

A Citation Analysis and Bibliometric Graph of Human Evacuation Research

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Abstract: Effective evacuation is vital for minimizing casualties during disasters. This study employed the Web of Science (WOS) database to perform a bibliometric analysis of the evacuation literature. VOSViewer (v1.6.20) and CiteSpace (v6.3.R1) software were used to visualize publication trends, international collaboration networks, keyword co-occurrence, clustering, and keyword bursts. The findings indicate that three research focuses are foundational to advancing the field of evacuation research, with shifts in these areas reflecting the dynamic nature of the field's transition. Four key research themes outline the core content of the field's investigation. Furthermore, this study identifies three key research phases in evacuation: the theoretical model development and foundational research phase, the behavioral dynamics and advanced simulation phase, and the data-driven intelligence and practical application phase. Future directions of evacuation research are discussed. This study provides a comprehensive analytical framework that deepens the understanding of the evacuation field.

Keywords: evacuation; bibliometric analysis; knowledge graph; literature review



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1. Introduction

With the rapid advancement of globalization and urbanization, evacuation management during emergencies has emerged as a critical public safety concern [1], garnering significant international attention. Developing and implementing effective evacuation strategies are paramount in mitigating the loss of life and property damage from natural disasters, accidents, and security-related incidents.

Effective evacuation is pivotal to safeguarding personnel safety during emergencies. A high-efficiency evacuation plan must integrate critical dynamic elements when confronted with urgent situations such as fires and natural disasters. These include crowd behavior [2], psychological reactions [3], and environmental factors [4] influencing evacuation efficiency. Furthermore, simulation experiments and field exercises can provide a more accurate understanding of crowd dynamics under conditions of stress and panic [5], facilitating the optimization of evacuation routes and guidance systems. Consequently, comprehensive and exhaustive research in evacuation is essential for devising scientifically grounded and human-centric evacuation strategies.

In recent years, Ref. [6] have evaluated the latest developments in evacuation modeling based on agent-based modeling (ABM) over the past decade, encompassing methodologies, validation practices, and associated challenges. Ref. [7] examined the manifestations of human behavior in the context of fire incidents, coupled with applying empirical methods in

pedestrian and crowd dynamics [8,9], underscoring evacuation studies' complexity and interdisciplinary nature. Despite these studies' valuable insights, the academic community's exploration of this domain remains inadequate. Current research tends to concentrate on specific areas, such as evacuation modeling or human behavior, resulting in a fragmented understanding of the subject. Consequently, it is imperative to take a comprehensive approach to bridge the disparities among these various dimensions and establish a cohesive body of knowledge. This, in turn, will facilitate future research endeavors and formulate pertinent policies, procedures, and safety measures. Our objective is to offer a holistic comprehension of evacuation research. This is achieved by assessing the volume of studies within the field, elucidating the diverse frontiers of evacuation research, objectively pinpointing the principal elements of the research, and delineating the prevailing and historical trends. Through this approach, we aim to enhance the clarity and accuracy of our understanding of evacuation studies in both the present and the past.

The spatiotemporal analysis of the global evacuation research network is pivotal for elucidating international collaboration and knowledge dissemination patterns within the field. This analysis not only exposes the activity levels and impact of different countries in evacuation research but also assists in identifying nations that assume leadership roles. It reveals potential opportunities for collaboration, thereby promoting international knowledge exchange and joint research endeavors.

Systematically reviewing the literature in the evacuation research domain is essential for uncovering pivotal research milestones and evolutionary trajectories, which in turn are critical for pinpointing the field's central themes and focal points. Employing visual keyword co-occurrence mapping allows us to monitor shifts in research hotspots, discern nascent areas of study, and observe topics waning in prominence. Such trend analysis is instrumental in forecasting impending research challenges, recalibrating research strategies, and streamlining resource allocation. By employing this methodology, we enhance our comprehension of the evolution of evacuation research, offering direction for future inquiries and ensuring that research endeavors are adeptly aligned with addressing tangible issues.

To elucidate the aforementioned issues, this study employs bibliometric methods and leverages the CiteSpace and VOSViewer tools to quantitatively analyze documents related to evacuation themes in scientific network databases. This research aims to construct a knowledge map that comprehensively examines evacuation research, revealing its developmental stages, mainstream research topics, and emerging research trends to provide researchers in this field with a more holistic analytical perspective.

2. Data and Method

2.1. Data

The literature data for this article were drawn from the Web of Science (WOS) database, renowned for its comprehensive array of journals, broad research article coverage, and extensive global data sources. To ensure the data's representativeness and credibility, the study exclusively used the SCI-EXPANDED and SSCI indexes from the Web of Science Core Collection (WoS CC) as the principal data source libraries. A systematic search was executed with the query "TS = (evacuation) AND (personnel OR behavior) OR crowd OR safe evacuation", limiting the document types to "Article" and "Review". This search yielded a total of 25,574 documents published through 17 November 2024. After the exclusion of documents related to medicine and astronomy, 11,007 documents were retained, followed by a meticulous manual screening process that culminated in a final dataset of 4100 documents.

2.2. Method

Bibliometrics, originating in the 20th century, became a distinct field of study in 1969 [10]. It employs quantitative methodologies to assess documents across various domains [11]. Bibliometrics provides in-depth insights into the development and evolution of academic fields and reveals pivotal elements associated with this progress through quantitative data [12]. With the progress of modern computer technology, graphical and visual research outputs have enhanced and complemented traditional document analysis, making bibliometric analysis more intuitive and comprehensive.

CiteSpace and VOSViewer are preeminent tools for visual analysis, and they have been extensively utilized in bibliometric research. This paper uses CiteSpace and VOSViewer as bibliometric tools to illustrate the development and structural relationships within the evacuation research field through scientific knowledge mapping. VOSViewer is lauded for its strong intuitiveness, aesthetically pleasing visualizations, and ease of understanding. It employs visualization methods such as network, overlay, and density analysis [13]. CiteSpace, on the other hand, is recognized for its citation network mapping capabilities, which delineate characteristics of research hotspots and trends [14]. The combined use of these two tools enables a comprehensive depiction of the knowledge landscape within the evacuation domain.

Using CiteSpace and VOSViewer, this study conducts the following detailed analyses and constructs maps of the literature data in the chosen field: (1) It analyzes publication trends in evacuation research to outline research activity and attention in this domain; (2) it examines the spatiotemporal distribution of each nation within the global evacuation research framework, assessing its influence and contribution to international research efforts; (3) it delineates the research focus, research focus transition, key research themes, and research phases evolution in this field by using keyword co-occurrence, clustering, and burst detection network diagrams; and (4) based on the aforementioned analyses, it predicts future research trends in the domain of evacuation.

3. Research Overview

3.1. Analysis of Annual Publication Trends

According to the data obtained from the literature search, the fluctuation in publication numbers over the years is illustrated in Figure 1.

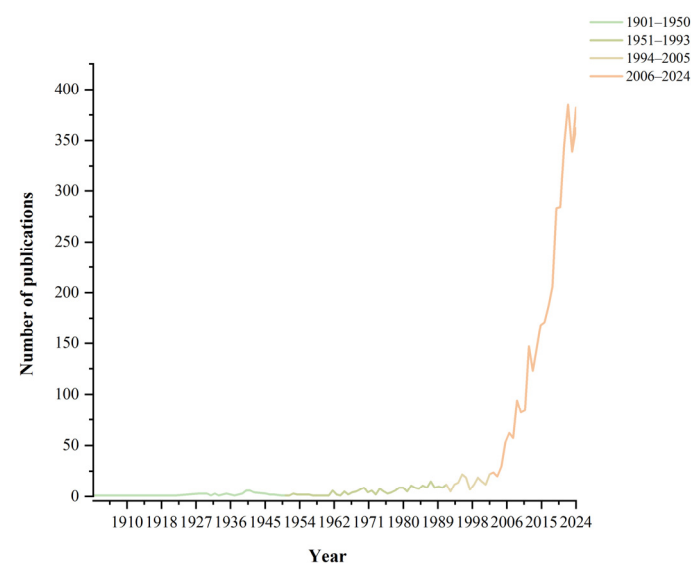


Figure 1. The trend of annual publication volume. Source: Data extracted from the Web of Science.

The publication trends in evacuation research have undergone the following phases. From 1901 to 1950, research activities were constrained by the nascent technological and disciplinary development stages, resulting in an average of only a few papers published annually. Between 1951 and 1993, there was a modest increase in relevant publications. From 1994 to 2005, the literature output consistently rose, mirroring the escalating demand. Since 2006, the field has witnessed swift growth, marked by a notable increase in publications, peaking at 385 publications in 2022, indicative of an exponential growth trajectory. The shift may be attributed to technological advancements, ongoing urbanization, and the increasing prominence of public safety issues. Additionally, the impact of specific emergencies and disasters on certain countries has also been a factor in the growth of research. For instance, the 1993 Midwest floods in the United States and the 1995 Hanshin earthquake in Japan significantly influenced research growth from 1994 to 2005. Similarly, the 2008 Wenchuan earthquake in China and the 2011 Fukushima nuclear disaster in Japan contributed to an exponential increase in publications after 2006. These events underscore the urgent need to improve evacuation strategies and public safety measures, driving academic interest in this field.

3.2. Analysis of National Publications Trends

As depicted in Figure 2, the publication outputs of the top 20 countries in evacuation research are presented.

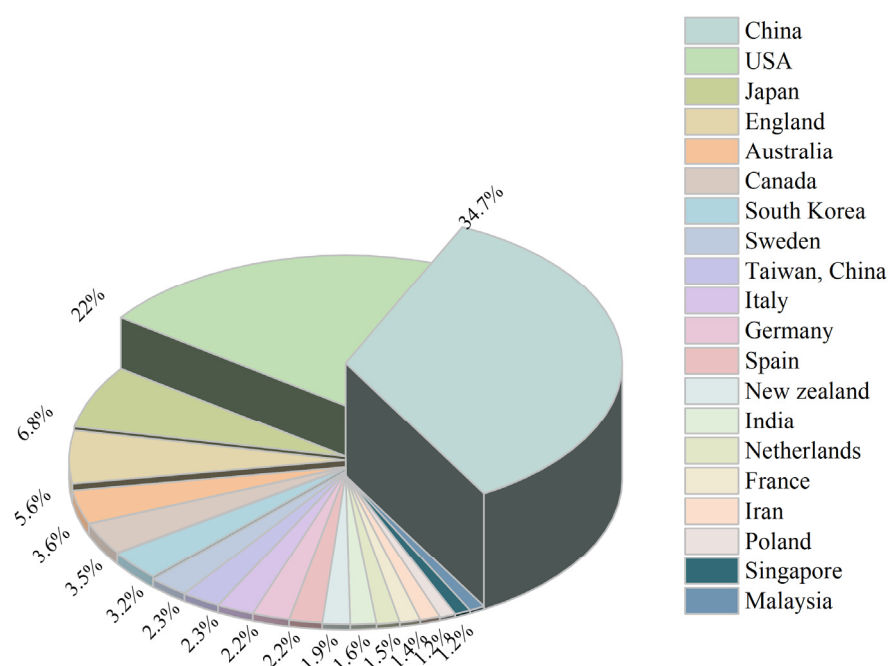


Figure 2. Trend chart of the top 20 countries. Source: Data extracted from the Web of Science.

Figure 2 illustrates that China and the USA dominate the landscape of evacuation research publications, accounting for 37% and 22% of the global total, respectively, which is significantly higher than other countries. This pattern highlights the rapid growth of evacuation research in China, driven by increasing investment in scientific research and a heightened focus on urbanization and public safety. Simultaneously, the USA remains highly influential in the field, probably driven by its well-established scientific research capabilities and extensive expertise in disaster management.

Countries such as Japan, England, Australia, and Canada exhibit moderate publication outputs, likely reflecting their established expertise in disaster management, particularly regarding earthquakes and fires. In contrast, publications from other countries are relatively

sparse, suggesting a correlation between the volume of evacuation research and factors such as economic development, research funding, and actual disaster mitigation needs.

3.3. Analysis of Spatiotemporal Collaboration Network

Figure 3 illustrates the collaboration network among authors from various countries in evacuation research and the publication years, revealing the temporal evolution of international cooperation and research trends. The size of the nodes represents the volume of publications from each country, with the USA and China occupying a prominent central position, indicating their high output and pivotal influence in the evacuation domain. The connections between nodes signify collaborative relationships between countries (co-authorship networks), with the United States having the broadest range of connections spanning multiple regions. Notably, the density of connections in China has increased significantly in recent years, particularly in collaborations with neighboring countries and emerging economies.

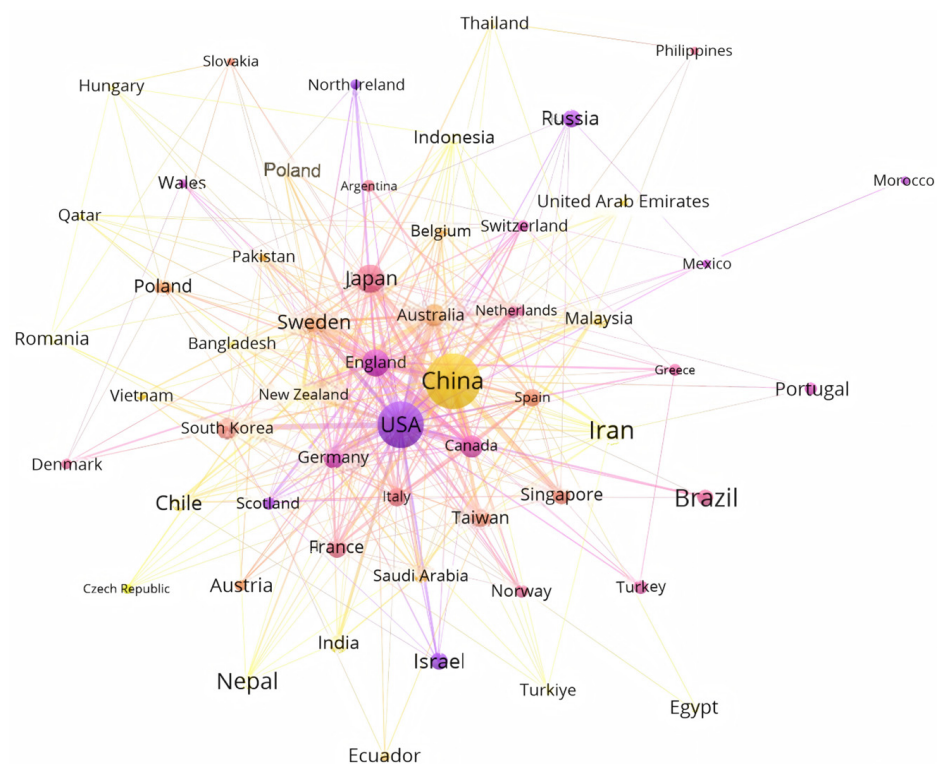


Figure 3. Map of the national cooperation network. Source: Data extracted from the Web of Science.

The nodes' color intensity and connections indicate that the lighter shades approaching yellow represent more recent publication years and collaboration periods, while the darker shades nearing purple signify earlier years. This gradient illustrates the evolution of collaboration over time and highlights concentrated research activities across different countries. Nodes and connections with more yellow hues, such as those representing countries like Vietnam, Iran, and India, suggest that their research in evacuation has emerged relatively recently, likely accelerated by the increasing demand for globalization and emergency management in recent years. In contrast, countries like the USA, Germany, and England exhibit earlier timeframes in node coloration, reflecting their sustained high output and central roles in research. Regional collaboration also displays distinct temporal characteristics; for instance, in recent years, the collaborative networks between Southeast Asian and South American countries may have been relatively new, while European nations established more mature collaborative networks much earlier.

Table 1. Keyword frequency and centrality ranking (top 5 of each type). (The frequency indicates how often a keyword appears, and the centrality suggests the significance of a keyword within the network).

High Frequency–High Centrality				High Frequency–Low Centrality				Low Frequency–High Centrality			
Keywords	Count	Centrality	Year	Keywords	Count	Centrality	Year	Keywords	Count	Centrality	Year
simulation	707	0.19	2002	social force model	247	0.00	2011	human behavior	125	0.23	2003
behavior	574	0.14	1995	pedestrian evacuation	233	0.00	2011	building evacuation	53	0.23	2008
dynamics	358	0.15	2004	optimization	216	0.08	2008	emergency management	37	0.18	2007
flow	291	0.16	2004	risk	122	0.07	2012	hurricane evacuation	74	0.18	2007
fire	134	0.26	2007	evacuation	250	0.06	2007	escape	77	0.16	2014

4.1.1. Dominant Trends and Central Themes

Keywords of high frequency and centrality, prominent within the knowledge network due to their commonality and pivotal roles, serve as key elements for theoretical and methodological advancement. These keywords epitomize the prevailing trends in the research domain and constitute the core of its technical infrastructure [17]. Within the evacuation research domain, keywords such as “Simulation”, “Behavior”, “Dynamics”, “Flow”, and “Fire” have emerged as central tenets due to their substantial impact. Simulation technology is pivotal in modeling crowd behavior and assessing evacuation efficiency. Behavioral research elucidates emergency response patterns, while dynamics research focuses on the evolving changes throughout the evacuation process. Research on flow characteristics provides theoretical underpinnings for path planning and fire scenarios, which are prevalent in application contexts and yield results of practical significance. The prominence of these keywords in frequency and centrality reflects the field’s principal trends and its foundational technological framework.

4.1.2. Specialized Scenarios and Subtopics

Keywords frequently appearing but not central are primarily associated with specific situations. These terms often pertain to particular scenarios or subtopics within the domain [18]. For example, the “Social force model”, a significant theory for simulating individual and group behavior, exhibits a relatively low connection within the research network despite its frequent citation. This suggests that its application is predominantly within specific behavior modeling studies. The term “Pedestrian evacuation” indicates research directions within specific contexts; its high frequency and low centrality suggest considerable practical importance in evacuation but a limited scope for theoretical development. The “Optimization” techniques, which are key for enhancing evacuation efficiency, are often employed by researchers to strengthen evacuation capabilities during emergencies by optimizing pathways and resource allocation. Despite its peripheral importance within the network, the frequent reference to “Optimization” underscores its essential role in practical applications. These keywords’ frequent occurrence and peripheral importance indicate their significance in specialized domains while highlighting their limitations within broader theoretical frameworks.

4.1.3. Catalysts for Innovation and Interdisciplinary Research Hubs

Keywords that are rare but significant serve as connectors within the research network, facilitating the integration of diverse topics and propelling field development [19]. “Human behavior” is a pivotal area where behavioral psychology intersects with dynamic modeling, substantially influencing the accuracy of evacuation and situational simulations. “Building evacuation” and “Emergency management” focus on evacuating in constructed settings

and managing emergency resources, providing theoretical support for path optimization and real-time emergency responses. “Hurricane evacuation” addresses the evacuation necessities during extreme weather events, closely related to meteorology and transportation engineering. “Escape behavior” research examines patterns of escape behavior, velocity, and congestion hazards, serving as an essential reference for optimizing evacuation routes and enhancing emergency response efficiency. These keywords epitomize the convergence of technology and management within evacuation research. Future research will concentrate more on personal differences, complex disaster response strategies, and immediate adjustment actions. Intelligent platforms and data-driven methodologies are expected to increase evacuation efficiency and emergency management capabilities. Evacuation research advances toward multidimensional development, offering scientific and systematic solutions for complex disaster scenarios.

4.2. Transition of Research Focus

4.2.1. Transition from Physical Movement to Information Dynamics

The focus within evacuation research has progressively shifted from a narrow focus on physical movement to a comprehensive examination of information flow dynamics. For instance, the term “Information” (cited 65 times in 2014) signifies its emergence as a pivotal concern in the discipline, particularly in high-intensity crowds or catastrophic incidents where information dissemination and communication are paramount. Additionally, the terms “Escape” (cited 77 times in 2014) and “Emergency management” (cited 37 times in 2007) highlight the recurring prominence of these concepts. The increasing frequency of these terms underscores the growing awareness that, in complex disaster scenarios, information transmission and management strategies are as pivotal as human behavior patterns.

4.2.2. Transition from Universal Models to Adaptive Decision-Making

With the progression of research, the term “Decision-making” (cited 121 times in 2011) has risen to prominence, alongside “Risk perception” (cited 30 times in 2013). These citation frequencies suggest a growing academic interest in decision-making dynamics throughout the evacuation process, reflecting an enhanced understanding and focus on the decision-making behaviors of individuals and groups during emergency evacuations. Particularly within evacuation strategy research, decision-making and risk perception are relevant not only to evacuation efficiency and safety but also to the mechanisms by which optimal decisions are made under conditions of uncertainty and time constraints. Understanding the significance of decision-making and risk perception in evacuation is crucial for developing effective strategies and improving evacuation efficiency.

4.2.3. Transition from Single to Multi-Scenario Disasters

While fire and hurricane studies continue to dominate, emerging areas such as “Building evacuation” (cited 47 times in 2012) and “Earthquake evacuation” (cited 30 times in 2016) are garnering increasing scholarly attention. Against the backdrop of climate change, research into complex disasters is experiencing a surge. These studies expand the evacuation research landscape within the safety field and establish new theoretical and practical foundations for addressing increasingly complex disaster scenarios.

4.3. Four Key Research Themes

Employing CiteSpace software, a keyword clustering analysis was conducted using the Log-Likelihood Ratio (LLR) algorithm, resulting in a cluster map visually delineating keywords’ distribution and structure across the research domain. The modularity value (Q-value) and silhouette coefficient (S-value) are key indicators for assessing the clustering

quality. The Q-value measures the independence of network modules, with values typically exceeding 0.5; higher Q-values indicate more reliable clustering outcomes. As depicted in Figure 5, the modularity Q-value for this analysis is 0.8641 (>0.5), signifying a substantial modular structure within the keyword clustering. Additionally, the average silhouette coefficient S-value is 0.9498 (>0.7), indicating a compact internal structure of the clusters and high clustering quality, which attests to the reliability of the clustering.

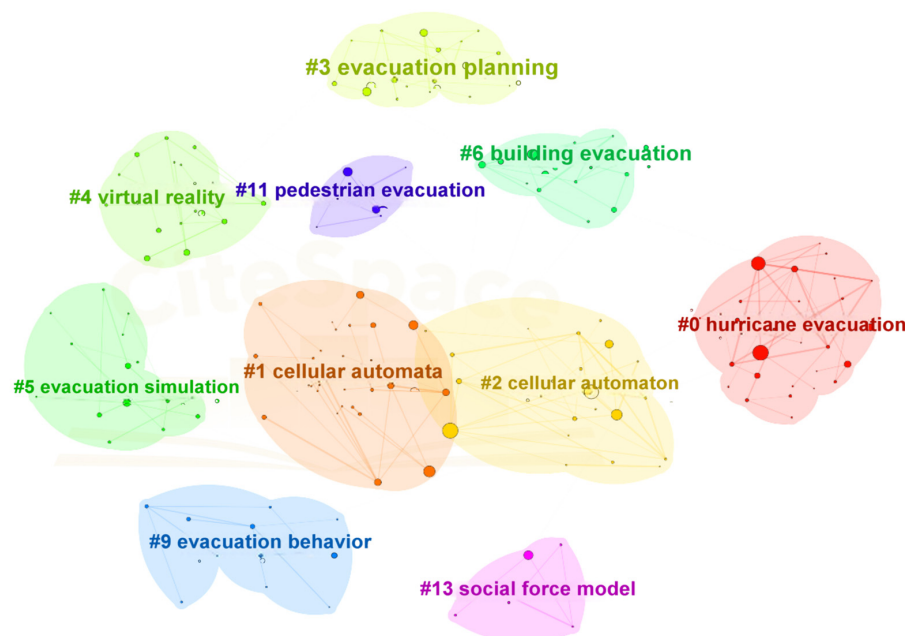


Figure 5. Keyword cluster map. Source: Data extracted from the Web of Science.

Figure 5 presents the keyword clustering map for evacuation research, which includes 10 clusters labeled according to central themes (e.g., #0 “Hurricane evacuation”, #1 “Cellular automata”, etc.). These clusters are distinguished by color and layout, representing distinct research modules. The clusters reflect a wide range of research topics, encompassing both theoretical and practical aspects. Notably, Table 2 shows that despite the varying sizes of the clusters, the S-values for all clusters exceed 0.7, signifying that the research modules demonstrate both autonomy and interconnectivity. Following a comprehensive analysis, this study endeavors to categorize evacuation research into the following four major themes.

Table 2. High-frequency keyword clustering table.

Cluster-ID	Size	Silhouette	Mean (Year)	LLR
#0	29	0.957	2010	hurricane evacuation; decision-making; disaster; risk; evacuation
#1	27	0.929	2010	cellular automata; emergency evacuation; pedestrian dynamics; human behavior; pedestrian evacuation
#2	22	0.975	2010	cellular automaton; crowd evacuation; pedestrian flow; dynamics; flow
#3	18	0.992	2011	evacuation planning; system; optimization; disaster response; cellular automata
#4	17	0.932	2017	virtual reality; exit choice; fire evacuation; fire safety; immersive virtual reality
#5	15	0.857	2014	evacuation simulation; emergency management; cellular automata model; simulation; cellular automata
#6	15	0.98	2017	building evacuation; phased evacuation; local density; mesoscopic model; route choice
#9	11	0.94	2015	evacuation behavior; agent-based modeling; crowd evacuation; agent-based simulation
#11	6	0.945	2007	pedestrian evacuation; planning; cellular automata; vulnerability; obstacles
#13	5	1	2018	social force model; analytical models; psychology; evacuation; sis model

4.3.1. Research on Modeling and Algorithmic Methods

In emergencies such as fires, earthquakes, or terrorist attacks, people's rapid and efficient evacuation is crucial. Researchers are dedicated to developing models and algorithms to accurately predict crowd dynamics, optimize evacuation routes, mitigate congestion, and enhance evacuation efficiency. These models and algorithms must consider the complexities of building layouts, transportation networks, environmental factors, and human behaviors, including panic responses, compliance, and decision-making processes. In the field of emergency evacuation, research on modeling and algorithmic methods is of paramount importance.

Currently, several mainstream approaches in evacuation research include the following:

- The Social Force Model:** This model regards pedestrian interactions as social forces, laying the theoretical groundwork for pedestrian evacuation studies [20]. Subsequent researchers have expanded upon this model to incorporate leadership effects [21], panic levels [22], group effects [23], rotational dynamics, and congestion effects [24], thereby enabling more accurate simulations of pedestrian evacuation across various scenarios.
- The Cellular Automata Model:** For instance, Ref. [25] introduced a dynamic cellular automaton model incorporating obstacles to simulate evacuation processes. A prime example in pedestrian evacuation research is the two-dimensional model Ref. [26] developed, which has been widely used. Subsequent studies further optimized and expanded the cellular automata model [27–29], integrating additional behavioral characteristics and environmental factors, significantly enhancing the model's accuracy and applicability in simulating pedestrian evacuation. Additionally, Ref. [30] incorporated CPT into the CA model, yielding evacuation patterns and times that closely match real-world data.
- Real-Coded Cellular Automata (RCA) Model:** This model transcends the limitations of traditional cellular automata by permitting the free assignment of position and velocity [31], offering a more flexible and efficient tool for simulating pedestrian evacuation.
- Cellular Transmission Model (CTM):** Concentrating on the macroscopic characteristics of pedestrian flow and network-level optimization, the CTM facilitates dynamic distribution and optimization of network traffic [32], thereby enhancing evacuation efficiency [33].
- Agent-based modeling (ABM) [34] and computational modeling [35]** have also become prominent tools in pedestrian evacuation research, reflecting the advancements in computational modeling for managing complex social interactions.

4.3.2. Research on Disaster Scenarios and Emergency Evacuation

Research on disaster scenarios and emergency evacuation centers on orchestrating evacuation during disaster events. This research domain encompasses disaster prevention, rapid response, evacuation efficiency, recovery, and reconstruction. Geographic Information Systems (GIS) and computer simulations are utilized to forecast disasters, assess evacuation routes, and allocate resources effectively. Scholars evaluate evacuation policies, planning, and operations to enhance emergency response capabilities, mitigate casualties, and minimize damage.

Key research areas focus on devising strategies to tackle challenges like hurricanes, wildfires, and other natural events. Notably, Ref. [36] examined hurricane evacuation behaviors, Ref. [37] crafted household-level evacuation decision models, Ref. [38] explored the impact of climate change on wildfire evacuations, and Ref. [39] dissected wildfire evacuation cases. Furthermore, Ref. [40] investigated evacuation processes under low visibility conditions, Ref. [41] established flood evacuation emergency planning models, and Ref. [42] assessed highway evacuation modeling.

In recent years, research has transitioned from a unidimensional to a multidimensional perspective. For example, Ref. [43] introduced a multi-objective evolutionary optimization

method, Ref. [44] contrasted actual evacuation drills with simulation results, Ref. [45] presented an agent-based simulation model, Ref. [46] analyzed evacuation behavior in high-rise buildings, and Ref. [47] explored the interplay between the built environment and risk perception on earthquake evacuation behaviors, all emphasizing the significance of the built environment on evacuation behaviors. Ref. [48] introduced a dynamic approach incorporating human behavior and gas dispersion modeling to enhance risk assessments in the context of toxic gas disasters. Ref. [49] used multi-agent modeling to simulate evacuation processes in chemical plants during toxic gas releases. Ref. [50] proposed a cellular automata-based methodology for post-earthquake evacuations, considering personal perceptions and safety protocols, thereby providing novel insights into the field. These studies highlight evacuation research's increasing complexity and multidimensionality within disaster scenarios.

4.3.3. Research on Human Behavior and Social Interaction

Research on human behavior and social interaction is crucial to the social sciences, particularly in emergency evacuations, where it addresses responses, decisions, and cooperation among individuals. Individuals' psychology, behavioral choices, and the dynamics within social networks can significantly impact evacuation efficiency and safety. Understanding these behaviors is vital for devising effective evacuation strategies and enhancing public safety.

The initial research focused on path optimization and network design, with Ref. [51] providing foundational network flow methods. Subsequently, the research shifted towards understanding dynamic evacuation characteristics, with Ref. [52] developing pedestrian traffic flow simulation tools and Ref. [53] reviewing evacuation modeling methods. This highlighted the dynamic nature of individual behavior and advances in path optimization, such as Ref. [54] integrating the social force model with the artificial bee colony algorithm in their path planning approach. The influence of social interaction and cognitive factors on evacuation behavior became a key research focus, as seen in Ref. [55] examining the role of social influence in emergency decision-making and Ref. [56] conducting simulation research based on affordance theory.

Research has expanded into group dynamics and multi-objective optimization, including models such as group behavior analysis by [57] and the multi-objective optimization framework by Refs. [58,59], who proposed a new pre-evacuation behavior model based on random utility theory. Ref. [60] introduced a new evacuation decision-making model that considers perceived risk, social influence, and behavioral uncertainty. Ref. [61] studied the impact of exit familiarity and neighbor behavior on evacuation behavior, finding that social influence intensifies with increased neighbors.

Empirical studies have been crucial for validating and refining models, with notable contributions from field experiments by Ref. [62] and research by Ref. [63]. Furthermore, Ref. [64] investigated evacuation behavior under varying visibility conditions. Ref. [65] studied the effects of spatial exploration patterns on pathfinding during building fires. Ref. [66] found that collective identity strengthens during large-scale emergency evacuations. Ref. [67] evaluated how repeated exposure and stress affect pathfinding in indoor settings. Currently, the focus of evacuation research is on intelligent evacuation systems, multimodal strategies, and the psychological and sociological factors influencing behavior.

4.3.4. Research on Technological Innovation and Multi-Factor Dynamics

Advancements in virtual reality (VR) technology have enabled its application in research, especially in simulation experiments and virtual environment studies, providing innovative tools for understanding human behavior and evacuation strategies. For example,

Ref. [68] developed a fire training simulator that integrates fire dynamics data, assisting the general public and novice firefighters in decision-making and response training. Ref. [69] performed a SWOT analysis to assess virtual reality as a research tool for studying human behavior in fire scenarios, concluding that VR is a promising supplementary laboratory tool for comprehending human behavior in fires and enhancing fire safety measures. Ref. [70] employed non-immersive VR to conduct online surveys regarding the impact of environmental and social factors on evacuation exit choices. Ref. [71] scrutinized the design of exit sign lighting during tunnel emergency evacuations via VR experiments. Ref. [72] tested public intervention measures for flash flood evacuations using VR, showing that altering environments or social conditions can encourage early evacuation decisions. Ref. [73] conducted a VR-based search and rescue experiment, examining firefighters' ability to acquire and use spatial information across different cultures. Research in virtual reality for crowd evacuation has substantially progressed, with researchers now exploring the intricate interplay among social interaction, individual behavior, and environmental factors within evacuation processes.

5. Research Phases Evolution

This section analyzes the evolutionary trends in evacuation research, aiming to encapsulate the discipline's pivotal milestones and inflection points. By employing CiteSpace for keyword burst detection, this study reveals the domain's evolutionary trends, identifying 54 keyword bursts. Due to space constraints, only the top 25 keywords are presented in Table 3. The progression of research topics across various stages can be distinctly illustrated by examining the intensity, emergence timing, and duration of these keywords. Based on these analyses, the trajectory of international research in this field can be broadly categorized into the following three phases:

Table 3. Keywords for sudden situation (top 25).

Keywords	Begin	Strength	End	Keywords	Begin	Strength	End
social force model	2002	16.24	2015	evacuation modeling	2012	5.8	2016
jamming transition	2003	13.76	2015	risk analysis	2013	6.02	2017
pedestrian flow	2003	10.05	2015	flows	2015	5.95	2019
physics	2003	7.15	2012	agent-based simulation	2018	5.94	2020
cellular automaton	2004	7.87	2012	performance	2019	5.85	2020
cell transmission model	2006	9.58	2015	understand	2019	5.54	2020
evacuation model	2006	7.13	2012	evacuation behavior	2021	9.99	2024
occupant evacuation	2006	6.1	2015	fire safety	2021	6.25	2024
fire	2007	5.62	2012	subway station	2021	5.86	2022
cellular automaton model	2008	13	2015	disaster response	2022	6.03	2024
lattice gas model	2008	5.74	2015	risk assessment	2022	5.76	2024
building evacuation	2008	5.47	2015	machine learning	2022	5.68	2024
evacuation planning	2011	10.01	2015				

5.1. Theoretical Model Development and Fundamental Research Phase (1994–2015)

The initial research was predominantly focused on constructing foundational theoretical models and advancing computational methodologies, thereby establishing a robust theoretical foundation for evacuation simulation and analysis. Keywords such as “Computational models”, “Social force model”, and “Cellular automaton” exhibited notable surges between 1998 and 2015. This phase focused on integrating computational simulation techniques into evacuation research, employing tools such as cellular automaton models to emulate individual and collective behavior. The significant increase in the keyword “Pedestrian flow” further suggests that researchers began to concentrate on the dynamics of interactions among individuals, establishing a basis for subsequent dynamic evacuation

models. In summary, research during this era was primarily dedicated to theoretical exploration and mathematical modeling, concentrating on the core issues of group dynamics.

5.2. Behavioral Dynamics and Advanced Simulation Phase (2015–2020)

As evacuation research deepens, scholars have progressively shifted their focus from macro-level group dynamics to micro-level individual behavior modeling, a transition underscored by the surge in keywords such as “Evacuation planning” and “Behavior”. This research phase highlights the growing emphasis on individual decision-making during evacuations and the dynamic interactions within groups in complex settings. Additionally, the emergence of keywords like “Dynamic networks” points to a burgeoning interest in evacuation path optimization and network flow analysis research. Furthermore, the prominence of keywords such as “Disaster management” and “Emergency preparedness” signifies a closer alignment of evacuation research with practical applications. Researchers have begun to concentrate on enhancing evacuation efficiency in disaster scenarios through optimized resource allocation and enhanced emergency management capabilities.

5.3. Data-Driven Intelligence and Practical Application Phase (2020–2024)

In recent years, advancements in artificial intelligence (AI) and big data technologies have steered evacuation research toward intelligent and data-centric methodologies. The significant surge in keywords like “Machine learning” and “Risk assessment” after 2020 indicates a growing adoption of advanced technologies, such as machine learning, to forecast individual behaviors and refine evacuation routes. Concurrently, the emergence of keywords such as “Fire safety” and “Earthquake” signals advancements in tailoring evacuation strategies and risk management for specific disaster contexts. Research in this phase highlights the utilization of real-time data and predictive analytics to augment the accuracy and efficacy of emergency responses, propelling the field toward more sophisticated and nuanced methodologies.

6. Discussion

In this study, a knowledge map that comprehensively examines evacuation research was constructed to deepen the understanding of this field.

Stable growth of research: Internationally, research on evacuation has seen continuous growth from 1994 to 2024, with a marked increase in publications post-2006. China and the USA are the primary contributors, followed closely by countries such as Japan, England, Australia, and Canada, which have also made significant contributions.

Research focus analysis: Our analysis provides crucial insights into the evolution of evacuation studies. The field mainly focuses on the development of theoretical frameworks and methodological advancements. Analysis of specific scenarios and subtopics enables the crafting of more targeted evacuation strategies across various contexts. Emerging innovation and interdisciplinary research hubs offer novel analytical approaches and research directions for evacuation studies.

Transition of research focus: The shift in research focus reflects the dynamic progression of evacuation research. The shift from physical movement to information dynamics underscores the increasing significance of information in evacuation processes. The transition from universal models to adaptive decision-making highlights the need for adaptable evacuation models that respond to rapidly changing environmental conditions and human behaviors. The expansion from single to multi-scenario disasters extends the scope of evacuation research to incorporate diverse disaster types and environmental conditions.

Four key research themes: The field of evacuation research is characterized by four fundamental themes that form its theoretical and practical foundation:

- (1) Research on modeling and algorithmic methodology aims to refine and innovate evacuation models for improved predictive accuracy.
- (2) Disaster scenarios and emergency evacuation research concentrate on devising evacuation strategies and emergency responses within specific disaster contexts.
- (3) Human behavior and social interaction research examine the psychological dimensions and social dynamics of evacuation processes, including how individual decision-making patterns and social network effects influence evacuation outcomes.
- (4) Technological innovation and multi-factor research integrate cutting-edge technologies such as the Internet of Things (IoT), drones, and augmented reality (AR) while contemplating environmental, cultural, and policy factors.

Research phases evolution: The analysis of research evolution trends offers an enhanced perspective on the field. The theoretical modeling and foundational research stage lays the groundwork. The behavioral and dynamic simulation deepening stage enhances our comprehension of evacuation dynamics and the anticipation of potential challenges. The data-driven and intelligent practice stage exemplifies the utilization of big data and intelligent technologies to streamline evacuation processes and augment efficiency.

These findings underscore that evacuation research is a multifaceted, interdisciplinary, and multi-objective domain. It necessitates both profound theoretical exploration and extensive practical application, showcasing a keen adaptability and innovation in response to new technologies. Thus, from a visual analysis and knowledge mapping perspective, there is ample potential to elevate research caliber and expand the scope of evacuation studies.

For future directions, evacuation research can be advanced by focusing on the following seven key areas:

- (1) Integrating virtual reality (VR) and artificial intelligence (AI): The convergence of VR and AI technologies presents opportunities for developing dynamic and intelligent evacuation simulation systems capable of handling complex scenarios.
- (2) Examining the interplay of individual psychological differences and social interaction: This avenue would dissect how individual behavioral traits and cultural backgrounds influence evacuation decision-making. Particular attention should be directed toward vulnerable groups, facilitating the transition from generalized to personalized models.
- (3) Concentrating on the nexus between evacuation behavior and environmental features: This encompasses understanding the influence of spatial configurations, resource allocation, and environmental hazards on individual behavior. The integration of sensor networks and IoT infrastructure will enable real-time monitoring and dynamic strategy optimization.
- (4) Multi-objective optimization models: These models should incorporate psychological comfort, physical needs, and other multidimensional factors, offering solutions for evacuation in complex scenarios.
- (5) Data-driven models and smart cities: Integrating data-driven models with smart city frameworks offers opportunities for enhanced simulation accuracy and urban resilience in emergency management contexts.
- (6) Harnessing VR for training platforms: VR technology can be employed to develop training platforms that bolster public preparedness and self-rescue capabilities, presenting an innovative approach to public safety education.
- (7) Interdisciplinary and systematic development: The field will continue to evolve through cross-disciplinary integration, synthesizing theoretical frameworks from various disciplines to establish a comprehensive evacuation science paradigm.

These future directions reflect the field's trajectory toward increasingly sophisticated and integrated approaches to evacuation management. The successful pursuit of these

research directions will enhance our capacity to address complex emergency scenarios and improve public safety outcomes.

7. Conclusions

This study conducted a comprehensive analysis of the existing literature on evacuation, integrating key indicators such as publication volume, collaboration networks, keyword co-occurrence frequency, centrality, burst, and clustering. These indicators serve as powerful analytical tools for uncovering significant themes and key nodes that have shaped the evacuation field and contributed to its development. This study provided a focused exploration of the fundamental components of evacuation research, offering a thorough review of the field's historical development, consolidating existing knowledge, and laying the foundation for future studies. It also contributed to a comprehensive understanding of all aspects of evacuation. As disaster-related events become increasingly frequent, this work emphasizes the importance of effective evacuation strategies and underscores the urgency of advancing research in this domain. Looking ahead, the rise of artificial intelligence (AI) is poised to have a transformative impact on the field of evacuation research. By leveraging AI, researchers can gain deeper insights into complex evacuation dynamics and develop more effective and adaptive strategies tailored to diverse scenarios. This integration of AI not only has the potential to revolutionize evacuation planning but also to significantly enhance the safety and efficiency of evacuation operations in the face of future disasters.

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