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Review of advanced emergency evacuation procedures in hospital buildings: comprehensive analysis and insights

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This research paper explores the integration of novel technologies in hospital emergency evacuations, particularly in Operating Rooms (ORs) and Emergency Departments (EDs). It examines the application of advanced tools like simulation modeling, Building Information Modeling (BIM), Digital Twin technology, sensor data, and Artificial Intelligence (AI) to improve evacuation strategies in the building. The study extends to in-depth case studies for assessing the practicality of existing protocols, while also highlighting the critical importance of staff training and preparedness. Additionally, it addresses the ethical and psychological impacts of emergencies on patients and healthcare staff, underscoring the need for technology to be complemented with human-centered care. The paper concludes by emphasizing the ongoing necessity for innovative research in enhancing safety and operational resilience in healthcare emergency management.

KEYWORDS

emergency evacuation, simulation modeling, AI-based systems, ethical aspects of hospital evacuation, Digital Twin, Internet of Things, Building Information Modeling

1 Introduction

The safety and wellbeing of patients and staff in hospital settings are of utmost importance, particularly in emergency situations where rapid and efficient evacuation becomes crucial (Bagaria et al., 2009; Kelly et al., 2021). Operating Rooms (ORs) and Emergency Departments (EDs) represent the most critical areas in healthcare facilities due to their high-stakes environment, where patients are often in vulnerable states, and life-saving procedures are conducted (Miao and Wang, 2021). The complexity of these environments demands a specialized approach to emergency evacuation planning and execution, which is the focus of this comprehensive review.

The importance of well-designed emergency evacuation plans in ORs and EDs cannot be overstated. These plans must account for the unique operational characteristics of these settings, such as the presence of immobile or sedated patients (Song et al., 2023), critical ongoing medical procedures, and the need for transporting sophisticated medical equipment (Dulebenets et al., 2020; Yazdani et al., 2021). Moreover, the diverse range of scenarios that might necessitate an evacuation, including natural disasters (Kelly et al., 2023; Salamati Nia and Kulatunga, 2017), fire outbreaks (Muhamad Salleh et al., 2020; Liu et al., 2023), or security threats (Ahouanmenou et al., 2023; Argaw et al., 2020), require a multi-faceted and adaptable approach to ensure safety and minimize disruption to critical medical care.

This paper aims to shed light on the current strategies, methodologies, and technologies employed in the design and optimization of emergency evacuation plans in ORs and EDs. The review will explore how hospitals currently prepare for and execute emergency evacuations, identifying key challenges and areas for improvement. It will also consider how advancements in technology, such as simulation modeling (Haghpanah et al., 2021; Kim and Heo, 2023), BIM (Akbar and Hassanain, 2023; TohidiFar et al., 2021), Digital Twin (Aluvalu et al., 2023; Moyaux et al., 2023; Sun et al., 2023; Mohamed et al., 2023) and artificial intelligence (Sahebi et al., 2023; Khaled Ahmed et al., 2023; Tang et al., 2021), can aid in the creation of more effective and efficient evacuation procedures.

Through an analysis of case studies and existing literature, this paper will provide a comprehensive overview of the current state of emergency evacuation practices in these critical hospital areas. The goal is to offer insights and recommendations that can guide healthcare facilities in enhancing their emergency response strategies, ensuring the safety of patients and staff, and maintaining the integrity of vital medical operations during crises.

This review is a step towards understanding and improving the intricate and crucial process of emergency evacuation in hospital settings, specifically focusing on the unique needs and challenges of operating rooms and emergency departments. The insights gathered here aim to contribute to the development of robust, effective, and adaptable evacuation plans that prioritize patient safety and operational efficiency in the face of emergencies.

The paper is structured around three key research questions that guide the review:

What are the Effective Strategies for Emergency Evacuation in Operating Rooms and Emergency Departments? This question searches into the variety of strategies and protocols currently employed for emergency evacuations in these settings. The focus is on how these strategies cater to the unique challenges of managing patients with varying levels of mobility and consciousness, handling critical medical equipment, and coordinating among diverse healthcare teams.

How Can Technological Advancements Enhance the Efficiency and Effectiveness of Evacuation Procedures? This explores the impact of emerging technologies such as simulation modeling, Digital Twin, artificial intelligence, and real-time monitoring systems on evacuation plans. It aims to understand how these technologies can contribute to route optimization, crowd management, and decision-making in emergency scenarios, thereby leading to more efficient and safer evacuations.

What are the Psychological and Ethical Considerations in Evacuating Patients and Staff from High-Risk Hospital Areas? This question probes into the ethical and psychological issues involved in evacuating patients, particularly those critically ill or in surgery, and staff from ORs and EDs. The goal is to explore ways in which evacuation plans can be structured to minimize psychological trauma and moral distress for both patients and healthcare professionals, while adhering to ethical standards.

TABLE 1 Summary of reviewed literature categorization and journal quality ranking.

Category	No. of papers
Journal	65
Conference Proceedings	8
Thesis	3
Book	2
Total Publications	78
Q1 Journals	45
Q2 Journals	12
Q3 Journals	2
Q4 Journals	1
Non-ranked Journals	5
Total Journals	65

2 Methodology

The methodology employed in this review is designed to be thorough and systematic, ensuring a comprehensive understanding of emergency evacuation procedures in hospital settings, particularly in Operating Rooms (ORs) and Emergency Departments (EDs). The process involves several stages, from the initial literature search to the final analysis and synthesis of the gathered data.

2.1 Literature search and database selection

- Initial Search: A broad search was conducted using scholarly search engines and specific databases to identify relevant literature. The primary databases used were Scopus, and Web of Science, complemented by a supplementary search in Google Scholar.
- Keywords and Search Tools: Keywords such as "emergency department," "evacuation planning," "hospital emergency procedures," "simulation in healthcare," and "operational efficiency in emergencies" were used to refine the search. Different search tools within these databases facilitated the identification of a large pool of potential literature.

2.2 Preliminary evaluation and filtering

- Title Evaluation: An initial evaluation was based on the titles of the articles, employing filters to remove duplicates and redundant papers.
- Abstract and Conclusion Skimming: The abstracts and conclusion of the remaining articles were skimmed to assess relevance and significance to the review's objectives. This step further narrowed down the selection to a more focused group of articles.

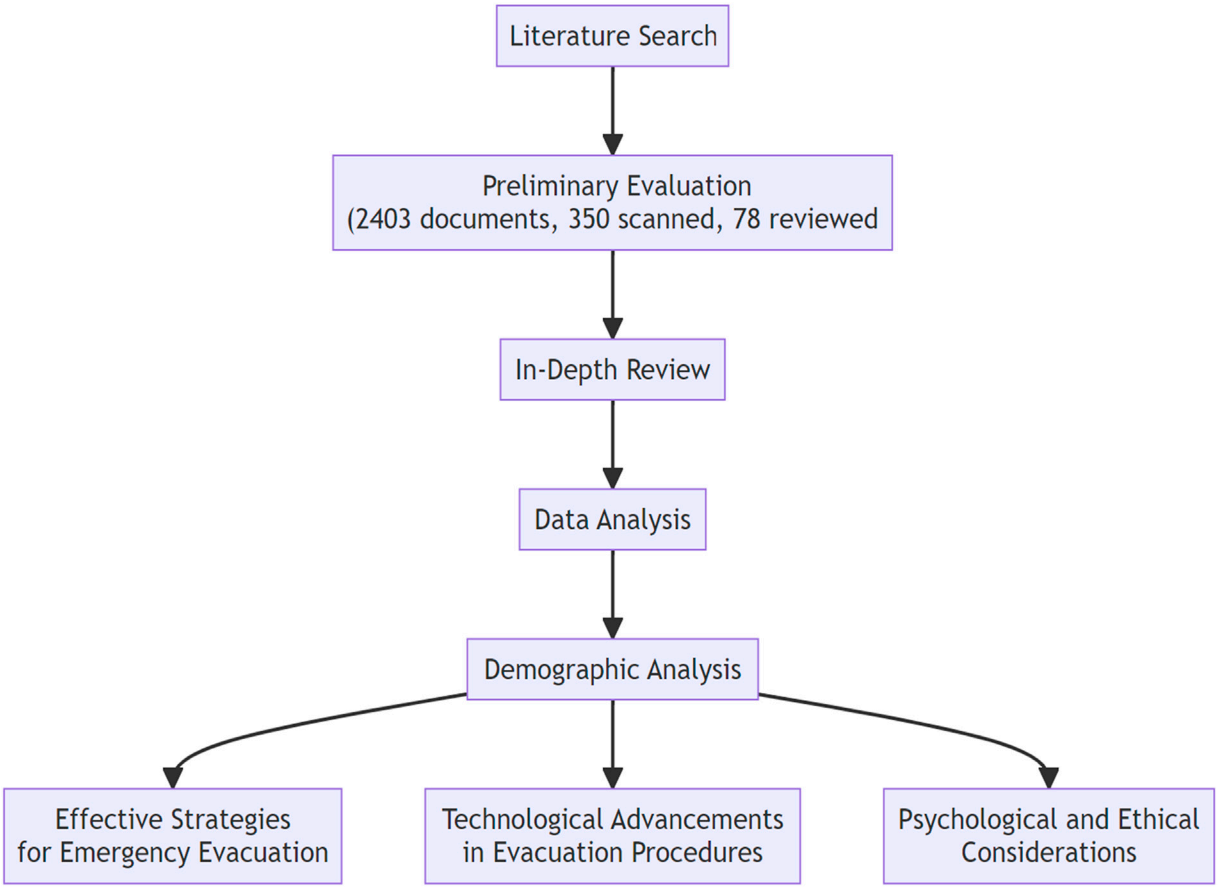

FIGURE 1
Flowchart of the review methodology for emergency evacuation procedures in hospital settings.

2.3 In-depth review and criteria application

- Full-Text Review: The selected articles underwent a full-text review to thoroughly understand their contributions and methodologies.
- Inclusion and Exclusion Criteria: Specific criteria were applied to include or exclude articles based on their relevance, quality, and contribution to the field of emergency evacuation in healthcare settings.

2.4 Data analysis and synthesis

- Comparative Analysis: The reviewed articles were compared and analyzed to identify trends, common practices, and novel approaches in evacuation procedures.
- Summary and Synthesis: Key findings were summarized, and a synthesis of the collective knowledge was performed to provide a comprehensive understanding of the topic.

2.5 Demographic and publication analysis

- Geographic and Publication Distribution: The geographic distribution of the studies and the types of publications (journal articles, conference proceedings, theses, books) were analyzed.
- Journal Quality and Publication Areas: The quality of the journals (based on quartile rankings) and the primary areas of publication (emergency healthcare, simulation, operations research, etc.) were examined to understand the research landscape.

The search and screening process, represented graphically, illustrates the step-by-step methodology of identifying and selecting relevant articles. This methodical approach led to the review of 78 key articles, revealing insights into the geographic and academic distribution of research in this area. The majority of the articles were found to be from high-quality journals (Table 1), with significant contributions from Europe, North America, and Australia, and a notable number of studies conducted by researchers with engineering or mathematical backgrounds, despite the healthcare-centric nature of the problem.

This methodology, combining extensive literature search, careful selection and evaluation, and thorough analysis, ensures a robust and comprehensive review of emergency evacuation procedures in hospital operating rooms and emergency departments. Figure 1 shows the review methodology flowchart.

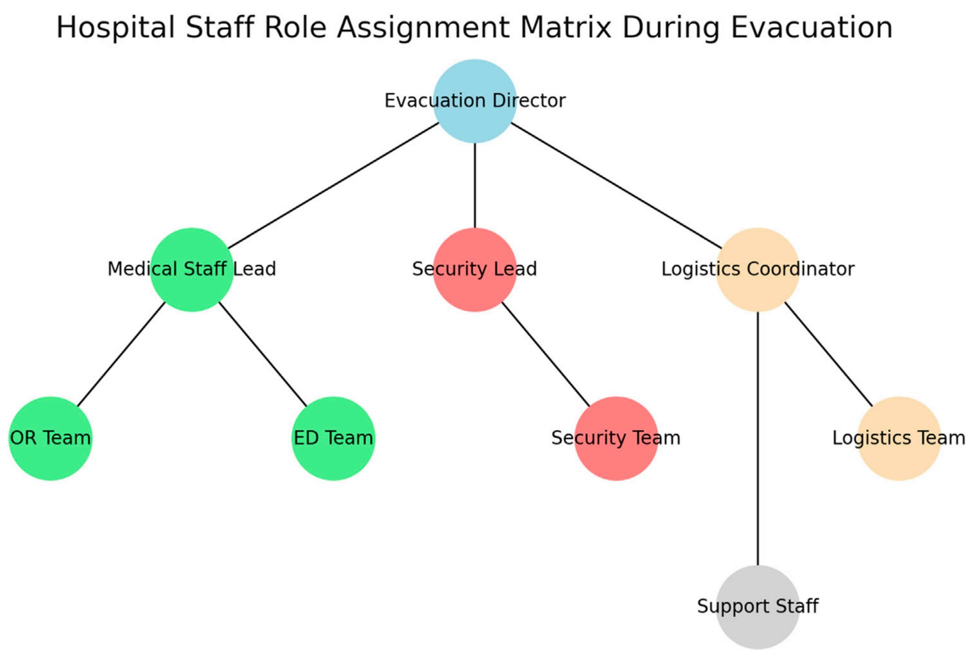

FIGURE 2
Hospital staff role during evacuation.

3 Results

3.1 Evacuation strategies and protocols

3.1.1 Context-specific evacuation protocols

The literature unequivocally supports the development of evacuation protocols that are intricately adapted to the operational dynamics of Operating Rooms (ORs) and Emergency Departments (EDs) (Berends and Antonacopoulou, 2014; Biswas et al., 2023). These protocols must consider the critical nature of activities performed in these settings (Iliopoulou et al., 2020; Kako et al., 2020; Bakhshian and Martinez-Pastor, 2023), the dependency of patients on life-support systems (Al Bochi et al., 2023; Lyng et al., 2021; Shackelford et al., 2024), and the swift adaptation to rapidly changing situations (Rodríguez-Espíndola et al., 2022; Phattharapornjaroen et al., 2023). The design of such protocols involves a comprehensive risk assessment, including potential hazards, patient demographics, and the physical layout of the facility (Grimaz et al., 2021; Yazdani et al., 2022a). The studies highlight that protocols should not only be detailed and specific but also flexible enough to accommodate the unpredictable nature of emergency scenarios. Effective evacuation plans also consider the potential need for partial or selective evacuation, recognizing that moving all patients may not always be feasible or safe.

3.1.2 Strategic use of alerts and role definition

The utilization of color-coded alerts as part of the evacuation strategy has been shown to enhance the ability of staff to quickly assess and act according to the level of urgency (Neußner, 2021). For example, a "Code Red" might indicate a fire, whereas a "Code Black" might pertain to a bomb threat. Each scenario dictates a different set of actions, and color-coding helps in embedding these actions into the hospital's emergency response culture (Rozenfeld et al., 2017; Lee and Lee, 2018). Additionally, clearly defined roles are essential for ensuring that all personnel, from surgeons to support staff, are aware of their duties during an evacuation (Sahebi et al., 2021; VanDevanter et al., 2017). The literature suggests that role-playing exercises and simulation training can be effective in reinforcing these roles, aiding memory recall under duress, and ensuring that each team member acts as a cogent unit in the emergency response machinery.

Out from that, Figure 2 represents a synthesized role assignment matrix derived from the comprehensive literature review on emergency evacuation procedures in hospitals. This matrix is a visual depiction of the hierarchical structure and the flow of responsibilities among hospital staff during an evacuation scenario, as suggested by various studies and best practices identified in the literature.

3.1.3 Emphasis on emergency drills and staff training

Emergency drills are more than just routine exercises; they are critical rehearsals that prepare staff for the high-stakes environment of an actual evacuation (Einstein et al., 2022; Power, 2018). These drills should simulate real-life scenarios as closely as possible, incorporating variables such as the presence of smoke or the need to navigate obstacles (Hunt et al., 2020; Rahouti et al., 2020a; Jacob et al., 2017). Staff training programs, which often include emergency drills, should also address the psychological readiness of the staff, equipping them with not just procedural knowledge but also the mental fortitude required in a crisis (Meredith et al., 2011; Yamamoto et al., 2022). The literature indicates that regular debriefings post-drills can provide valuable feedback, allowing for the continuous evolution of evacuation procedures. Furthermore, incorporating the latest best practices

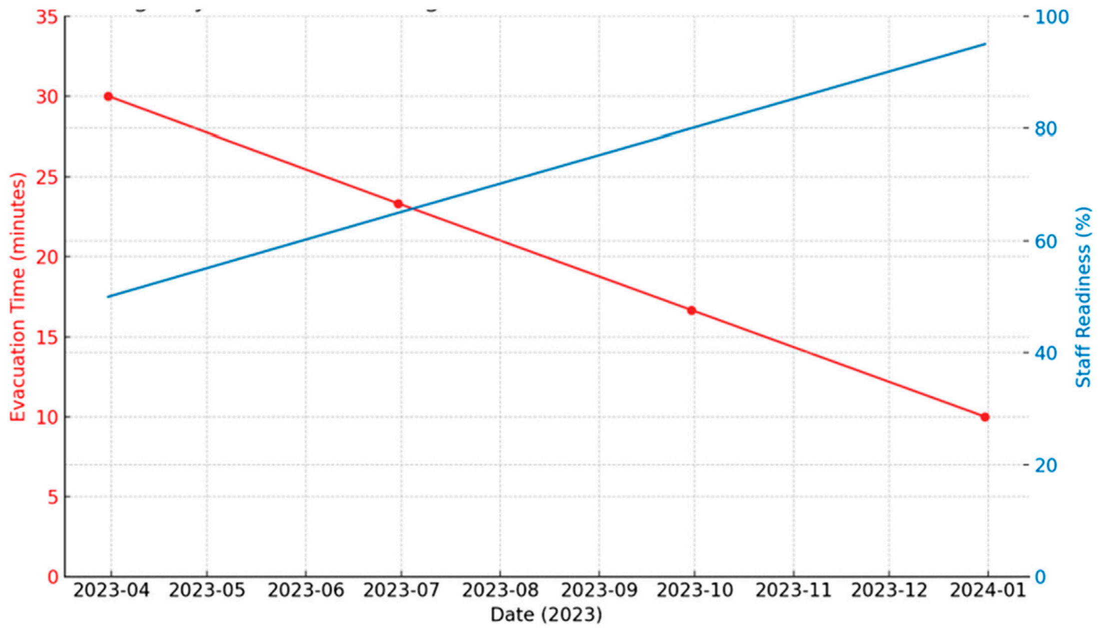

FIGURE 3
Emergency drills and training timeline.

from across the globe can ensure that the training programs remain current and effective.

Figure 3 illustrates a "2023 Emergency Drills and Training Timeline," derived from the above literature review on emergency preparedness in hospital settings. It represents the hypothetical improvements in evacuation times and staff readiness metrics.

Spanning across the year 2023, the timeline is marked at quarterly intervals to show the regular scheduling of emergency drills and training sessions in a hospital environment.

The red line with circular markers depicts a simulated decrease in evacuation times, from approximately 30 min at the start of the year to about 10 min by the end. This trend suggests a notable improvement in the efficiency of evacuation procedures over time, likely attributed to the regular practice and refinement of protocols during the drills.

The blue line with "x" markers shows a simulated increase in staff readiness, from 50% to 95% over the year. This metric indicates the progressive enhancement of the staff's capability to respond effectively to emergencies, possibly due to ongoing training and accumulated experience from the drills.

The converging trends depicted in the figure align with findings from the literature, highlighting the positive impact of consistent and regular emergency training on a hospital's evacuation preparedness. The decreasing evacuation times and increasing staff readiness underscore the importance of continuous practice, training, and procedural reviews in improving the overall effectiveness and efficiency of emergency responses in healthcare settings.

3.1.4 Importance of clear communication channels

Clear communication channels are identified as a vital component in the labyrinth of emergency response. This encompasses not just the ability to broadcast information but also to ensure its reception and comprehension (Kunguma, 2020; Muthere, 2018). Effective communication strategies often include redundancy to counteract the failure of one system during an emergency (Rådestad et al., 2023; Tekin et al., 2017; Yaghoubi et al., 2023). For instance, visual signals, such as flashing lights, can complement auditory announcements. The literature points to the use of technology, such as dedicated communication devices (Benssam et al., 2013) and centralized control centers (Sawano et al., 2022), to facilitate uninterrupted communication flow. Additionally, the role of non-verbal communication cues and the physical presence of designated "communication officers" during an emergency are explored as means to foster clarity and reassurance among patients and staff alike (Crisis and emergency risk communication, 2024; Majd et al., 2020).

3.2 Technological integration in evacuation planning

3.2.1 Role of simulation tools in evacuation planning

Simulation tools are increasingly recognized in the literature for their crucial role in evacuation planning (Chen et al., 2015; Yazdani and Haghani, 2023a; Wu et al., 2020). These tools enable the creation of detailed virtual models of hospital environments, particularly ORs and EDs. By simulating various emergency scenarios, these models help in testing the effectiveness of evacuation routes and identifying potential challenges. This approach allows for the refinement of evacuation strategies based on realistic, data-driven simulations, leading to enhanced safety and efficiency.

3.2.2 Implementation of real-time tracking and AI-based systems

The literature review underscores the emergence of real-time tracking systems and AI-based decision support as game-changers in emergency evacuation (Munawar et al., 2022; Marian Sorin et al., 2020). Real-time tracking technologies, such as RFID and GPS, provide continuous monitoring capabilities crucial for the safety and accountability of patients and staff during evacuations (Patel et al., 2022; Misra et al., 2022). AI-based systems, through their ability to process and analyze large volumes of data, offer invaluable support in making quick and informed decisions (Aboualola et al., 2023; Himeur et al., 2023; Damaševičius et al., 2023). These systems can dynamically suggest optimal evacuation routes, manage crowd dynamics, and adapt to evolving emergency conditions, thus enhancing the overall responsiveness of the evacuation process.

3.2.3 Advanced technologies in evacuation planning

3.2.3.1 Building information modeling (BIM)

BIM plays a transformative role in evacuation planning by providing a detailed 3D representation of the healthcare facility (Feng et al., 2021; Kanak et al., 2020; Ding et al., 2023a; Cepa et al., 2023). This model includes intricate details of the physical layout, enabling planners to visualize and plan evacuation routes accurately. The integration of BIM with evacuation strategies allows for the identification of structural impediments and optimal pathways, ensuring a smoother evacuation process.

The strategic design of hospital emergency departments requires meticulous planning and precision in the spatial distribution to adapt to changing needs, such as increases in patient numbers and alterations in treatment procedures (Khatib and Alshboul, 2022). The implementation of systematic layout planning strategies, supported by BIM and genetic algorithm methods, offers a novel approach to redesigning the layout of emergency departments (Ko et al., 2023; Wang et al., 2022; Li et al., 2022). Such planning is crucial for adapting to patient volume shifts and procedural changes from the design stage. Analyzing patient movement and the spatial dynamics between different hospital areas significantly boosts layout functionality, illustrating the power of advanced planning in elevating patient care and operational efficiency (Schwarzweller, 2023; Demirdöğen et al., 2023).

Upon the hospital's alarm activation, the BIM-integrated system developed by Wu et al. (2020) initiates automatic recording of the total evacuation timeframe until the complete evacuation of patients and staff from the chemotherapy section is achieved. This study evaluates varied patient evacuation strategies, providing BIM technology to assess their responsiveness and health status, significantly impacting the simulation times for evacuation. An illustrative simulation, enhanced by BIM for a scenario where all beds are occupied, alongside eleven nurses and seven wheelchairs, is depicted in Figure 4. Utilizing the Monte Carlo method within the BIM framework for simulating the unpredictable nature of nurse-led rescue efforts which can be used as lessons for the next building design.

Moreover, BIM was used for the optimization of fire safety measures right from the design stage of hospital case study (Sabbaghzadeh et al., 2022). This framework was structured around four phases: initial preparation, optimization with a meta-heuristic algorithm, decision-making considering budget constraints, and applying selected measures into BIM. Another study used BIM tools such as Revit, Pyrosim, and Pathfinder software that highlighted the process of constructing a BIM in 1:1 scale, determining the evacuation passage with the highest utilization, and simulating fire scenarios to assess smoke spread and evacuation conditions (Zheng et al., 2022). The study found that strategic man-made route planning could significantly improve evacuation efficiency by 13.67%, suggesting that similar strategies could be applied to hospital settings to optimize the layout of operating rooms and evacuation routes, thereby enhancing overall safety during emergencies.

In this research we proposed the following framework for the emergency evacuation. Figure 5 conceptually represents the integration between the BIM platform and an Emergency Management Platform (EMP), illustrating the flow of information and interaction between various subsystems within a building's management framework. The BIM platform encompasses core building elements such as equipment, furnishings, and the building layout, which are essential for the operational integrity of the building. It also includes systems like the alarm and monitoring systems that play a critical role in safety and security.

The Emergency Management Platform interacts with the BIM platform, utilizing information from the building elements to enhance its functionalities in spatial planning, occupant distribution, maintenance scheduling, and emergency analysis and planning. This interaction ensures that the management of the building is not only optimized for daily operation but is also prepared for emergency situations, with plans and protocols that are informed by the building's actual configurations and monitoring systems.

3.2.3.2 Digital Twins

Digital Twins in the context of evacuation planning mark a revolutionary leap, particularly in healthcare settings, where the stakes are high and the need for precision is paramount (Almatared et al., 2024; Lv et al., 2023; Ding et al., 2023b). This advanced technology transcends the traditional scope of Building Information Modeling (BIM) by constructing a living, virtual model of the hospital environment. Unlike static 3D representations, Digital Twins integrate and process real-time data to reflect the current state of the facility dynamically (Hosamo et al., 2022a; Hosamo et al., 2022b; van Dinter et al., 2022). This includes tracking the movement of individuals–patients, staff, and visitors–as well as monitoring the operational status of critical systems and equipment.

The theoretical framework depicted in Figure 6 showcases the sophisticated interplay between physical and virtual spaces in the intelligent control of a Building Fire Protection (BFP) system. In physical space, IoT devices collect real-time dynamic monitoring information, such as sensory data and device statuses, which is then conveyed to virtual space. Within this virtual realm, the framework integrates five core models: the geometric model, semantic model, Digital Twin (DT) data model, rule model, and process model, mirroring the physical domain. The geometric model, built on BIM, captures static data like building topology and spatial relations, while the semantic model, or BFP ontology, provides the domain knowledge linking this data and enables the fusion of static and dynamic data into a coherent linked-data diagram (Jiang et al., 2023).

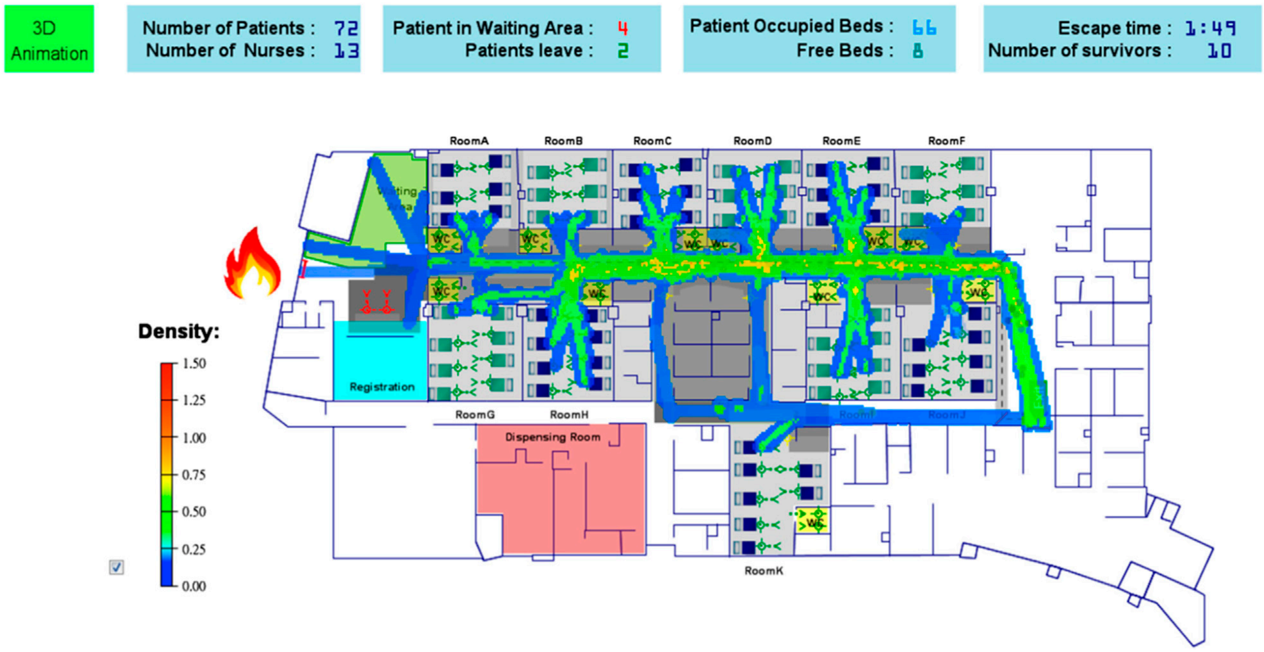

FIGURE 4
Simulation results of the evacuation process, focusing on pedestrian density (Wu et al., 2020).

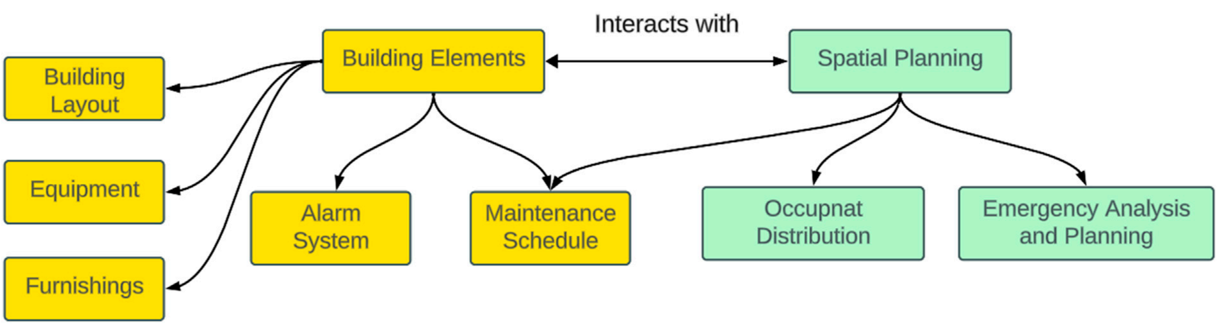

FIGURE 5
A symbiotic framework for operational excellence and emergency preparedness.

This integrated data model is then transformed into a DT data model, represented as an RDF graph, which serves as the foundation for the intelligent control mechanisms. These mechanisms, informed by the DT data model, utilize diagnosis rules, process rules, and update rules to generate and execute control commands within the physical BFP system. The process model outlines the control strategies and is triggered by diagnosis rules, with each step targeting specific control objects informed by the DT data model. Feedback from the physical environment is used to update the DT data model, ensuring it remains an accurate digital mirror of the physical space. Through iterative updates and activations, the system achieves intelligent control, highlighting a seamless integration of physical and virtual dimensions for fire safety and protection.

The power of Digital Twins lies in their ability to simulate complex evacuation scenarios with a high degree of accuracy (Liu et al., 2020a; Meuser et al., 2021). By incorporating variables such as people flow, equipment functionality, and environmental factors, these simulations can anticipate challenges and bottlenecks in evacuation routes. This foresight is invaluable in planning and executing safe and efficient evacuation strategies, particularly in emergencies where every second counts.

Furthermore, Digital Twins enable continuous optimization of evacuation plans (Goodwin et al., 2022; Fan et al., 2021). As conditions within the hospital change, for instance, changes in layout, introduction of new equipment, or varying occupancy levels–the Digital Twin adapts, ensuring that evacuation plans remain relevant and effective. This adaptability is crucial in healthcare facilities, where evolving medical technologies and patient demographics can significantly impact evacuation dynamics.

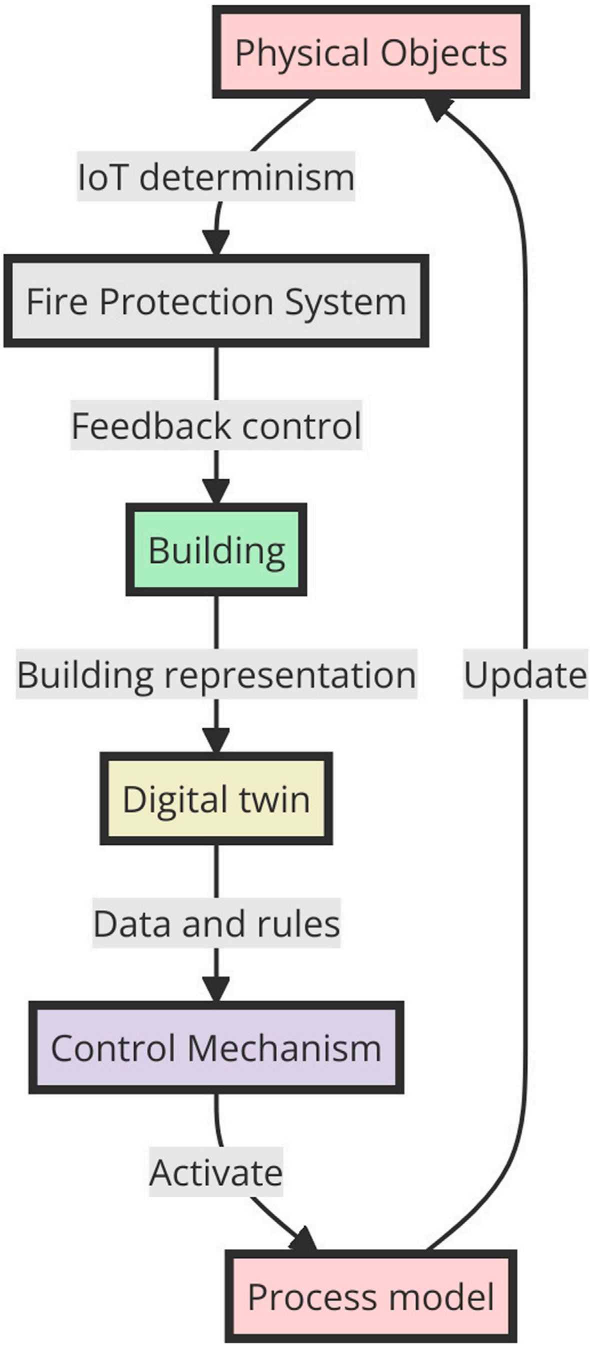

FIGURE 6
Intelligent Control Framework for Building Fire Protection System—This figure illustrates the integration of real-time data from IoT devices in the physical environment with a multi-faceted virtual modeling system. The framework combines geometric, semantic, and process models to create a Digital Twin data model that informs and optimizes the fire protection system's response in a dynamic and interactive manner.

In addition to emergency preparedness, Digital Twins serve as a training tool for staff. By rehearsing evacuation procedures in a virtual environment that closely mirrors their actual workplace, staff can better understand and prepare for real-life emergencies. This training aspect enhances overall readiness and confidence among the personnel responsible for executing evacuation plans.

3.2.3.3 AI and Machine Learning

The integration of Artificial Intelligence (AI) and Machine Learning into the realm of evacuation planning represents a significant advancement in ensuring safety and efficiency during emergencies, particularly in complex environments like healthcare facilities (Liang et al., 2023; Ogie et al., 2018). These cutting-edge technologies are increasingly utilized to analyze and interpret vast amounts of data, offering insights that were previously unattainable with traditional methods.

AI and Machine Learning algorithms excel in their ability to sift through historical data, identifying patterns and trends that might not be immediately apparent to human planners. This capability is crucial in predicting potential challenges in future evacuations, allowing for proactive rather than reactive planning (Idoudi et al., 2023; Alrehaili, 2021; Hosamo et al., 2023). By understanding past events, AI can forecast scenarios that might occur under similar conditions, thereby preparing evacuation teams to handle a wide range of situations effectively.

Moreover, these technologies go beyond mere prediction. AI algorithms are instrumental in providing actionable recommendations during emergencies. They can optimize resource allocation, ensuring that essential assets and personnel are positioned where they are most needed (Adam et al., 2022; Katzman et al., 2023). This optimization is vital in healthcare settings, where the allocation of medical staff, equipment, and patients plays a crucial role in a successful evacuation.

Route optimization is another area where AI and Machine Learning make a significant impact. During an evacuation, the selection of the safest and most efficient routes is critical (Bi et al., 2019; Huang et al., 2024; Zhu et al., 2023). AI algorithms can analyze the layout of a facility, along with real-time data on hazards or obstacles, to suggest the best possible evacuation paths. This aspect is particularly important in dynamic situations where conditions can change rapidly, requiring immediate re-routing.

In addition to planning and execution, AI and Machine Learning also contribute to the post-evacuation analysis. By reviewing how an evacuation was handled, these technologies can provide insights into what worked well and what could be improved. This continuous learning process ensures that each evacuation plan evolves and becomes more refined over time.

The use of AI and Machine Learning in evacuation planning thus marks a transformative shift towards more data-driven, efficient, and effective emergency management. In healthcare facilities, where the stakes are inherently high, the ability to leverage these advanced technologies can make a significant difference in safeguarding lives and maintaining critical operations during emergencies.

3.2.3.4 Sensor technology

The integration of sensor technology in evacuation planning is highlighted in recent studies. Sensors can monitor environmental conditions, such as smoke or hazardous material levels, and provide critical information for safe evacuation (Khan et al., 2020). They can also track the location and movement of individuals within the hospital, ensuring that all patients and staff are evacuated efficiently and safely (Petinaux and Yadav, 2013; Han et al., 2023).

These advanced technologies collectively represent a paradigm shift in how evacuation planning is approached in hospital settings. By harnessing the power of BIM, Digital Twins, AI, and sensors, healthcare facilities can significantly enhance the safety and efficiency of their emergency evacuation procedures.

As we search deeper into the realm of technological advancements, it becomes evident that each innovation addresses specific challenges inherent in emergency evacuation scenarios. To encapsulate this relationship between challenges and technological solutions, Table 2 has been developed. This table is a culmination of extensive research, drawing from a multitude of studies and practical applications in emergency evacuation planning.

The table presented next is a distillation of the research findings, connecting each identified challenge in hospital evacuation with a corresponding technological solution. It provides a clear overview of how various technologies, including AI and Sensor Technology, can be strategically employed to overcome specific obstacles. Each row of the table correlates a particular challenge encountered during hospital evacuations with an innovative technological solution, illustrating the practical implications and benefits of these advancements in real-world settings.

3.2.4 Evacuation tech in hospitals: high-rise vs. low-rise buildings

In the context of emergency evacuations in hospitals, the architectural design and the building's height play pivotal roles in determining the complexity and strategy of evacuation processes (Abir et al., 2022). Hospitals located in high-rise buildings face inherently different challenges compared to those housed in structures with only a few floors (Boonngam and Patvichaichod, 2020). High-rise hospitals must contend with longer evacuation times, the logistical difficulties of moving patients vertically, especially those who are critically ill or mobility-impaired, and the challenge of coordinating evacuations across numerous floors (Golmohammadi and Shimshak, 2011). These factors necessitate a more sophisticated approach to evacuation planning, often involving advanced technologies and detailed strategies to ensure the safety of all occupants.

On the other hand, hospitals with fewer floors, while not dealing with the complexities of vertical evacuation, still face significant challenges that require careful planning and the integration of technology (Su et al., 2022). The layout of these buildings, including the placement of exits, the distribution of patient rooms, and the accessibility of evacuation routes, must be meticulously planned to facilitate a swift and safe evacuation (Agca, 2013). In such settings, the focus may be more on horizontal movement, ensuring that exits are clear, and that patients and staff can reach safety quickly and efficiently (Kwak et al., 2021). The use of technology in these scenarios can greatly enhance the effectiveness of evacuation plans, providing real-time information and guidance to occupants.

The advent of new technologies, particularly digital twins, offers remarkable opportunities for improving evacuation procedures in both high-rise and fewer-floor hospital buildings (Almatared et al., 2024). Digital twins allow for the creation of a virtual model of the hospital, incorporating detailed information about the building's layout, occupancy, and even the behavior of individuals during an evacuation (De Benedictis et al., 2023; Ham and Kim, 2020). In high-rise hospitals, digital twins can simulate various evacuation scenarios, identify potential bottlenecks, and optimize evacuation routes (Ariyachandra and Wedawatta, 2023).

Based on the literature above, Table 3 provides a comparative overview for the differences and similarities in the integration of new technologies for evacuation purposes in high-rise versus fewer-floor hospitals.

TABLE 2 Addressing challenges in hospital evacuation planning through technological solutions.

Challenge in evacuation planning	Technological solutions	Impact and benefits
Rapid Decision Making	AI-based Decision Systems	Enhances speed and accuracy of decisions
Efficient Patient Tracking	Real-time Tracking and RFID Systems	Ensures accurate monitoring and safety of patients
Evacuation Route Optimization	Simulation Tools and BIM	Facilitates the identification of the most efficient evacuation paths
Staff Training and Preparedness	Virtual and Augmented Reality Training	Improves readiness and response skills of staff
Data Management and Analysis	Big Data Analytics	Aids in the effective handling of large datasets for informed decision-making
Communication During Crisis	Emergency Communication Systems	Ensures clear and timely communication across all levels
Integrating Diverse Technologies	Internet of Things (IoT) Integration	Allows seamless operation of various tech systems together
Patient Safety and Comfort	Wearable Health Monitoring Devices	Monitors patient health vitals during evacuation
Resource Allocation	Cloud Computing Platforms	Optimizes the use of available resources during emergencies
Adapting to Changing Scenarios	Digital Twins and Dynamic Modeling	Adapts plans in real-time to the evolving nature of the emergency

TABLE 3 Comparative overview of the integration of new technologies in evacuation strategies for high-rise vs. Fewer-floor hospitals.

Aspect	High-rise hospitals	Fewer-floor hospitals
Evacuation Challenges	Vertical movement, longer egress times, coordination across many floors	Primarily horizontal movement, ensuring clear and accessible exits
Technology Use	Simulation of various scenarios with digital twins, real-time monitoring with IoT devices, optimization of vertical evacuation routes	Efficiency in horizontal evacuation planning, real-time route optimization, use of digital twins for scenario planning
Safety Protocols	Advanced protocols for the use of elevators in evacuations, specialized training for vertical evacuation	Focus on clear signage, accessible exits, and minimizing obstacles in evacuation paths
Training and Preparedness	Virtual reality simulations for staff training, detailed evacuation drills focusing on vertical strategies	Drill simulations and staff training with an emphasis on quick, efficient horizontal evacuation

3.3 Ethical and psychological aspects of emergency evacuation

3.3.1 Ethical considerations in patient prioritization

The ethical challenges inherent in emergency evacuations, particularly concerning patient prioritization, are a significant focus in numerous studies (Leider et al., 2017; Childers et al., 2014; Goniewicz et al., 2023). This aspect involves critical decisions about which patients should be evacuated first, based on factors such as the severity of their medical conditions, mobility, and overall vulnerability. These decisions are fraught with ethical complexities, as they often have to be made rapidly in life-threatening situations. The literature calls for the establishment of robust ethical guidelines that healthcare professionals can rely on during such high-pressure scenarios (Zavala et al., 2017; Wall et al., 2016; Haahr et al., 2020). These guidelines should ideally be developed through a consultative process, involving ethicists, healthcare professionals, and patient advocacy groups, to ensure that they are comprehensive, practical, and sensitive to the diverse needs of patients.

3.3.2 Psychological impact on patients and staff

The psychological ramifications of emergency evacuations are extensively discussed in the literature (Quarantelli, 1980; Thompson et al., 2017; Lin et al., 2020). These situations can be highly traumatic for patients, particularly for those who are vulnerable, such as the critically ill or elderly, and for those with pre-existing mental health conditions (Whytlaw et al., 2021; Marchand, 2022). The stress and anxiety experienced by healthcare staff, who must make rapid and often distressing decisions, are also significant. The studies reviewed suggest that the psychological impact of evacuations can be profound and lasting, affecting both patients and staff long after the event. Consequently, there is a growing recognition of the need for mental health support mechanisms to be integrated into emergency response plans. This includes training for staff on how to provide psychological first aid, the availability of mental health professionals as part of the emergency response team, and the implementation of strategies to help manage stress and trauma.

3.3.3 Addressing psychological impacts through counseling and support

In addressing the psychological impacts, the literature emphasizes the importance of comprehensive mental health support (Knez et al., 2021; La Greca et al., 2022). This includes both pre-evacuation counseling to prepare patients and staff for the possibility of an emergency evacuation and post-evacuation support to help them cope with the aftermath (Augustine, 2023). Effective support strategies can involve debriefing sessions after the evacuation, where individuals can share experiences and receive emotional support, and the provision of ongoing counseling services. Furthermore, training programs for healthcare staff that include components on managing their own mental health and

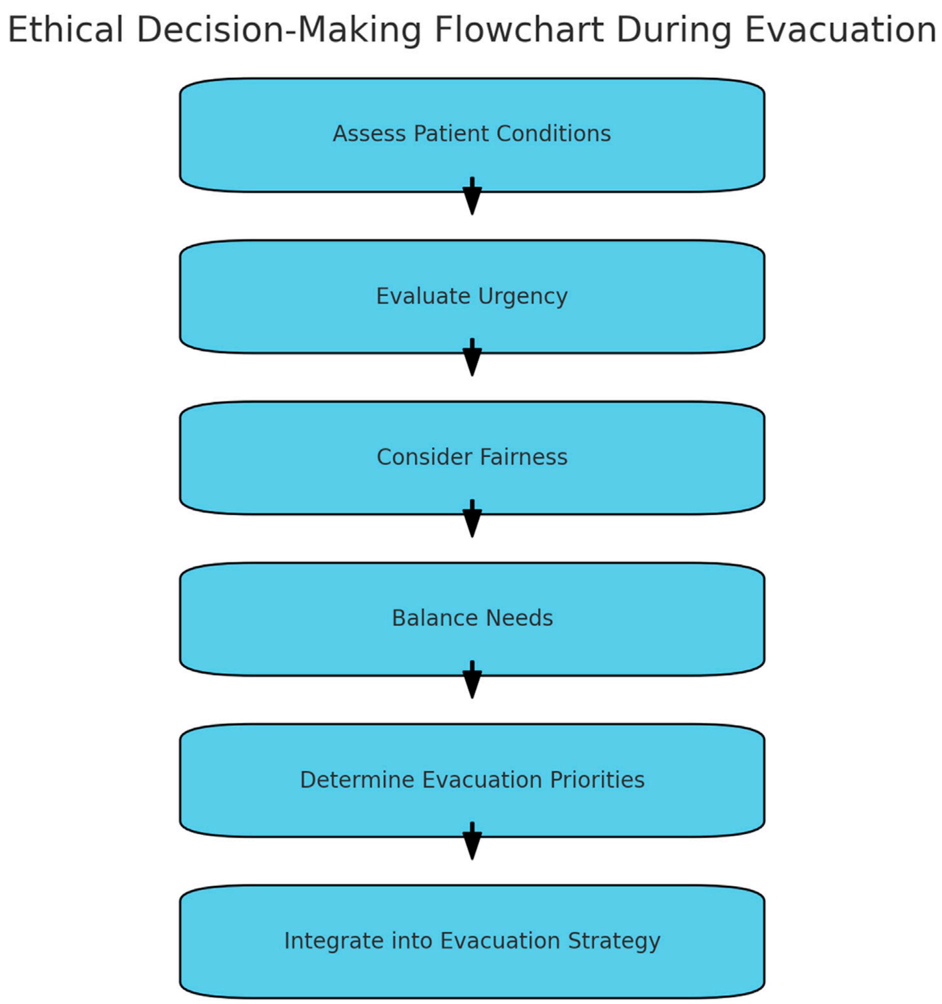

FIGURE 7
Emergency evacuations in hospital settings.

providing psychological support to patients during crises are recommended (Harrell et al., 2020). The development of these programs requires a multidisciplinary approach, involving psychologists, psychiatrists, and emergency planning experts, to ensure they are effective and tailored to the specific challenges of emergency evacuations.

The "Ethical Decision-Making Flowchart" in Figure 7 is a critical tool derived from comprehensive research on emergency evacuation in hospital settings, specifically designed to guide healthcare professionals through the complex ethical landscape of emergency evacuations. This flowchart delineates a step-by-step process, beginning with the assessment of patient conditions, evaluating the urgency of each case, and considering the principles of fairness in decision-making. It emphasizes the need to balance the diverse needs of patients, integrating these factors into determining evacuation priorities. The final step involves incorporating these ethical considerations into the overall evacuation strategy, ensuring that decisions are not only effective in terms of logistics but also uphold the highest ethical standards. This visual representation serves as a practical guide for healthcare staff, aiding them in navigating the challenging decisions they face during an evacuation, ensuring that patient care remains compassionate and ethically sound even in the most pressing circumstances.

The "Psychological Impact Assessment Diagram" in Figure 8 serves as a vivid illustration of the varied psychological effects experienced by different groups during hospital evacuations. Each group is distinctly represented by a unique color, enhancing the visual clarity and facilitating an immediate understanding of the diverse mental health challenges faced in such high-pressure scenarios. For instance, the red markers representing vulnerable patients vividly underscore their susceptibility to anxiety, fear, and trauma, while the blue markers associated with medical staff highlight the significant stress, burnout, and trauma they endure due to their critical roles in managing the evacuation. Similarly, elderly patients, children, those with pre-existing mental health conditions, and hospital administrators are each uniquely colored, illustrating the range of psychological impacts such as confusion, heightened anxiety, and decision fatigue that they are likely to experience. This diagram effectively communicates the necessity for targeted mental health support strategies tailored to each group's specific needs. It emphasizes the critical importance of

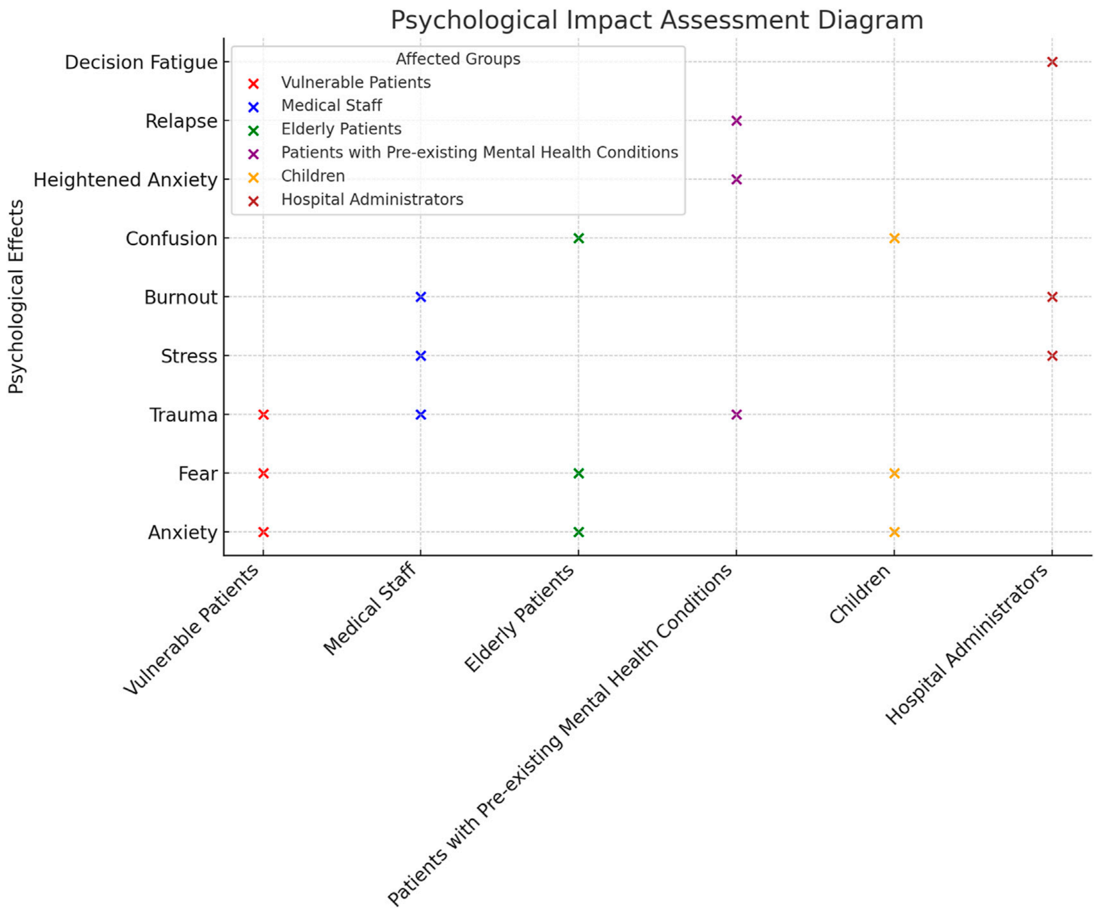

FIGURE 8
Psychological effects experienced by various affected groups during hospital evacuations.

integrating psychological care into emergency evacuation plans, ensuring a comprehensive approach that addresses both the emotional and physical wellbeing of all individuals involved in such emergency situations.

3.3.4 Evacuation protocols for vulnerable groups in hospital ORs and EDs

The evacuation of vulnerable groups within hospital settings, particularly in high-stakes areas such as Operating Rooms (ORs) and Emergency Departments (EDs), presents a complex and critical challenge that necessitates meticulous planning and continuous analysis (Kreisberg et al., 2016). Vulnerable patients, including those with mobility impairments, critical health conditions, and those undergoing surgery or in recovery, are at significant risk during emergencies (Nandra et al., 2020). The unique nature of ORs and EDs, where patients are often in a compromised state and unable to self-evacuate, underscores the need for specialized evacuation procedures. This involves not just the physical means of evacuation but also considerations for maintaining essential medical care during the process.

The development and implementation of comprehensive evacuation strategies for these groups require a multifaceted approach. Hospitals must integrate advanced technologies, such as digital twin simulations that can model and predict the outcomes of different evacuation scenarios, with traditional emergency preparedness practices (Basaglia et al., 2022). Training hospital staff, from clinicians to support personnel, in these procedures is crucial to ensure a swift, organized, and safe evacuation. Additionally, these strategies must be adaptable to various emergencies, including fires, natural disasters, and human-made threats, each presenting unique challenges to safe evacuation (Haverkort et al., 2016). The role of communication technologies in coordinating these efforts cannot be overstated, ensuring that all team members are informed and responsive to the dynamic nature of emergency situations.

Further analysis and discussion on this topic are imperative for advancing hospital safety protocols. Research and case studies focusing on past evacuation efforts can offer valuable insights into best practices and areas needing improvement (Voyer et al., 2016). Collaboration across hospitals, emergency services, and academic institutions is essential to develop innovative solutions that address the specific needs of vulnerable groups in ORs and Eds (Liu et al., 2020b). By prioritizing the safety and wellbeing of these individuals in emergency preparedness planning, hospitals can significantly improve their resilience to crises and their capacity to protect those most in need during critical times. Through continuous improvement and adaptation of evacuation strategies, the healthcare sector can better safeguard the lives of its most

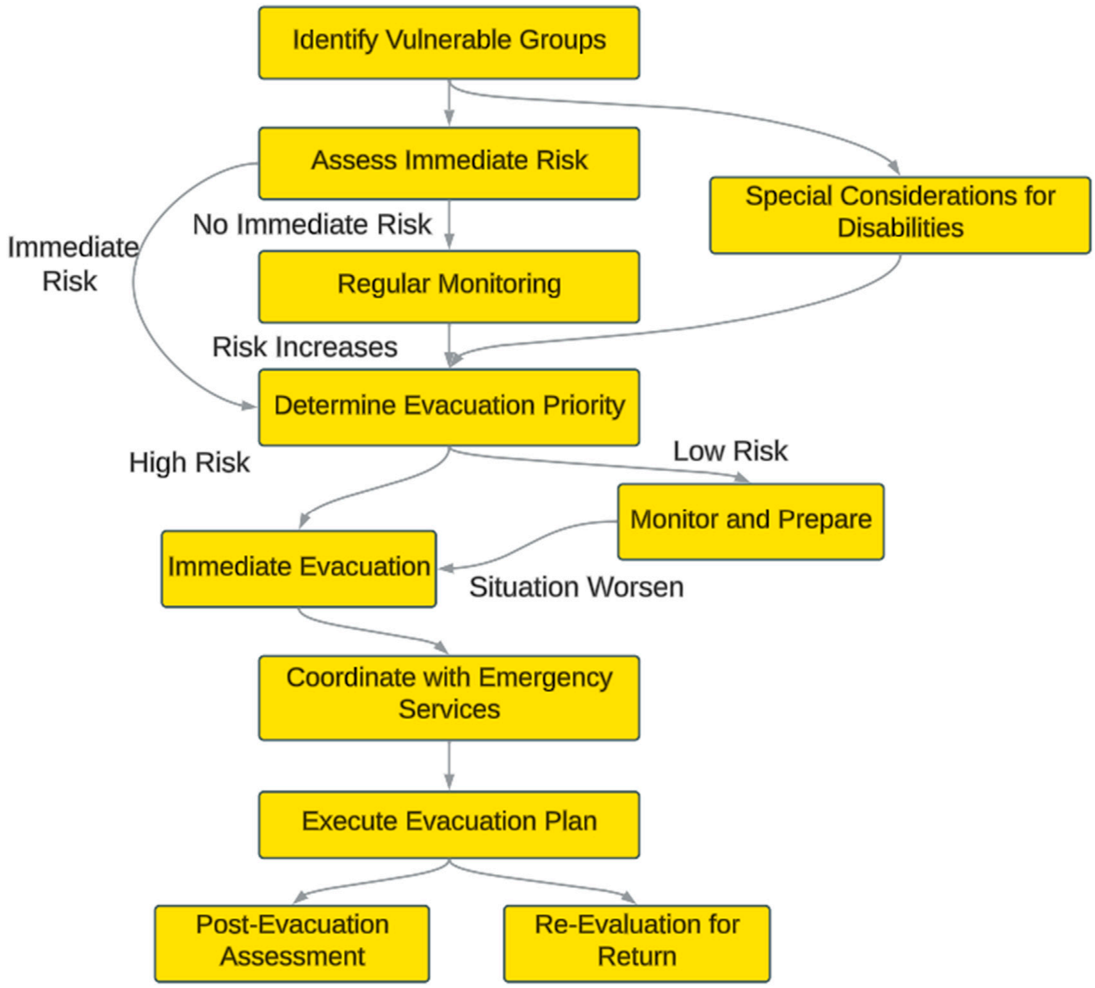

FIGURE 9
Emergency evacuation decision-making process for vulnerable group.

vulnerable patients, ensuring that in times of emergency, no one is left behind.

In this context, the framework in Figure 9 proposed in this paper as a systematic approach to evacuation planning, emphasizing the critical initial step of identifying vulnerable populations to tailor the risk assessment accordingly. Upon evaluating the immediate risk, if no immediate threat is detected, a protocol of regular monitoring is instituted, maintaining vigilance should risk levels escalate, thereby necessitating the determination of evacuation priorities. In instances of heightened risk, the framework prescribes an immediate evacuation, entailing close coordination with emergency services to implement the evacuation plan effectively. Conversely, for scenarios assessed as low risk, a strategy of ongoing surveillance coupled with preparatory measures is advised, with a provision for escalating to evacuation should conditions deteriorate. The framework underscores the necessity of integrating special considerations for individuals with disabilities throughout the evacuation process to ensure comprehensive inclusivity. Subsequent to evacuation, the framework advocates for a post-evacuation assessment, culminating in a re-evaluation that informs the decision-making process regarding the safe return of evacuees, thereby encapsulating a complete cycle of emergency evacuation planning.

3.4 Case studies and real-world applications in emergency evacuation

This section is based on Table 4 extracted from several articles to show some specific case studies related to this research.

3.4.1 Insights from practical challenges and successes

The review of various case studies sheds light on the practical aspects of implementing emergency evacuation procedures in real-world hospital settings. These case studies encompass a range of scenarios, including natural disasters, fires, and other crises, providing a diverse look at the challenges faced during actual evacuations. For example, a case study might detail how a hospital responded to a sudden fire, highlighting both the effective strategies employed and the areas where the response could have been improved (Fukushima and Moriya, 2021).

TABLE 4 A comprehensive overview of diverse emergency situations from different case studies.

Case study	Key insights	Lessons learned
Hospital Fire Evacuation Fukushima and Moriya, (2021)	Effective response to sudden fire, areas for improvement identified	Need for flexibility in emergency plans, continuous improvement
Natural Disaster Response Yulianto et al. (2021)	Logistical challenges in natural disaster, importance of preparedness highlighted	Importance of adaptability, resource allocation, and coordination
Power Outage Adaptation Barten et al. (2021)	Adaptation of evacuation plan during unexpected power outage	Quick decision-making and plan modification under pressure
Hazardous Material Spill Response Karma et al. (2022)	Effective execution of specific protocols for hazardous material spill	Specialized protocols for specific types of emergencies
Cybersecurity Threat Evacuation Rahouti et al. (2020b)	Response to cybersecurity threat, need for comprehensive emergency plans	Diverse emergency scenarios require versatile response plans
Earthquake Evacuation Hori et al. (2023)	Challenges and strategies in responding to an earthquake scenario	Training for natural disaster scenarios, structural readiness
Flood Emergency Response Yazdani and Haghani, (2023b)	Dealing with flood conditions and ensuring patient safety	Flood response strategies, prioritization of vulnerable patients
Pandemic-Induced Evacuation Yazdani and Haghani, (2023c)	Managing evacuation amidst pandemic constraints and health risks	Balancing evacuation with pandemic safety measures
Evacuation During Renovation Mousavi and Grosskopf, (2020)	Challenges in evacuating during ongoing hospital renovation	Evacuation logistics in constrained physical spaces

Another case study could focus on an evacuation during a natural disaster, revealing the logistical difficulties and the critical role of preparedness (Yazdani et al., 2022b). These real-world examples offer valuable insights into the complexities of evacuation planning and execution, emphasizing the need for comprehensive strategies that are both flexible and robust.

3.4.2 Lessons learned and importance of adaptability

The lessons learned from these case studies are instrumental in understanding the key elements of successful evacuation plans. One recurring theme is the importance of adaptability; the ability to modify plans quickly in response to changing circumstances is crucial. For instance, a case study might demonstrate how a hospital's evacuation plan was adapted on the fly during a power outage, ensuring patient safety despite the unforeseen challenge. Another critical lesson is the need for well-coordinated efforts among various hospital departments and external emergency services. Coordination ensures that resources are utilized effectively, and patients are evacuated safely and efficiently. These real-world examples also highlight the significance of regular training and drills, as they prepare staff to respond effectively under pressure.

3.4.3 Implementing swift and diverse emergency responses

The case studies further illustrate how diverse emergency situations require tailored responses. Hospitals must have evacuation plans that can be swiftly implemented regardless of the nature of the emergency. For example, a case study might describe a hospital's response to a hazardous material spill, showcasing how specific protocols for such incidents were effectively executed. Another instance could involve an evacuation in response to a cybersecurity threat, underlining the need for plans that cover a wide range of potential emergencies. These examples underscore the necessity of having a comprehensive emergency response framework that is not only well-planned but also versatile and quick to activate.

4 Discussion

In the discussion section, we delve into the findings and implications related to three primary research questions, all of which stem from an exhaustive review of literature and case studies focused on emergency evacuation planning in hospital settings, with a special emphasis on Operating Rooms (ORs) and Emergency Departments (EDs).

4.1 Discussion of research question 1: strategies for effective emergency evacuation in ORs and EDs

The literature review has illuminated various effective strategies for emergency evacuation in hospital settings. Foremost among these is the formulation of evacuation protocols specifically designed for the distinct challenges in ORs and EDs, such as the immobility of patients and the handling of critical medical equipment. The need for flexible and adaptable evacuation plans, capable of responding to unexpected challenges like power outages or natural disasters, emerged as a key theme. Case studies highlighted the importance of synchronized collaboration across different hospital departments and with external emergency services. The critical role of regular training and drills was emphasized to ensure staff preparedness and effective implementation of evacuation plans. Additionally, the integration of advanced technologies such as real-time tracking systems and AI-based decision-making tools was identified as vital in improving the efficiency and effectiveness of evacuation processes.

4.2 Discussion of research question 2: the impact of technological advancements on evacuation efficiency and effectiveness

This discussion recognizes the significant role that technological advancements play in enhancing the efficiency and effectiveness of emergency evacuations. Tools such as Simulation software and Building Information Modeling (BIM) are vital for designing and testing evacuation routes and strategies. The application of real-time tracking systems and AI-based decision support systems greatly improves the responsiveness and adaptability of evacuation plans. The advent of Digital Twins offers dynamic, real-time modeling capabilities, enabling the simulation of various evacuation scenarios for better preparation and response strategies. The deployment of sensor technologies and the integration of the Internet of Things (IoT) provide essential real-time data for efficient and safe evacuations, underlining the increasing relevance of technology in evolving and refining evacuation strategies.

4.3 Discussion of research question 3: ethical and psychological aspects of emergency evacuations

In addressing this question, the discussion highlights the often-underestimated ethical and psychological dimensions of emergency evacuations. Ethical challenges, especially concerning the prioritization of patients during evacuations, necessitate the development of comprehensive ethical guidelines that balance fairness, urgency, and patient needs. The psychological impact of evacuations on patients and staff is substantial. The research suggests the importance of incorporating mental health support mechanisms, such as pre- and post-evacuation counseling and continuous psychological support. Customizing mental health strategies to cater to specific groups affected by evacuations, like vulnerable patients and frontline medical staff, is crucial for effectively addressing the diverse psychological needs that arise during and after such events.

5 Conclusion

This extensive review of emergency evacuation planning in hospital settings, particularly in operating rooms (ORs) and emergency departments (EDs), has yielded critical insights into safeguarding patients and healthcare staff during emergencies. The study focused on three main areas: effective evacuation strategies, the impact of technological advancements, and the ethical and psychological factors in emergency evacuations.

The research reveals that successful evacuation strategies must be context-specific, adaptable, and prepared for a variety of emergency situations, ranging from natural disasters to cybersecurity threats. Key lessons underline the need for flexible planning, interdepartmental coordination, and consistent training to ensure operational readiness.

Technological innovations have proven to be crucial in evacuation planning. Tools like simulation software, Building Information Modeling (BIM), Digital Twins, AI-based decision support systems, and sensor technologies have greatly improved the efficiency and effectiveness of evacuation processes. These technologies are instrumental in providing crucial data, optimizing resources, and aiding in high-pressure decision-making.

The study also emphasizes the importance of ethical considerations, especially in patient prioritization, highlighting the need for guidelines that balance fairness, urgency, and patient needs. Moreover, the significant psychological impact of evacuations on both patients and healthcare staff demands comprehensive mental health support.

In conclusion, emergency evacuation planning in hospital settings is an evolving and multifaceted challenge that necessitates a comprehensive approach. Continuous adaptation and refinement of evacuation strategies are essential to meet diverse emergency scenarios. The integration of advanced technologies is pivotal in enhancing preparedness and response capabilities. Furthermore, a compassionate and patient-centered approach, addressing both ethical and psychological aspects, is crucial. This research lays a foundation for future studies and practical applications, aiming to prioritize safety and wellbeing in hospital environments during critical emergencies.

Author contributions

HW: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing–original draft. RN: Conceptualization, Methodology, Resources, Writing–original draft. XZ: Conceptualization, Methodology, Writing–original draft. CC: Data curation, Investigation, Writing–original draft. JP: Conceptualization, Methodology, Writing–original draft. DH: Methodology, Writing–original draft. HH: Conceptualization, Investigation, Supervision, Writing–original draft.

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Conflict of interest

Authors RN, XZ, and JP were employed by China Design Digital Technology Co.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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