacuation Routing System. *J. Appl. Math.* **2018**, *2018*, 7962952. [CrossRef]
118. Chetehouna, K.; El Tabach, E.; Bouazaoui, L.; Gascoin, N. Predicting the Flame Characteristics and Rate of Spread in Fires Propagating in a Bed of Pinus Pinaster Using Artificial Neural Networks. *Process Saf. Environ. Prot.* **2015**, *98*, 50–56. [CrossRef]
119. Macchi, M.; Roda, I.; Negri, E.; Fumagalli, L. Exploring the role of digital twin for asset lifecycle management. *IFAC-PapersOnLine* **2018**, *51*, 790–795. [CrossRef]
120. Silva, B.N.; Khan, M.; Han, K. Integration of big data analytics embedded smart city architecture with RESTful web of things for efficient service provision and energy management. *Future Gener. Comput. Syst.* **2020**, *107*, 975–987. [CrossRef]
121. Ke, S.; Xiang, F.; Zhang, Z.; Zuo, Y. A enhanced interaction framework based on VR, AR and MR in digital twin. *Procedia CIRP* **2019**, *83*, 753–758. [CrossRef]
122. Yoo, S.J.; Choi, S.H. Indoor AR navigation and emergency evacuation system based on machine learning and IoT technologies. *IEEE Internet Things J.* **2022**, *9*, 20853–20868. [CrossRef]
123. Chen, P.H.; Feng, F. A Fast Flow Control algorithm for real-time emergency evacuation in large indoor areas. *Fire Saf. J.* **2009**, *44*, 732–740. [CrossRef]
124. Tsai, M.K.; Yau, N.J. Enhancing Usability of Augmented-Reality-Based Mobile Escape Guidelines for Radioactive Accidents. *J. Environ. Radioact.* **2013**, *118*, 15–20. [CrossRef]

125. Zhu, Y.; Li, N. Virtual and augmented reality technologies for emergency management in the built environments: A state-of-the-art review. *J. Saf. Sci. Resil.* **2021**, *2*, 1–10. [CrossRef]
126. Cruz, H.; Raheem, A.; Nazarian, S. Computing in Civil Engineering 2021. Proceedings of Computing in Civil Engineering 2020, Digital Twin Technology Applications for Transportation Infrastructure—A Survey-Based Study, Orlando, FL, USA, 12–14 September 2021; pp. 811–818.
127. Perno, M.; Hvam, L.; Haug, A. Enablers and Barriers to the Implementation of Digital Twins in the Process Industry: A Systematic Literature Review. In Proceedings of the 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, 14–17 September 2020; pp. 959–964. [CrossRef]
128. Perno, M.; Hvam, L.; Haug, A. Implementation of digital twins in the process industry: A systematic literature review of enablers and barriers. *Comput. Ind.* **2022**, *134*, 103558. [CrossRef]
129. Opoku, D.G.J.; Perera, S.; Osei-Kyei, R.; Rashidi, M.; Bamdad, K.; Famakinwa, T. Barriers to the adoption of digital twin in the construction industry: A literature review. *Informatics* **2023**, *10*, 14. [CrossRef]
130. Hellenborn, B.; Eliasson, O.; Yitmen, I.; Sadri, H. Asset information requirements for blockchain-based digital twins: A data-driven predictive analytics perspective. *Smart Sustain. Built Environ.* **2023**. [CrossRef]
131. Siebelink, S.; Voordijk, H.; Endedijk, M.; Adriaanse, A. Understanding barriers to bim implementation: Their impact across organizational levels in relation to BIM maturity. *Front. Built Environ.* **2021**, *8*, 236–257. [CrossRef]
132. Mostafa, A.; Alaqeeli, A. Benefits and Challenges of Integrating IoT, VR & AR in the BIM-Based Facility Management Process: Literature and Case-Based Analysis. *J. Eng. Res.* **2022**, *6*, 25–40. [CrossRef]
133. Lu, Q.; Chen, L.; Li, S.; Pitt, M. Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings. *Autom. Constr.* **2020**, *115*, 103183. [CrossRef]
134. Ozturk, G.B. Digital twin research in the AECO-FM industry. *J. Build. Eng.* **2021**, *40*, 102730. [CrossRef]
135. Rasheed, A.; San, O.; Kvamsdal, T. Digital twin: Values, challenges and enablers from a modeling perspective. *IEEE Access* **2020**, *8*, 21980–22012. [CrossRef]
136. Azhar, S. Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadersh. Manag. Eng.* **2011**, *11*, 241–252. [CrossRef]
137. Jiang, A.; Mo, Y.; Kalasapudi, V.S. Status Quo and challenges and future development of fire emergency evacuation research and application in built environment. *J. Inf. Technol. Constr.* **2022**, *27*, 781–801. [CrossRef]
138. Khajavi, S.H.; Motlagh, N.H.; Jaribion, A.; Werner, L.C.; Holmström, J. Digital twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access* **2019**, *7*, 147406–147419. [CrossRef]
139. Sacks, R.; Brilakis, I.; Pikas, E.; Xie, H.S.; Girolami, M. Construction with digital twin information systems. *Data-Centric Eng.* **2020**, *1*, e14. [CrossRef]
140. Opoku, D.-G.J.; Perera, S.; Osei-Kyei, R.; Rashidi, M. Digital twin application in the construction industry: A literature review. *J. Build. Eng.* **2021**, *40*, 102726. [CrossRef]
141. Pregnolato, M.; Gunner, S.; Voyagaki, E.; De Risi, R.; Carhart, N.; Gavriel, G.; Tully, P.; Tryfonas, T.; Macdonald, J.; Taylor, C. Towards civil engineering 4.0: Concept, workflow and application of digital twins for existing infrastructure. *Autom. Constr.* **2022**, *141*, 104421. [CrossRef]
142. Fuller, A.; Fan, Z.; Day, C.; Barlow, C. Digital twin: Enabling technologies, challenges and open research. *IEEE Access* **2020**, *8*, 108952–108971. [CrossRef]
143. Saporiti, N.; Cannas, V.G.; Pozzi, R.; Rossi, T. Challenges and countermeasures for digital twin implementation in manufacturing plants: A Delphi study. *Int. J. Prod. Econ.* **2023**, *261*, 108888. [CrossRef]
144. Ullah, F.; Sepasgozar, S.M.; Thaheem, M.J.; Al-Turjman, F. Barriers to the digitalisation and innovation of Australian Smart Real Estate: A managerial perspective on the technology non-adoption. *Environ. Technol. Innov.* **2021**, *22*, 101527. [CrossRef]
145. Shahzad, M.; Shafiq, M.T.; Douglas, D.; Kassem, M. Digital twins in built Environments: An investigation of the characteristics, applications, and challenges. *Buildings* **2022**, *12*, 120. [CrossRef]
146. Botín-Sanabria, D.M.; Mihaita, A.-S.; Peimbert-García, R.E.; Ramírez-Moreno, M.A.; Ramírez-Mendoza, R.A.; Lozoya-Santos, J.D.J. Digital twin technology challenges and applications: A comprehensive review. *Remote Sens.* **2022**, *14*, 1335. [CrossRef]
147. Leng, J.; Chen, Z.; Sha, W.; Ye, S.; Liu, Q.; Chen, X. Cloud-edge orchestration-based bi-level autonomous process control for mass individualization of rapid printed circuit boards prototyping services. *J. Manuf. Syst.* **2022**, *63*, 143–161. [CrossRef]
148. Rathore, M.M.; Shah, S.A.; Shukla, D.; Bentafat, E.; Bakiras, S. The role of AI, machine learning, and big data in digital twinning: A systematic literature review, challenges, and opportunities. *IEEE Access* **2021**, *9*, 32030–32052. [CrossRef]
149. Li, L.; Mao, C.; Sun, H.; Yuan, Y.; Lei, B. Digital twin driven green performance evaluation methodology of intelligent manufacturing: Hybrid model based on fuzzy rough-sets AHP, multistage weight synthesis, and PROMETHEE II. *Complexity* **2020**, *2020*, e3853925. [CrossRef]
150. Sheng, D.; Ding, L.; Zhong, B.; Love, P.E.; Luo, H.; Chen, J. Construction quality information management with blockchains. *Autom. Constr.* **2020**, *120*, 103373. [CrossRef]
151. Agnusdei, G.P.; Elia, V.; Gnoni, M.G. Is digital twin technology supporting safety management? A bibliometric and systematic review. *Appl. Sci.* **2021**, *11*, 2767. [CrossRef]
152. Shahat, E.; Hyun, C.T.; Yeom, C.J.S. City digital twin potentials: A review and research agenda. *Sustainability* **2021**, *13*, 3386. [CrossRef]

153. Liu, H.; Holmwood, B.; Sydora, C.; Singh, G.; Al-Hussein, M. Optimizing multi-wall panel configuration for panelized construction using BIM. In Proceedings of the 2017 International Structural Engineering & Construction Conference (ISEC), Valencia, Spain, 24–29 July 2017; pp. 24–29. [CrossRef]
154. Liu, H.; Al-Hussein, M.; Lu, M. BIM-based integrated approach for detailed construction scheduling under resource constraints. *Autom. Constr.* **2015**, *53*, 29–43. [CrossRef]
155. Liu, H.; Zhang, Y.; Lei, Z.; Li, H.X.; Han, S. Design for manufacturing and assembly: A BIM-enabled generative framework for building panelization design. *Adv. Civil Eng.* **2021**, *2021*, 5554551. [CrossRef]