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Review

Mapping the knowledge domain of soft computing applications for emergency evacuation studies: A scientometric analysis and critical review

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ABSTRACT

Emergency evacuation is viewed as a common strategy adopted during the disaster preparedness stage of evacuation to ensure the safety of potentially affected populations. In emergency evacuation studies, soft computing approaches and methodologies have been widely used to support effective decision-making, providing robust and low-cost solutions. To understand the current status and trends of research on soft computing applications for emergency evacuation studies, 778 related studies published in the core database of Web of Science from 2000 to 2020 were considered in this study. A scientometric analysis and a comprehensive review were performed using a scientific mapping of the knowledge domain. This paper presents a set of analyses with the following primary objectives: (1) to explore and visualize the bibliometric characteristics and contents of the academic field concerned with the soft computing approaches for emergency evacuation; and (2) to review and analyze the knowledge, hotspots, and future outlooks related to soft computing approaches for emergency evacuation. The results provide some important insights regarding the existing soft computing methods that have been used in the emergency evacuation field over the past 20 years. Based on the conducted review, this paper proposes that future studies should concentrate on exploring the potential of innovative soft computing approaches for crowd modelling and enabling more accurate evacuation simulation and optimization.

1. Introduction

In recent years, the increasing frequency of extreme weather and natural disasters, such as wildfires, hurricanes, earthquakes, tsunamis, and floods, has posed devastating threats to human life and social stability (Liu et al., 2021a). Examples include the Wenchuan earthquakes in China in 2008 (Song et al., 2019), Australia's catastrophic 2019/20 bushfires (Filkov et al., 2020), Hurricane Sandy (October 2012) in the United States of America (U.S.) (Sadri et al., 2017), and the 2011 Tohoku Earthquake Tsunami in Japan (Takabatake et al., 2020). In addition to these natural disasters, newly emerging cases of hazards, such as chemical accidents, terrorist attacks, and crowd-stampedes, have led to significant human casualties and property losses as well (Liu et al., 2020). Emergency evacuation has become of significant importance for emergency management in facing these natural and human-made disasters.

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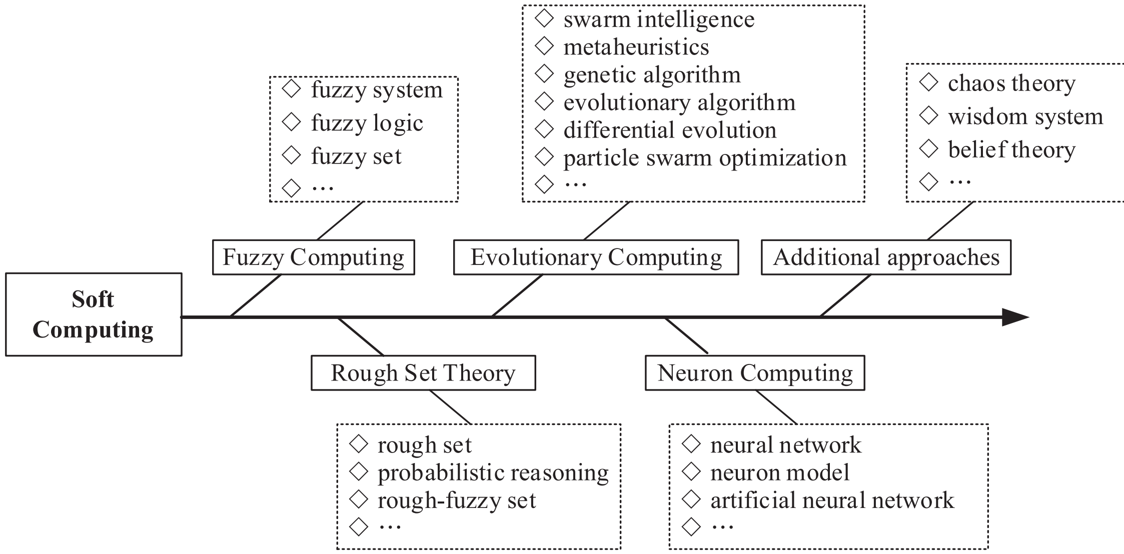

Fig. 1. Classification of soft computing approaches.

The field of emergency evacuation has become more prominent over the past few decades with numerous studies published using experimental data, optimization methods, and modelling simulations that were once infeasible (Bendali-Braham et al., 2021). Emergency evacuation refers to the process of rapidly and safely transferring occupants out of danger areas utilizing various forms of transportation (Joo et al., 2013; Kim et al., 2020). To be specific, emergency evacuation is a systematic and complex process, that includes monitoring and forewarning in the *pre-evacuation period*, evacuation planning and optimization, traffic management and logistics organization, etc. in the *intermediate stage*, and tackling the incomplete activities and restoration of the key resources in the *post-emergency phase* (Dulebenets et al., 2020; Gwynne et al., 2020; Lu et al., 2017; Xie et al., 2019). Therefore, there is a need to study all aspects of evacuation to prevent injuries and fatalities (Darvishan and Lim, 2021; Liu et al., 2022).

Due to the heterogeneity of crowd dynamics and the complexity of the environment, an interdisciplinary perspective should be considered to understand human evacuation behaviour (Bouzat and Kuperman, 2014). For instance, to model pedestrian dynamics, multi-disciplinary approaches, such as social force model (SFM), cellular automata (CA), fluid dynamics (FD), multi-agent simulation (MAS), and game theory, have increased understanding of mass movements and public evacuations by developing mathematical models for prediction of the crowd behaviours and pedestrian flow (Chen et al., 2021b; Haghani, 2021; Mohd Ibrahim et al., 2022; Yang et al., 2020; Zheng et al., 2009). Other interdisciplinary research that combines insights from Physics, Psychology, Operations Research, and Computer Science has focused on planning and optimizing certain important elements (e.g., crowd monitoring, building design, intelligent evacuation management systems, transportation allocation, evacuation path optimization, etc.) during the evacuation process (Akbari et al., 2021; Jin et al., 2021; Liu et al., 2021b; Shiwakoti et al., 2019; Wang and Sun, 2021; Xu et al., 2021).

Traditional modelling of evacuation problems is often based on physics or knowledge-driven methods, which requires well-defined mathematics to model the underlying processes (Supharatid, 2006). This is referred to as hard computing. Due to accurate statistical foundations and strong modelling capabilities, hard computing approaches have been successful in the emergency evacuation field (Sharbini et al., 2021). These approaches have increased understanding of crowd or pedestrian evacuating behaviours by developing analytical and numerical models that reflect the consequences of real evacuation scenarios. One of the widely applied microscopic models, called SFM (Helbing et al., 2000; Helbing and Molnár, 1995), is frequently used for pedestrian motion modelling by identifying people as inertial particles. SFM is intermittently challenged for its initial assumptions and its inability to account for individual differences. To address these limitations, scholars have promoted several extensions to SFM, such as the ESFM (Liu et al., 2018) and more recently the mixed fuzzy model (Cao et al., 2020).

While recognizing the modelling capabilities of hard computing approaches, some researchers think that they fail to accurately solve the problems at hand (Fan et al., 2020; Sharbini et al., 2021; Zhu et al., 2022). Emergency evacuation problems are always complex and influenced by various fuzzy elements with many constraints. For instance, when hard computing approaches are used to solve routing decision problems for emergency evacuation with complex geometric spaces, there is an exponential relationship between the required calculation time and the problem scale (Dulebenets, 2021; Esmin et al., 2006). For large-scale evacuation problems, especially for highly nonlinear problems, it is often difficult to obtain optimal solutions due to time constraints. From a mathematical point of view, existing hard computing approaches cannot find high-quality approximate solutions to large-scale combinatorial optimization problems.

A number of recent publications have suggested that Soft Computing (SC) approaches can achieve higher predictive accuracy than traditional computing methods (Haghani, 2020c). In other words, compared to static, strict, precise, and symbolic hard computing, SC methods are more suitable for dealing with complex evacuation problems (Ibrahim et al., 2016). Soft computing, which was first introduced by Professor Lotfi A. Zadeh in 1992, refers to “a collection of methodologies that aim to exploit the tolerance for imprecision and uncertainty to achieve tractability, robustness, and low solution cost” (Zadeh, 1996). As shown in Fig. 1, SC approaches include Fuzzy Computing (FZ), Rough Set Theory (RS), Neuron Computing (NC), Evolutionary Computing (EC), and others. These constituents are inspired by the reasoning, intuition, awareness, and wisdom that humans possess, primarily through iterative development or learning based on empirical data. Accordingly, they are effective tools to cope with the issues of imprecision, uncertainty, partial truth, learning, and optimization in emergency evacuation studies (Falcone et al., 2020; Sharbini et al., 2021). Ibrahim (2016) pointed out that all these sub-methods are not mutually exclusive and can be combined to solve problems. Artificial Intelligence (AI), as a natural interdisciplinary domain, is generally based on the synergistic use of NC and EC, having their inherent characteristics (Chen and Chu, 2016). SC approaches in emergency evacuation studies have demonstrated their modelling and optimization capabilities for non-

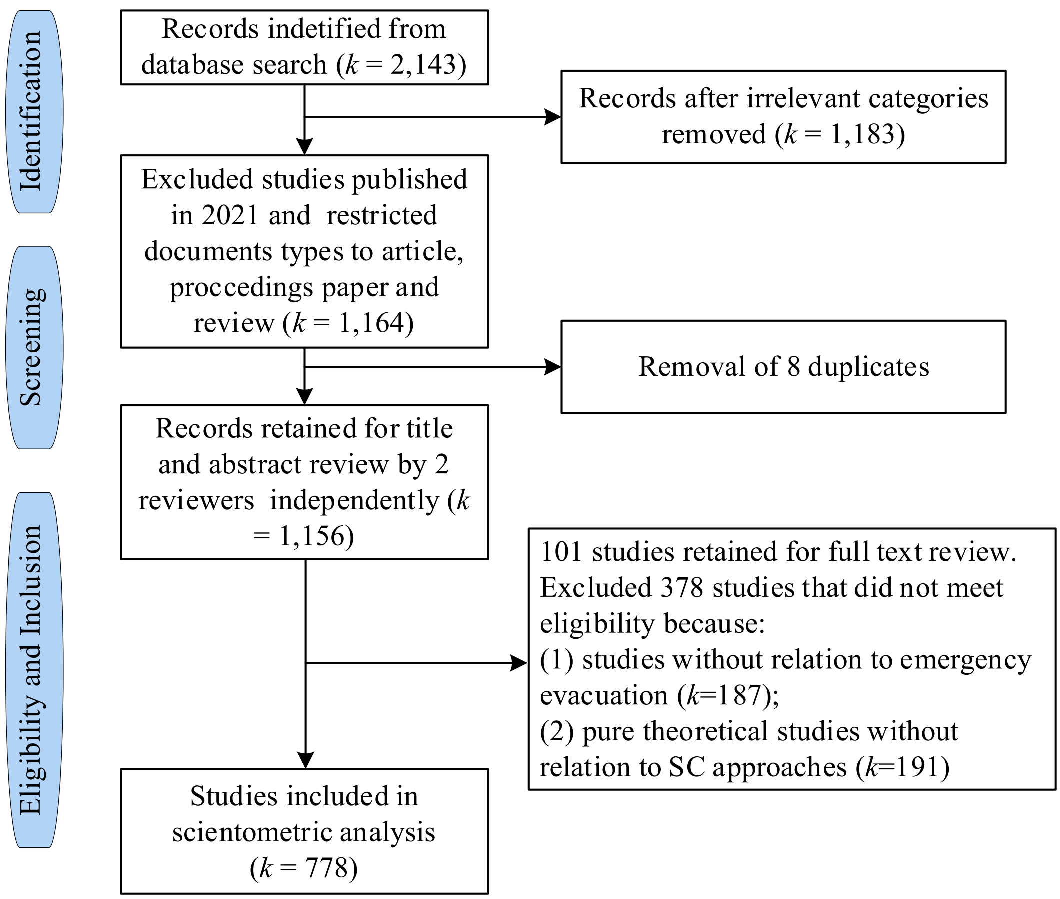

Fig. 2. Data retrieval and processing.

deterministic polynomial-time hard (NP-hard) problems by providing solutions to emergency evacuation problems in a reasonable computational time.

Sharbini et al. (2021) have provided an overview of SC optimization techniques in crowd evacuation simulation models and discussed the microscopic evacuation model integrated with SC approaches. More recently, various applications of Deep Learning (DL), Self-learning, Reinforcement Learning, deep Q-learning, and other AI approaches developed over the last decade for emergency evacuation planning have been published (Bahamid et al., 2020; Chen et al., 2020; Sreenu and Durai, 2019; Tan et al., 2021; Zhang et al., 2021a; Zhang et al., 2021b). However, these studies are limited to certain types of evacuations (e.g., building evacuations (Şahin et al., 2019), fire evacuations (Thompson et al., 2018), evacuation behaviour (Haghani, 2021), and simulation methods (Chen et al., 2021a)). Furthermore, these publications often do not reflect the interdisciplinary characteristics of this domain. Additionally, only a few publications have mapped the relationship between the SC approaches and emergency evacuation studies by analyzing literature distributions, keyword co-occurrence, and evolutionary analysis (Li et al., 2020, 2021a). There is still a lack of survey studies that provide a holistic and comprehensive review of the literature on the application of SC methods for emergency evacuation.

To address the above needs, this paper does not only present an up-to-date holistic and comprehensive review of the literature on the application of SC approaches for emergency evacuation studies but also proposes a quantitative visualization and systematic analysis of the existing studies. In particular, the scientometric analysis deployed in this study provides (a) a better understanding of the knowledge domain related to the application of SC methods for emergency evacuation, (b) a higher level of objectivity than in other reviews, and (c) a quantitative visualization. The main objective of this research is to answer the following research questions (RQs):

RQ1. What is the extent of research on SC approaches in emergency evacuation?

RQ2. What are the developments that have occurred throughout the past years?

RQ3. What are the geographic distribution of studies and collaborative efforts in this field?

RQ4. What is the multidisciplinary knowledge involved in the application of SC approaches for emergency evacuation studies?

RQ5. What are the current research hotspots and the future outlook for the applications of SC approaches in the emergency evacuation domain?

The remainder of this paper is organized into five main sections. Section 2 introduces the research methodology and the literature retrieval process adopted in this study. The bibliometric results and analysis along with supporting discussions are provided based on the research questions and the research trends in Section 3 and Section 4. The last section outlines the main conclusions and findings for each research question and identifies directions for future research.

2. Methodology

2.1. Data sources

Data collection was conducted by employing the PRISMA (Preferred Reporting Items for Systematic Reviews and meta-Analysis) methodology (Page et al., 2021). The literature was retrieved from the core collection database in the Web of Science (WOS) comprehensive bibliographic database, including the *Science Citation Index Expanded*, the *Social Sciences Citation Index*, and *Conference Proceedings Citation Index*. Initial searches for the topic “application of SC for emergency evacuation" were performed from October 2020 to November 2020 to determine a minimum of 19 benchmark studies (Afshar and Haghani, 2008; Alam and Habib, 2021; Dulebenets et al., 2020; Gerakakis et al., 2019; Ghasemi et al., 2019; Ibrahim et al., 2016; Krasko and Rebennack, 2017; Li et al., 2019a; Li et al., 2019b; Liu et al., 2020; Luh et al., 2012; Mei and Xie, 2019; Peng et al., 2019; Rabbani et al., 2018; Şahin et al., 2019; Sharbini et al., 2021; Shen et al., 2019; Wen et al., 2019; Zhang et al., 2021a) for further research in the WOS. A limited set of keywords was extracted from these benchmark studies. Then, the search terms were enhanced by referring to the professional field thesaurus (Liu et al., 2020), Medical Subject Headings (MeSH) thesaurus (Medicine, N.L.o., 2020), suggestions from experts in the field, and snowballing of benchmark studies mentioned above (Wee and Banister, 2016). The main literature search was conducted via the WOS database in January 2021 using the combination of terms "evacuation" and "soft computing". This set of search terms can be found in Appendix A. Considering the scope of the WOS and the development process of the SC, the retrieval time span was set from 2000 to 2020, and the document types were restricted to "article", "review", and "proceeding papers". Only documents published in English were considered throughout the literature search. Each record included the title, author, institution, abstract, keywords, published year, and references.

The literature retrieval procedure and results are shown in Fig. 2. The first search included a total of 2,143 potential documents. After removing duplicates and irrelevant categories (e.g., Archaeology, Ophthalmology, or Plant Sciences), 1,156 publications were retained for the title and abstract review. Then, a manual abstract review was conducted independently by two authors to remove the studies that did not meet the retrieval criteria. In the meantime, these two authors determined the types of emergency evacuation and SC approaches to be considered during the screening procedure. The experts did not achieve a consensus on 101 studies, so another author was invited to resolve the issues until an agreement was reached. In total, 778 papers were contained in the final dataset and classified for emergency evacuation and SC approaches. These publications included 468 Articles (60.15 %), 300 Proceeding Papers (38.56 %), and 10 Reviews (1.29 %).

2.2. Taxonomy of emergency evacuations

Recent works have recognized the importance of different evacuation types (Bendali-Braham et al., 2021; Gelenbe and Wu, 2012; Haghani, 2020c; Liu et al., 2020; Şahin et al., 2019). A categorization of different types of emergency evacuation is thus needed, considering whether SC approaches could be applicable to certain types of emergency evacuation. Hence, the selected emergency evacuation studies were categorized based on the two parallel considerations: (1) evacuation scenarios taxonomy (e.g., building evacuation, large-scale evacuation, mixed traffic evacuation, and others); and (2) evacuation causes taxonomy (e.g., natural disaster evacuation, manmade disaster evacuation, hybrid disasters evacuation, and evacuation experiments) (Feng et al., 2021a; Haghani, 2021; van der Wal and Kok, 2019). Appendix B summarizes the presentation of benchmark studies, including the taxonomy of emergency evacuations. Next, these taxonomies are explained in more detail.

From an evacuation scenario's point of view, a category of emergency evacuation can be distinguished considering the hazardous areas: building evacuation, large-scale evacuation, mixed traffic evacuation, and others. If accidents (e.g., fire, earthquake, or toxic gas release) happen in a building (e.g., a residential building, a theatre, a train station, a stadium, or a shopping mall), and evacuees have to escape from a building in time, this is called a building evacuation (Luh et al., 2012; Zheng et al., 2009). Compared to building evacuation, large-scale evacuation (e.g., earthquake, hurricane, or other natural disasters causing mass evacuation) involves millions of people, requires walking/driving a long distance, generally takes place outdoors, and lasts an extended period of time (Darvishan and Lim, 2021; Murray-Tuite et al., 2018). On the other hand, mixed traffic evacuations involve people evacuating by car or by using other public/mass transportation means, requiring significant improvisation due to disaster intensity and traffic capacity, disrupted communication and transportation systems (Alam and Habib, 2021; Du et al., 2022; Wu et al., 2022; Zhang and Chang, 2014).

To adequately prepare and respond to disasters, the classification of evacuations should account for the specific type of disaster as well. Disaster types have been reviewed by various experts and organizations, such as Turner and Pidgeon (1997), Gill and Malamud (2014), Shi (2019), World Health Organization (WHO 1998), and the Disaster Database (Guha-Sapir, 2001; Voigt et al., 2016). The distinction between natural, man-made, and hybrid disasters has been found to cover all types of catastrophic events (Mohamed Shaluf Ibrahim, 2007b). Natural hazards result from internal (beneath the Earth's surface, e.g., earthquakes, tsunamis, and volcanic eruptions), external (topographical, e.g., landslides and avalanches), weather-related (meteorological/hydrological, e.g., windstorms, tornados, floods, and drought), and biological phenomena (e.g., epidemics, infestations, and locust swarms) (Avanzi et al., 2017; Sun et al., 2020; Young et al., 2004). Man-made disasters (or technological hazards) are those catastrophic events that result from human decisions including socio-technical (e.g., technological disasters, transport failures, stadia or other "public place" failures, and production failures) and warfare disasters (e.g., terrorism, inter-state and international conflicts, and non-conventional wars) (Gai et al., 2017; Shaluf and Said, 2003; Xu et al., 2016). Hybrid disasters are a result of both natural forces and human activities (e.g., landslides caused by deforestation and heavy rain) (Mohamed Shaluf Ibrahim, 2007a; Shi, 2019). Compared to the above specific disaster-causing evacuations, some evacuation studies, namely evacuation experiments (e.g., evacuation drills, laboratory experiments, and evacuation simulations), do not contain real disaster sources. According to the previous systematic analyses (Haghani, 2020a, b), an evacuation experiment is a type of evacuation that simulates evacuation based on social animals or human experiments or with the help of modelling and simulations. This paper adheres to this convention.

2.3. Analytical methods

Over the last decades, scientometric methods have been widely applied in Safety research. As an emerging approach to Scientometrics, the concept of a scientometric analysis was first defined by Nalimov and Mul'chenko (1971) as "a quantitative study of the research on the development of science" that can critically assess the State of the Art throughout scientific research using visualization techniques (Börner et al., 2003). This paper presents a scientometric analysis of the studies that apply SC approaches for emergency evacuation to create a comprehensive and systematic overview of this research domain along with the literature distribution characteristics. The literature distribution characteristics, including the research subject type composition, total scientific production, collaborating authors and countries worldwide, number of authors' affiliations and citations, are directly utilized in this method.

Next, the knowledge structure was investigated by employing co-occurrence methods. An analysis of fields, categories, and document citation networks has been automatically conducted using the scientometric software CiteSpace and VOSviewer. CiteSpace stands for *Citation Space* and was developed by Prof. Chaomei Chen (Chen, 2006; Chen et al., 2010). CiteSpace is the most widely used tool for scientific domain mapping (Li et al., 2021a). VOSviewer developed by Dr. Nees Jan van Eck and Prof. Ludo Waltman (Van Eck and Waltman, 2010) is a tool for scientometric visualization (Waltman et al., 2010). Both software packages have been used to perform a knowledge domain mapping analysis using bibliographic data (Li et al., 2022b; Van Nunen et al., 2018).

Additionally, keyword co-occurrence and cluster analyses were

Table 1
Descriptive statistics of applied soft computing approaches for different evacuation types.

Evacuations types		Soft computing approaches				
		NC	EC	FZ	RS	NC&EC
Evacuation scenarios	Building evacuation	142	121	20	8	16
	Large-scale evacuation	55	65	9	4	9
	Mixed traffic evacuation	63	135	18	6	23
	Others	30	28	12	5	9
Evacuation causes	Natural disaster evacuation	50	95	9	7	13
	Manmade disaster evacuation	56	57	15	8	7
	Evacuation experiments	164	168	29	5	32
	Hybrid disasters evacuation	20	29	6	3	5

Notes: neuron computing (NC), evolutionary computing (EC), fuzzy computing (FC), and rough set theory (RS).

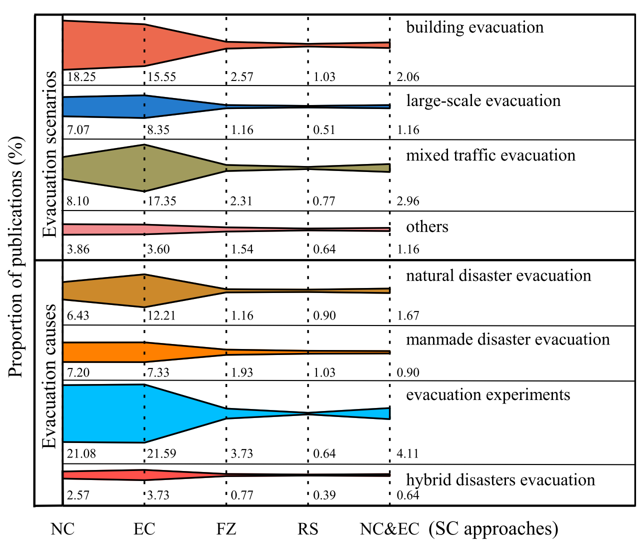

Fig. 3. Distribution of the reviewed studies by the SC approach.

conducted to develop the framework for the critical review and to identify hot topics and frontier trends. Based on the textual data, a cluster analysis was performed (Waltman et al., 2010). Then, a critical review was carried out to explore the underlying semantic themes. The combination of critical review and cluster analysis can improve the objectivity of the literature review and provide a comprehensive understanding of the results (Zhong et al., 2019).

3. Results

This section is organized into six parts. Section 3.1 concerns the categorical distribution of the reviewed studies according to RQ1. Section 3.2 describes the publication trends in response to RQ2. The geographic distribution and collaborative efforts of the reviewed studies are summarized in Section 3.3 and Section 3.4, respectively, based on RQ3. Section 3.5 analyses the multidisciplinary knowledge involved in the reviewed studies to address RQ4. The keyword co-occurrence analysis is used to partially respond to RQ5 in Section 3.6, and more details regarding RQ5 are provided in Section 4.

3.1. The categorical distribution of the reviewed studies

At present, scholars have contributed various studies in the field of

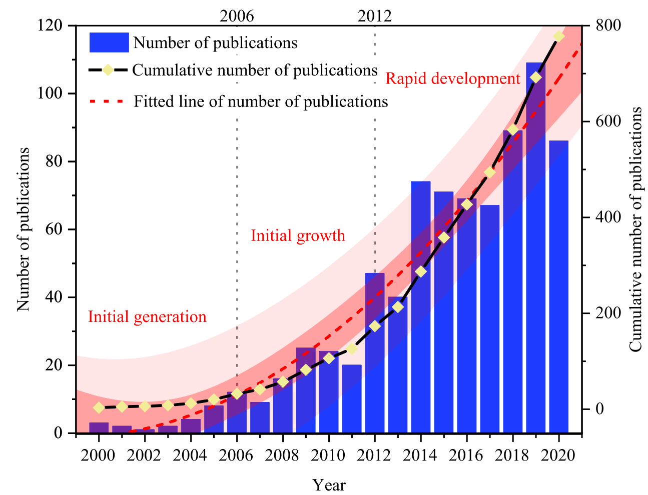

Fig. 4. The annual trends of publications from 2000 to 2020.

SC approaches for emergency evacuation (Liu et al., 2020). Existing research mainly employs FZ, RS, NC, and EC methods for different categories of evacuation (Ibrahim et al., 2016; Liang and He, 2019). A manual review of these categories added precision. The descriptive statistics of the final dataset are summarized in Table 1 and Fig. 3. As shown in Table 1 and Fig. 3, different SC approaches have been applied for different emergency evacuation types. Overall, for the two emergency evacuation taxonomies (i.e., evacuation scenarios and evacuation causes), the NC and EC methods are the most widely used SC approaches and have been applied for calculating the shortest path or minimizing travel time (Stolfi and Alba, 2014; Toutouh and Alba, 2017). These objectives were most often achieved by means of applying the Dijkstra algorithm, simulated annealing, genetic algorithm, and other SC methods (Ji et al., 2021). More fundamentally, for the studies dealing with the determination of the exit routes, the evacuation scenarios were often conducted for enclosed buildings, where NC and EC demonstrated their effectiveness as nature-inspired SCs (Ghaheri et al., 2015; Nakib et al., 2017; Seo et al., 2022). The results from the conducted analysis demonstrate that the NC and EC methods were found to be the common SC approaches for building evacuations and evacuation experiments.

There are relatively few studies applying FZ and RS. These studies mainly focused on man-made disaster evacuations. Such a finding can be explained by the unique advantages of FZ and RS in modelling complex human behaviour. For instance, Gerakakis et al. (2019) incorporated fuzzy logic in exit selection based on the criterion of distance during evacuation. Unlike hard computing approaches, AI methods allow for more flexible model structures, more complex input data, and more accurate predictions, which can improve the fit between the empirical data and the final model (Xie et al., 2003; Zhao et al., 2020). In other words, AI methods can demonstrate predictive power in large-scale evacuation scenarios with multiple variables (Bucar and Hayeri, 2022; Seo et al., 2022). NC&EC were mostly used in the research related to mixed traffic evacuation and natural disaster evacuation, because these scenarios often require the pedestrian flow predictions and involve various variables, such as vehicles and disaster propagation.

3.2. Publication trends

A statistical analysis of the temporal distribution of the literature can help to understand the developing progress in a certain domain (Zou et al., 2018). The number of publications focusing on the application of SC approaches for emergency evacuation is influenced by the developments in this area of research. Fig. 4 illustrates the annual number and the cumulative number of studies that were selected for review as part of the present survey. A surge of publications can be observed over

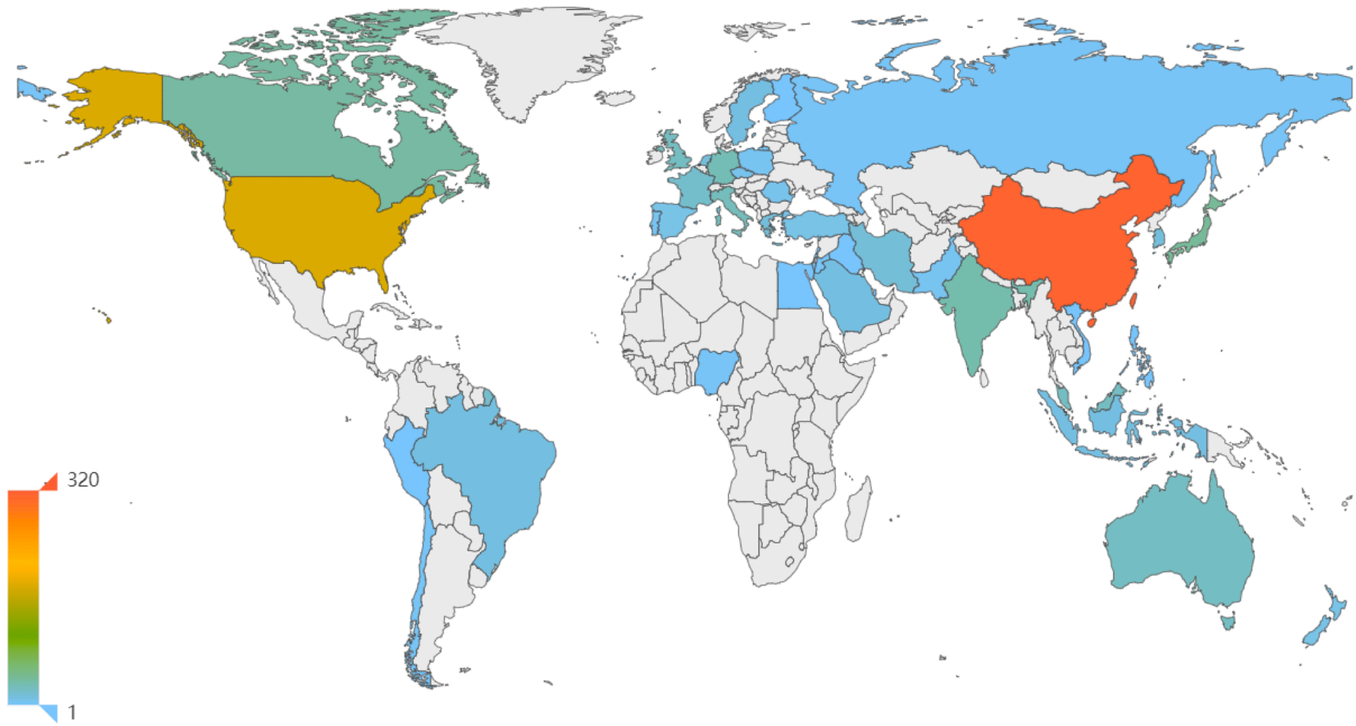

Fig. 5. Distribution of the reviewed studies by country and region.

the last 20 years. As pointed out by Liu et al. (2020), emergency evacuation studies remain to be a hotspot research field. The entire trends graph can be divided into three separate stages: (1) initial generation; (2) initial growth; and (3) rapid development.

The annual number of publications was less than 10 studies until 2005. This indicates that there was an initial generation stage (before 2006), where only a few relevant studies explicitly focused on the application of SC approaches for emergency evacuation. Although there was a lack of publications during this initial stage, several explorations (Church and Cova, 2000; Hamacher and Tjandra, 2001; Zou et al., 2005) opened up and led to many research directions, providing the foundation for the subsequent development. From 2006 to 2012, a steady growth in the number of publications can be observed (approximately 17 papers per year), following the rapid development of SC methods and computers. Specifically, evacuation modelling and simulations provided means for identifying risks and opportunities in emergency evacuation management (Benbu et al., 2017; Chen et al., 2021a). It can be considered that this field was initially formed at the initial growth stage (2006–2011). With the advent of Industry 4.0, the rapid development stage started in 2012 (Karnik et al., 2021; Sharma et al., 2022), the year that brought numerous emerging techniques, including the Internet of Things (IoT), Building Information Modelling (BIM), Geographic Information System (GIS), Virtual Reality (VR), and AI (Feng et al., 2022; Li et al., 2021d; Mei et al., 2019; Zhang et al., 2022). An exponential growth in the literature quantity can be observed during this phase.

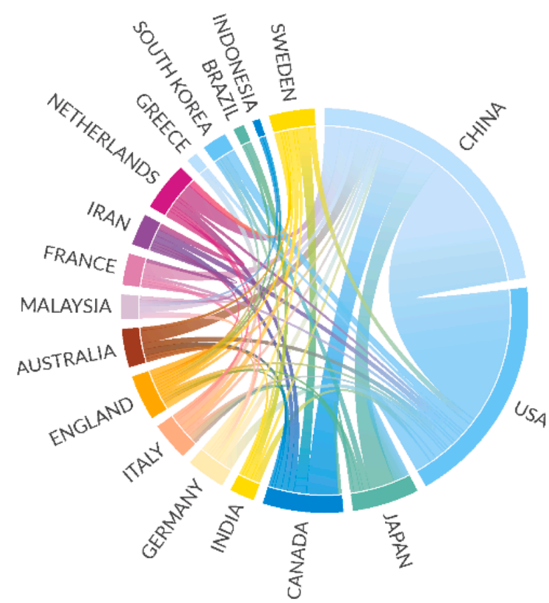

Fig. 6. Distribution of the reviewed studies by cooperative countries.

3.3. The distribution of the reviewed studies by country and institution

Fig. 5 represents the geographic distribution of the reviewed studies on the application of SC approaches for emergency evacuation globally. It can be seen that, in total, 47 countries/regions have contributed to the 778 documents reviewed. The results show that the relevant research is widely distributed across the world, and the high-yielding countries are mainly located in the Asia-Pacific region and the Western developed countries. The vast majority of publications originate from China (318 studies, 32.62 %) and the U.S. (179, 18.36 %), far exceeding other countries and regions. In addition, Japan (42, 4.31 %), Canada (37, 3.79 %), India (33, 3.38 %), Germany (29, 2.97 %), Italy (27, 2.77 %), the United Kingdom (the U.K., 25, 2.56 %), Australia (24, 2.46 %), and Malaysia (24, 2.46 %) have published more than 20 papers, which together with China and the U.S. constitute the most productive countries in this field. Note that the total number of records for the identified geographical locations exceeds the final 778 documents because the authors of a given study may come from different countries or regions.

Fig. 6 shows the distribution of the reviewed studies by cooperating countries. The portion of the circle is determined by the number of collaborative publications, and the thickness of lines between each country represents the strength of cooperation. Based on the data observed in Fig. 6, China and the U.S. are the core countries of the two

Table 2
Top 17 most productive institutions.

Rank	Institution	Country	Quantity	TLS	*ACI*
1	Tsinghua University	China	23	153	6.65
2	Wuhan University Technology	China	22	95	4.32
3	Beijing Jiaotong University	China	20	94	4.70
4	Chinese Academy of Sciences	China	16	159	9.94
5	Tongji University	China	14	44	3.14
6	Purdue University	U.S.	13	107	8.23
7	National University of Defense Technology	China	12	101	8.42
7	University of Maryland	U.S.	12	215	17.92
9	Beijing Normal University	China	11	91	8.27
10	Wuhan University	China	10	96	9.60
10	Northeastern University	U.S.	10	171	17.10
10	Southeast University	U.S.	10	73	7.30
10	University of Science & Technology China	China	10	51	5.10
14	University of Tokyo	Japan	9	88	9.78
14	Delft University of Technology	Netherlands	9	65	7.22
14	University of Arizona	U.S.	9	187	20.78
17	University of Regina	Canada	8	138	17.25
17	University of Tennessee	U.S.	8	175	21.88
17	Southwest Jiaotong University	China	8	23	2.88
17	Hong Kong Polytech University	Hong Kong (China)	8	167	20.88
17	Huazhong University Science & Technology	China	8	72	9.00
17	Science University of Malaysia	Malaysia	8	42	5.25

Notes: TLS means total link strength, and *ACI* means the average citations per item.

main groups in the national cooperation network. One cooperative group is a China-centered cooperation group, with major collaborating countries and regions from North America, East Asia, and Europe. As the most productive country, China has cooperated with many countries, especially with the U.S. (43 articles), Canada (10 articles), Japan (8 articles), and the Netherlands (5 articles). Another cooperative group comes from the Western developed countries collaborating with the U.S. as the core, including Germany, the Netherlands, the U.K., and Sweden. Additionally, Australia and India also have a strong international cooperation with other countries. In the global network of cooperation, the U.S. is the most influential country (cooperating with 14 countries), followed by the U.K. and China (11 countries).

The 778 documents selected in this study for a detailed review were retrieved from 232 research institutions around the world, among which 13 institutions have published at least 10 studies, all from China and the U.S. Table 2 summarizes the 17 most productive institutions using the VOSviewer, among which the top 5 institutions are all from China, including Tsinghua University (23 studies), Wuhan University of Technology (22), Beijing Jiaotong University (20), Chinese Academy of Sciences (16), and Tongji University (14). Purdue University (13), University of Maryland (12), and Northwestern University (10) are the U.S. institutions that are ranked as 6th, 7th, and 10th, respectively. These findings further reflect the dominance of China and the U.S. in this field. The total link strength (TLS) and the average citations per item (*ACI*) indicate the institutional influence from another perspective. The TLS metric represents the total strength of co-authorship of a given institution with other institutions. As can be seen from Table 2, the University of Maryland (TLS, 215), the University of Arizona (187), and the University of Tennessee (175) are ranked as the top three for TLS. University of Tennessee (21.88) and University of Arizona (20.78) from the U.S. and Hong Kong Polytech University (20.88) from China have the top 3 highest *ACI*. A comprehensive comparison shows that the institutions from China are generally more productive, but there is a gap with the U.S. in terms of research cooperation. In summary, the scholars from China and the U.S. have contributed most of the research and influence in the field of SC applications for emergency evacuation.

3.4. Cooperation network analysis

An author co-authorship analysis assists with the identification of relationships between researchers related to common research interests.

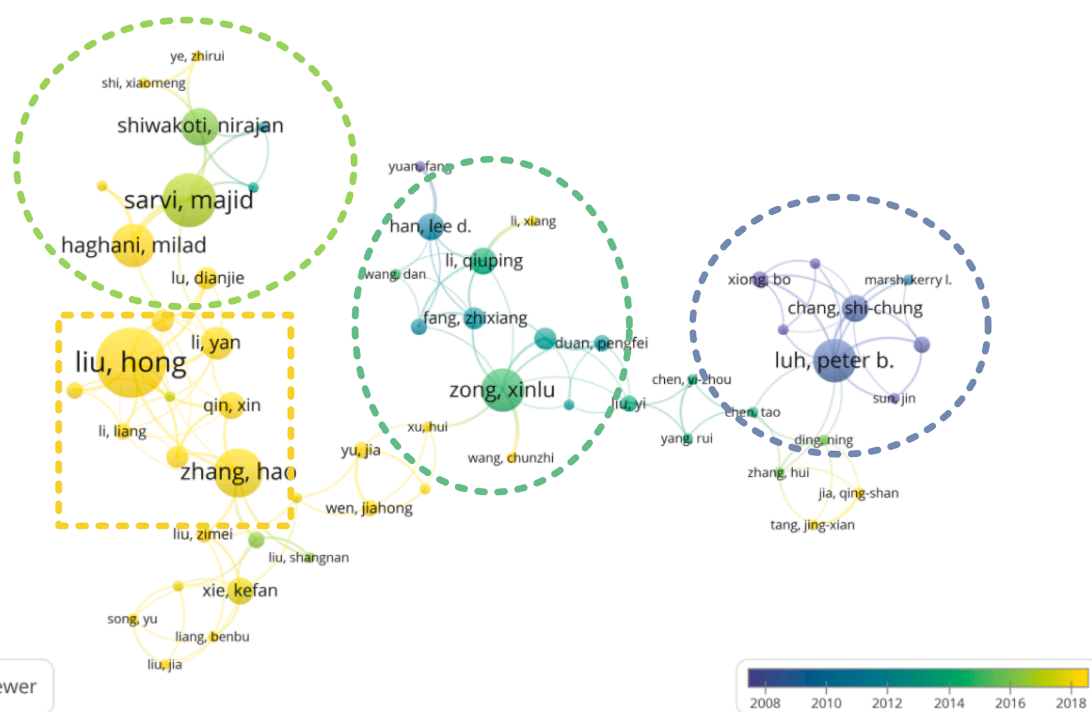

Fig. 7. Collaborative network map of authors.

Table 3
Distribution of top 10 disciplines: Global and stage analysis.

Rank	Initial generation (before 2006) (N = 17)			Initial growth (2006–2011) (N = 30)			Rapid growth (2012–2020) (N = 40)			Global (N = 42)		
	Discipline	F	P	Discipline	F	P	Discipline	F	P	Discipline	F	P
1	Computer Science, Artificial Intelligence	7	17.07 %	Transportation Science & Technology	25	11.06 %	Transportation Science & Technology	108	9.63 %	Computer Science, Artificial Intelligence	150	9.95 %
2	Transportation Science & Technology	4	9.76 %	Computer Science, Artificial Intelligence	23	10.18 %	Computer Science, Theory & Methods	103	9.19 %	Transportation Science & Technology	137	9.08 %
3	Operations Research & Management Science	4	9.76 %	Engineering, Civil	23	10.18 %	Engineering, Electrical & Electronic	90	8.03 %	Computer Science, Theory & Methods	127	8.42 %
4	Transportation	3	7.32 %	Computer Science, Theory & Methods	21	9.29 %	Engineering, Civil	87	7.76 %	Engineering, Civil	111	7.36 %
5	Computer Science, Software Engineering	3	7.32 %	Computer Science, Interdisciplinary Applications	17	7.52 %	Operations Research & Management Science	85	7.58 %	Operations Research & Management Science	104	6.90 %
6	Computer Science, Theory & Methods	3	7.32 %	Operations Research & Management Science	15	6.64 %	Computer Science, Interdisciplinary Applications	76	6.78 %	Engineering, Electrical & Electronic	104	6.90 %
7	Computer Science, Information Systems	2	4.88 %	Engineering, Electrical & Electronic	14	6.19 %	Computer Science, Information Systems	60	5.35 %	Computer Science, Interdisciplinary Applications	95	6.30 %
8	Mathematics, Applied	2	4.88 %	Transportation	12	5.31 %	Engineering, Multidisciplinary	56	5.00 %	Computer Science, Information Systems	69	4.58 %
9	Computer Science, Interdisciplinary Applications	2	4.88 %	Computer Science, Software Engineering	11	4.87 %	Engineering, Industrial	53	4.73 %	Engineering, Multidisciplinary	66	4.38 %
10	Engineering, Multidisciplinary	2	4.88 %	Engineering, Multidisciplinary	8	3.54 %	Computer Science, Software Engineering	47	4.19 %	Computer Science, Software Engineering	61	4.05 %

Notes: N denotes the total number of the subject categories, F represents the frequency of each subject, and P is the corresponding proportion.

By exploring the network of collaborative publications by different authors, cooperation among these authors can be identified along with influential scholars and important research groups (Zou and Vu, 2019). Fig. 7 shows the collaborative network map of authors in the field of SC methods for emergency evacuation that was developed using the VOSviewer. In the developed network, the node represents the author, the lines denote the intensity of cooperation between different researchers, and the colours indicate the average number of publications of their relevant works per year. It can be seen that the size and distribution of nodes can be divided into 4 research groups according to the similarities in the author's activities in the considered research field. As can be observed in Fig. 7, Majid Sarvi (The University of Melbourne, 3 publications), Hong Liu (Shandong Normal University, 5 articles), Peter B. Luh (University of Connecticut, 5 articles), and Xinlu Zong (Hubei University of Technology, 3 articles) published most of the co-authored documents. The majority of collaborating researchers are from China and the U.S., which is consistent with the above findings that China and the U.S. are the two most productive countries.

In addition, as the top 2 % scholar in the areas of Traffic and Transport Engineering based on the WOS, Majid Sarvi is another core author of an important research group, including the researchers he supervised (Alhawsawi, 2021; Haghani, 2017; Li, 2020; Shahhoseini, 2018). His recent work extended the application of AI approaches in large-scale mixed traffic evacuation and crowd dynamic modelling and simulation. Similar to Majid Sarvi's group, Hong Liu and her team have focused on applying the DL methods in the fields of path planning, crowd counting, crowd emotional contagion, and other emergency evacuation management processes (Li et al., 2021c; Shi et al., 2021; Xie et al., 2022). In particular, the publications of these two research groups are relatively concentrated in recent years, which further reflects the research upsurge of machine learning applications in emergency evacuations. Compared to the above two research groups, Peter B. Luh's and Xinlu Zong's groups started related research earlier than others and preferred exploring emergency evacuation questions with hybrid optimization techniques (Ding et al., 2015; Duan et al., 2014; Ye et al., 2014; Zong et al., 2014). Xinlu Zong is a graduate of Wuhan University of Technology, which is the second most productive institution in the field of SC applications for emergency evacuation.

3.5. Multidisciplinary knowledge analysis

Every publication indexed in the WOS Core Database is assigned at least one subject category, indicating its research field. Generally, a high proportion of subject terms, which also can be called a leading discipline, means that the subject has a strong knowledge background, many academic achievements, and high research demands increasing attention from the scientific community (Liu et al., 2020; Yang et al., 2019). Considering the interdisciplinary characteristics of emergency evacuation and SC methods, the knowledge involved in this field can be further analyzed by exploring the subject classification of the 778 retrieved publications (Haghani et al., 2022).

Table 3 summarizes the top 10 related subjects of this research field from the perspective of the whole and three development stages. From Table 3, 42 disciplines were identified from all publications on a global scale, widely distributed in Computer Science, Engineering, Transportation Science, Management Science, and others. In addition, there is a little difference in the composition distribution of the top 10 subjects at different development stages, indicating that the knowledge structure required by this field is relatively fixed. In particular, the total number of interdisciplinary subjects increased from 17 at the initial generation stage to 40 in the rapid growth stage, showing that new disciplines are constantly added to enrich the research content and methods in this field. Computer Science is the most widely applied discipline, but the sub-disciplines distribution is slightly different in these three development stages. For instance, the discipline of AI has provided a strong motivation for development in the first two stages. However, with the significantly increasing scale and complexity of emergency evacuation problems, and new requirements being put forward for hardware and SC

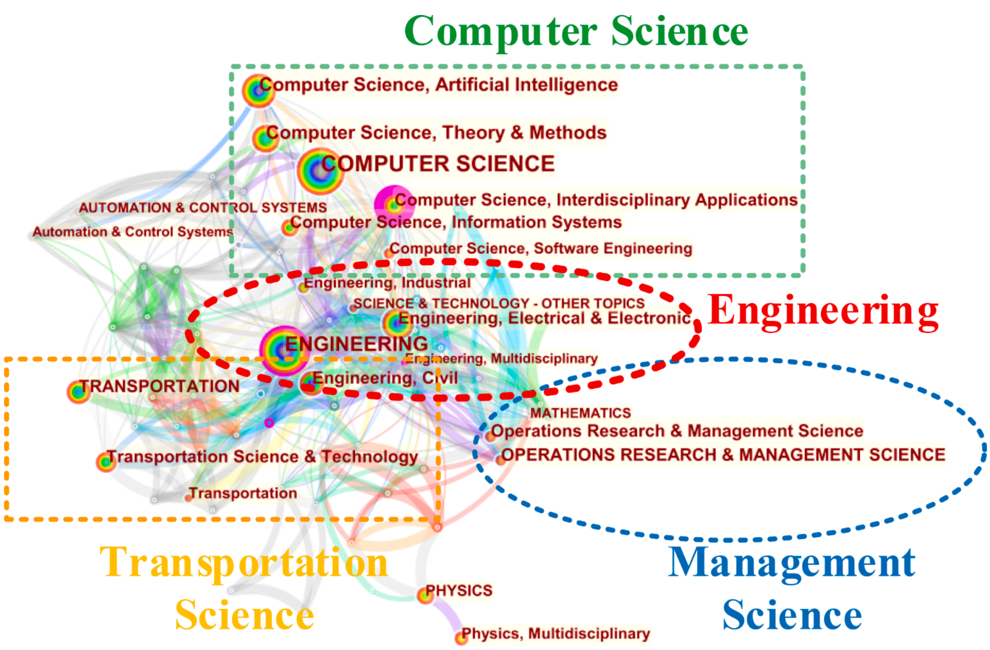

Fig. 8. Cluster label network with the main research disciplines.

algorithm performance, the relevant disciplines (e.g., Theory & Methods, Information Systems, and Software Engineering) have received more and more attention during the rapid growth stage.

A subject co-occurrence analysis was conducted using CiteSpace, of which the analysis results are presented in Fig. 8. These results show that the knowledge structure of this research field is mainly distributed among the themes of Computer Science, Engineering, Transportation Science, and Management Science. The core of SC approaches is a human-like thinking method, with a mathematical modelling idea in essence. Calculation of the mathematical model relies on expertise in Computer Science. Based on Fig. 8, various Engineering sub-disciplines play a critical role in connecting different subjects. Especially in recent years, various emerging technologies, such as Information and Communication Technology, IoT, BIM, GIS, VR, and simulation technologies, provide new platforms and technical support for applying SC approaches in emergency evacuations. For example, in the field of mixed

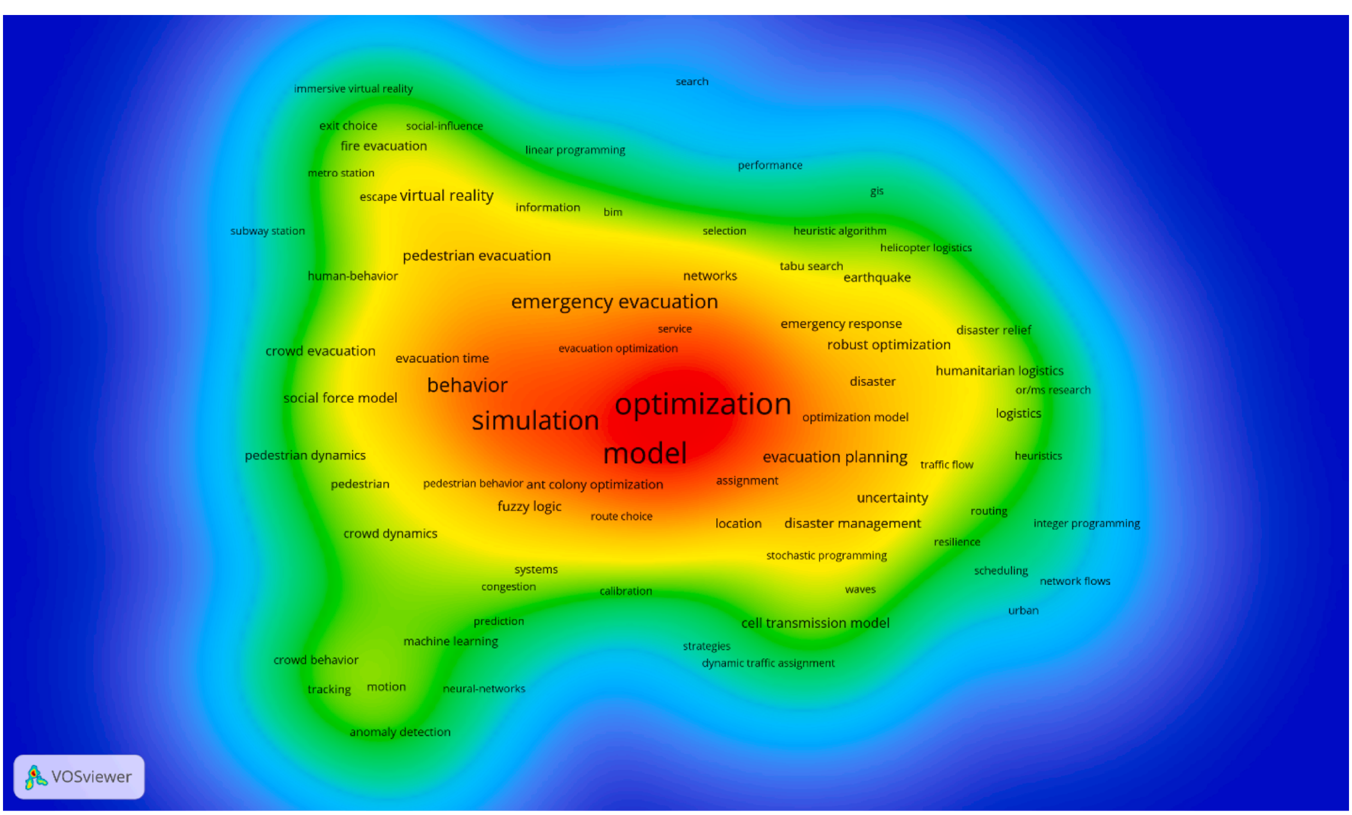

Fig. 9. Keyword density visualization map of publications based on the full-counting method.

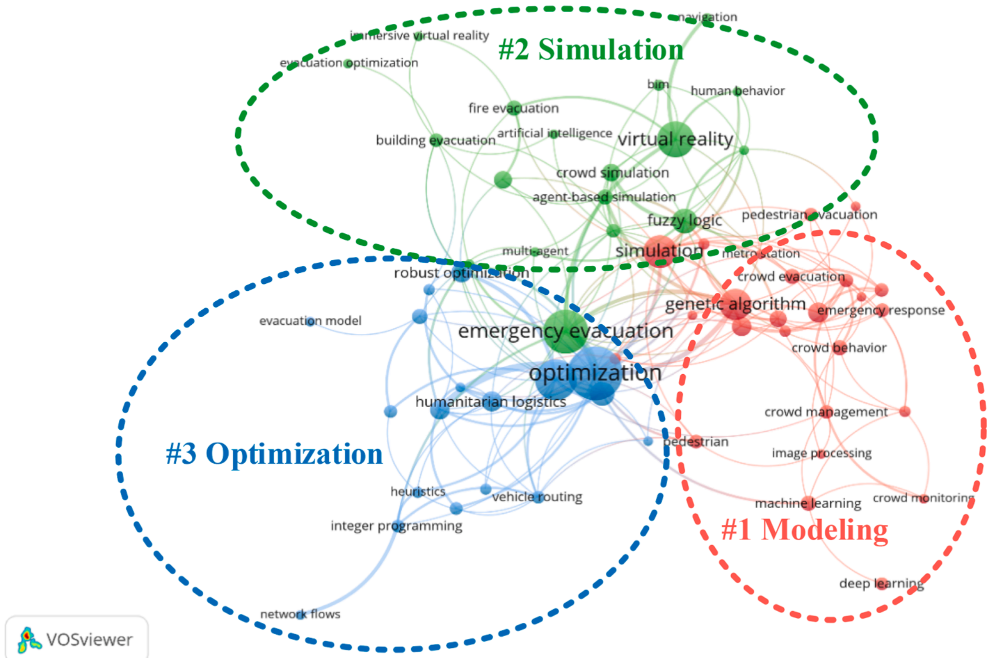

Fig. 10. Keyword co-occurrence network of publications.

traffic evacuation, Vehicle-mounted Internet, Radio Frequency Identification, and GIS have greatly promoted the development of intelligent traffic evacuation (Chen and Chung, 2017; Du et al., 2021; Liu et al., 2022; Wang et al., 2022b). Recent popular technologies, such as Big Data, VR, 5G, Sensors, and Cloud technology, enable scholars to accurately quantify and analyze human psychology, social behaviour, and crowd dynamics during large-scale emergency evacuation situations, hence, to better set the parameters for pedestrians or crowds in SC models (Diao and Shih, 2018; Feng et al., 2022; Li and Hsiao, 2018; Zhang et al., 2016). The development of platforms and solvers (e.g., FICO Xpress Optimization, Gurobi Optimizer, and IBM ILOG CPLEX Optimization Studio) provides new solutions for SC algorithms and can be used to address mass evacuation optimization problems. For example, Evolutionary Algorithms can well balance the precision and exponential explosion of the search space in a large-scale emergency evacuation planning problem, but the optimal solution for small-scale instances still needs to be determined by employing a general solver (e.g., CPLEX) or an alternative exact optimization approach to establish the benchmark for solution quality (Dulebenets et al., 2020; Pasha et al., 2020).

3.6. Keywords co-occurrence analysis

The keywords used by the collected studies are representative descriptions of the research content. Hence, the current research hotspots can be identified in a keyword co-occurrence network (Zou et al., 2020). With the help of VOSviewer, a keyword co-occurrence map of existing studies has been developed to identify the relationship between the adopted keywords (both *Author's keywords* and *Keywords Plus* indexed in the WOS). Setting the minimum number of occurrences of all keywords (i.e., two times), Fig. 9 shows the 132 main keywords selected from a total of 2,603 keywords. As shown in Fig. 9, the size of the labels represents the number of keyword occurrences (full-counting), and the shades of colour indicate the density of keyword occurrences. The top ten keywords were found to be *optimization* (occurrences: 169, total link strength: 690), *model* (156, 653), *simulation* (127, 527), *emergency evacuation* (67, 275), *behaviour* (64, 308), *algorithm* (45, 206), *genetic algorithm* (34, 87), *evacuation planning* (33, 132), *virtual reality* (28, 88), *and social force model* (19, 103). Other popular keywords are also related to certain SC approaches, such as fuzzy logic, neural networks, and machine learning.

4. Discussion

4.1. Current research hotspots

To better understand the current research foci, a keyword clustering was performed using the VOSviewer. Fig. 10 shows the three core clusters that occur together between the most popular keywords. The higher the frequency of co-occurrence of different keywords, the closer and larger the labels. The stronger related keywords are collected together in a cluster represented with the same colour (Chen et al., 2022). Similar to the keywords in Fig. 9, the vast majority of the identified terms are related to emergency evacuation issues. As a result of the conducted analysis, the following major keyword clusters have been distinguished: (1) the red clustering that corresponds to the #1 crowd modelling; (2) the green cluster that corresponds to the #2 evacuation simulation; and (3) the blue cluster that corresponds to the #3 emergency evacuation optimization. Note that the clustering was performed by focusing mainly on the application of SC approaches from the perspective of emergency evacuations. More details regarding each cluster are provided next.

4.1.1. Cluster #1: Crowd modelling

The high-frequency keywords contained in this cluster include the following: crowd behaviour, crowd management, machine learning, deep learning, image processing, and genetic algorithm. Actually, the previous literature offers a traditional overview of the crowd modelling taxonomy (e.g., a taxonomy based on the macroscopic model, microscopic model, and mesoscopic model proposed by the Federal Highway Administration (Agnelli et al., 2015)), or the taxonomy based on continuous models and discrete models (Lu et al., 2017)). Macroscopic models (e.g., Lattice Gas and FD) analyze emergency evacuation from the whole level, aiming to explore the characteristics of crowd flow rather than the individuals (Kalogeiton et al., 2015; Xie et al., 2018). They allow studying evacuation planning and local collision conflicts in the same framework but fail to contain the influence of crowd emotions. Conversely, microscopic models and mesoscopic models (e.g., SFM (Helbing et al., 2000)) not only focus on the psychological and dynamic

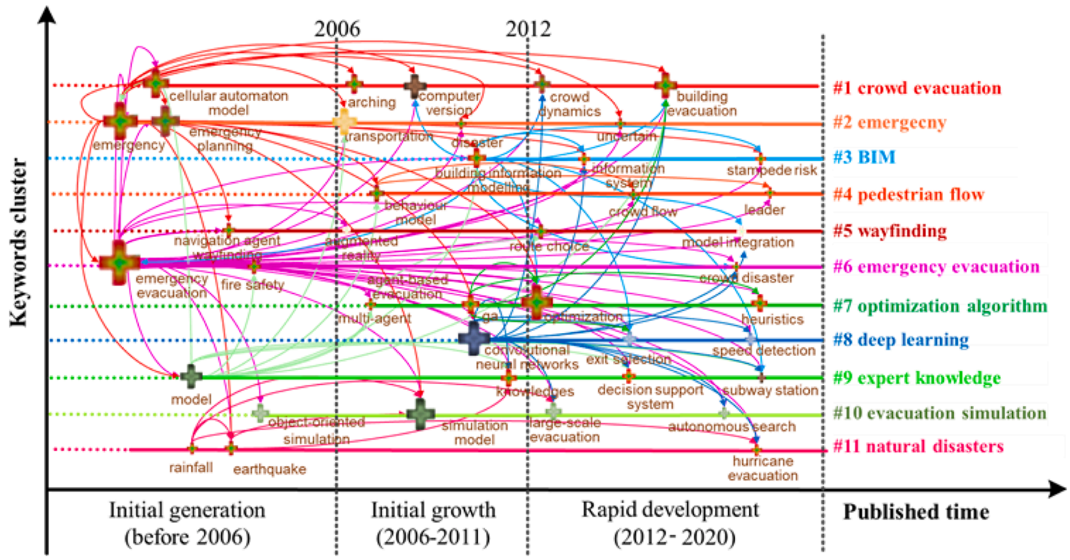

Fig. 11. Keyword timeline view of publications from 2000 to 2020. The horizontal axis represents the time of publication, the links show the connection relationship among the co-occurred keywords, and the node labels denote the keywords (larger nodes indicate the higher frequency of co-occurred keywords).

characteristics of evacuees but also study the interaction between individuals and the environment as well as their spatio-temporal behaviour (Cao et al., 2017; Liu et al., 2021a).

However, considering the application of SC approaches, it is more appropriate to divide crowd modelling methods into vision-based approaches (e.g. crowd monitoring system, pedestrian detecting, and crowd optical flow analysis) and non-vision approaches (e.g., physics-based, cellular-based, nature-based, sociology-inspired, and biology-based approaches), according to Zhan et al. (2008)'s survey. In the field of non-vision approaches, numerous relevant studies have been published, and many scholars have made detailed summaries and generalizations (Feng et al., 2021b; Grant and Flynn, 2017; Haghani, 2021). In addition, various traditional non-vision modelling methods also combine several SC approaches. As the DL is ubiquitous in computer vision, it has made great achievements with wide implications for vision-based approaches to evacuation modelling. Especially in certain areas of crowd counting, evacuation tracking, crowd density estimation, crowd dynamics, crowd flow prediction, and evacuation video analysis, the DL can be viewed as a promising SC method. Hundreds of studies involving Convolutional Neural Networks (CNNs) and DL have shown their ubiquity in every vision sub-domain of emergency evacuations (Afiq et al., 2019; Hou and Wang, 2022; Lamba and Nain, 2017; Nasr Esfahani et al., 2022; Tripathi et al., 2019).

4.1.2. Cluster #2: Evacuation simulation

Fig. 10 shows that the most popular keywords in this cluster contain agent-based simulation, fuzzy logic, virtual reality, and crowd simulation. Based on the information presented in Fig. 10, there is a potential to hybridize the SC approaches with agent-based simulation in improving the emergency evacuation efficiency. From the perspective of the process of emergency evacuations, these approaches can be, and are, divided into simulation techniques during the stages of pre-emergency and post-emergency. According to the work of Liao et al. (2019), the focal points of pre-emergency studies distribute in the fields of evacuation risk analysis, evacuation management, and public space design. A computer decision support system with an agent-based simulation can significantly reduce the associated test costs and unpredictable dangers. In addition, with the help of an agent-based computational system and intelligent algorithms (e.g., the ant colony algorithm and the particle swarm algorithm), the architecture design and evacuation planning for multiple scenarios can be better evaluated to promote evacuation safety (Li et al., 2021b).

Post-emergency research generally focuses on evacuation dynamics, evacuation planning, and loss prevention (Bakar et al., 2017; Liao et al., 2019). Previous studies usually assume that crowding makes evacuation planning similar to that of a normal situation (Hobeika and Kim, 1998; Prato, 2009). However, in contrast to crowd dynamics, evacuation dynamics emphasizes the issue of mass behaviour (e.g., self-organization, route choice, herd behaviour, and crowd merging (Han et al., 2017; Liu and Mao, 2022; Sano et al., 2017; Wang et al., 2022a; Xie et al., 2019; Yi et al., 2020)) at high densities in an emergency situation or under a stress condition (e.g., panic or anger) (Dong et al., 2019). Inevitably, evacuation dynamics, evacuees' preference diversity, and traffic states have to be considered when developing evacuation plans. Many scholars have incorporated SC approaches, especially FZ techniques, to model the uncertainties of evacuees' subjective perceptions and the emotional crowd dynamics (Popescu et al., 2013; Sharbini et al., 2021). Hence, their application can significantly improve the reliability of evacuation multi-agent simulation. Another emerging approach to increase the integration of evacuees' subjectivity involved in the perception and interpretation of evacuation dynamics is the combination of computational simulation and VR (Gath-Morad et al., 2022; Gath-Morad et al., 2021).

4.1.3. Cluster #3: Emergency evacuation optimization

According to Fig. 9 and Fig. 10, optimization is the most popular keyword with the highest co-occurrence frequency in the field of SC applications for emergency evacuation. The high-frequency keywords in this cluster contain humanitarian logistics, heuristics, vehicle routing, robust optimization, and network flows. Based on the literature review findings, the combination of optimization algorithms with other methods is useful to have a critical improvement for resolving emergency evacuation issues (Muhammed et al., 2020). In addition, the optimization algorithms can serve as effective approaches to solve complex problems, namely NP-hard problems, multi-criteria decision-making problems, and multi-objective problems. From the perspective of the universality of the application of SC approaches involving emergency evacuation optimization, the majority of optimization algorithms are inspired by nature or the extension of animal behaviour. Popular optimization algorithms in the existing literature include bio-inspired (e.g., Bacterial Foraging Optimization, Genetic Algorithm), insect-inspired (e.g., Ant Colony Optimization, Artificial Bee Colony), and animal-inspired (e.g., Particle Swam Optimization, Whale Optimization, Bat Optimization Algorithm, Grey Wolf Optimizer, and Artificial Fish

Swarm) (Cui et al., 2021; Peng and Zhang, 2013; Sharma et al., 2021; Tang et al., 2021; Tzanetos and Dounias, 2020; Yang and Karamanoglu, 2013).

The main objective of these optimization algorithms is to obtain local (or even global) optimal solutions by simulating the rules of an agent's movement and interaction with its environment. Generally, the first objective of emergency evacuation optimization is to minimize evacuation time or maximize evacuation efficiency. Other objectives may also consider factors, such as evacuation dynamics, geometric conditions, varying weather, and traffic risks along evacuation paths (Alam and Habib, 2021; Dulebenets et al., 2019; Sharbini et al., 2021). Another type of optimization for emergency evacuation, using a probabilistic graphical model, aims to predict the probability of an event happening by considering previous information. There are two main types of approaches in this taxonomy, namely Bayesian Network and Markov Random Models (Sharbini et al., 2021). Compared to the nature-inspired optimization approaches, probabilistic graphical models mainly focus on reducing the total loss during the evacuation. The combination of a Bayesian network learning method and a Markov method can also serve as a hybrid approach to predict the reliability of the evacuation, and to analyze the critical risk elements for the success of an Escape, Evacuation, and Rescue plan.

4.2. Research frontier identification

A keyword co-occurrence analysis of retrieved publications identifies current research hotspots, providing insights into future outlook. Consequently, the keyword timeline view analysis was conducted using CiteSpace to identify how hotspots changed over the past years extrapolating for future outlook (Chen et al., 2022). In Fig. 11, the horizontal axis represents the published time of retrieved documents, the nodes denote the keywords, and the links show the connection relationship among the co-occurred keywords. In addition, larger nodes indicate a higher frequency of co-occurred keywords (Huang et al., 2020; Liu et al., 2019). Based on the co-occurrence relationship of keywords, 11 clusters have been detected in the timeline view. These keywords in Fig. 11 are marked in the year when they were first mentioned.

As Fig. 11 shows, many hot keywords, such as "evacuation", "emergency", "simulation", and "optimization", were already available at the stage of initial generation (before 2006). "Cellular automata", "transportation", "computer version", "pedestrian dynamics", and other hot keywords appeared during the stage of initial growth (2006–2011). From 2012 to the following years, the keywords including "fuzzy logic", "decision support system", "exit selection", "speed detection", "evacuation planning", "virtual reality", "neural network", and "motion crowd flow" started attracting more interest. In summary, as mentioned in Section 3.5, the research focus in the domain of SC applications for emergency evacuation between 2000 and 2020 progresses and varies during different development stages. Furthermore, the overall research tendency and prominent research topics are visible in the identified 11 clusters of keywords. To better analyze the future outlook from various topics and subtopics, three frontiers have been identified that focus on the research topic, research method, and research technology.

4.2.1. Research topic frontier: Multiple topic interactions (#1 crowd evacuation, #2 emergency, #4 pedestrian flow, #5 wayfinding, #6 emergency evacuation, and #11 natural disasters)

Climate change and industrial activities have led to the frequent occurrence of natural disasters and new types of accidents, increasing the number of disaster-prone areas and exacerbating the hazardous effects. As a means of preparedness for approaching disasters, emergency evacuation is viewed as a spontaneous escape behaviour (Murray-Tuite and Wolshon, 2013; Zhou et al., 2018). In the literature, mutual intersections, mutual support, and mutual promotion are found between emergency evacuation and SC approaches, covering many topics and multi-topic interactions, such as public safety, fire safety, traffic safety, building safety, urban safety, and safety technology. Hence, multi-disaster coupling and system complexity have gradually become an emerging theme and a challenge in this domain.

Generally, Risk Evaluation, Monitoring and Early-warning (ME), and Emergency Rescue are common basic topics in Evacuation Science. SC techniques are mainly applied in the analysis of these 3 basic topics. At the same time, various relevant topics can be extended vertically and horizontally based on the above 3 themes. The vertical extension refers to the enrichment of research topics on certain evacuation issues. For example, in case of a natural disaster evacuation, post-disaster management has extended to a prior assessment and ME; evacuation planning has expanded from relying on expert experience to intelligent evacuation; and rescue has extended from evacuation resettlement to optimizing relevant activities during evacuation progress (Chang et al., 2022). The horizontal extension represents the exploration of the research topic from different disaster types and different scale perspectives, or analysis of the topic in a different space–time dimension. For instance, in case of pedestrian evacuation behaviour, relevant studies include pedestrian dynamics, crowd dynamics, and then evacuation dynamics, providing theoretical support for solving large-scale evacuation problems. Therefore, an extension of research topics will inevitably bring challenges of multi-disaster coupling and system complexity. Fortunately, SC approaches have the potential to provide solutions. For example, when several evacuation nodes in metro stations face the adverse effects of multiple disasters, evolutionary computing can effectively balance the global evacuation time and local evacuation density, so as to disperse regional evacuation risks (Jin et al., 2020). The evacuation problem has the critical characteristics of a complex system, that is, the shift from order to disorder, and the subsequent multiple scales in space and time (such as crowd stampedes, mass evacuation problems, etc.). In particular, collective behaviour in the evacuation process includes the interaction between the collective movement and individuals. Giorgio Parisi, one of the founders of the Complex System Theory and a winner of the Nobel Prize in Physics in 2021, found the scale-free correlations in starling flocks (Cavagna et al., 2010) that provided a new idea for applying SC approaches in emergency evacuations.

4.2.2. Research method frontier: man–machine collaboration method (#7 optimization algorithm, and #9 expert knowledge, and #10 evacuation simulation)

As mentioned in Section 3.5, the application of SC approaches to Evacuation Science itself is an emerging overlapping field that involves interdisciplinary knowledge, such as Computer Science, Engineering, Transportation Science, Management Science, and other subjects. There are interdisciplinary approaches in evacuation risk assessment and simulation, evacuation safety monitoring and early warning, comprehensive emergency response, and evacuation evolution mechanism. In addition, facing the contingency of events and the uncertainty of crowd behaviour, pedestrians are vulnerable to cognitive biases, availability bias, and anchoring effects when evaluating risks and making evacuation decisions (Blumenthal-Barby and Krieger, 2015). Hence, human–machine collaboration has become a popular trend in developing future methods in this field. The #9 expert knowledge and #10 evacuation simulation and are the two vital keywords in this cluster for human–machine collaboration.

The term "machine" here represents an intelligent system that makes decisions autonomously and independently (wholly or partly), and its autonomy is primarily achieved through simulation, artificial intelligence, and heuristic algorithms (Roth et al., 2019; Xiong et al., 2022; Li et al., 2022a). In order to make an evacuation decision, expert experience plays a critical role, especially in the preparation of evacuation plans, safety evacuation regulations, and rescue resource allocation, and often relies on expert knowledge and previous experience (Korbmacher and Tordeux, 2021). However, when facing large-scale complex evacuation problems, expert knowledge systems often fail to make optimal decisions. Although an expert knowledge system also relies on machine intelligence to search and make evacuation plans, it cannot truly reflect the adaptability and universality of human judgment. For example, when experts and machines approach evacuation planning differently, the machine needs to be able to explain the sources of difference and the human cognitive bias, so as to truly establish interpersonal trust and coordination (Edmonds et al., 2019). Undoubtedly, the application of SC in the man–machine collaboration method still focuses on the fields of simulation and optimization of emergency evacuations. In contrast to the ethical risks of crowd experiments and animal experiments, evacuation simulation can eliminate safety risks, but the consistency and error between evacuation simulation and reality are worthy of future exploring (King et al., 2022).

Optimization is an important theoretical bridge for human–machine collaborative intelligent decision making, and it brings unique advantages for SC techniques to solve emergency evacuation decision problems. The existing heuristic algorithms have been widely used in Evacuation Science, but with increasing complexity, more attention should be paid to the refinement of agents, the convergence of human behaviour and animal behaviour (Hill and Boyd, 2021), and the application of collective intelligence in optimization algorithms (Ha and Tang, 2022), so as to improve performance of swarm intelligence algorithms. Several researchers (Sharbini et al., 2021) also suggest that future research should explore hybrid SC approaches with the latest nature-inspired optimization methods in promoting the human–machine collaboration for Evacuation Science.

4.2.3. Research technology frontier: New technology convergence (#3 BIM, #8 deep learning)

In contrast to the frontier of research methods that aims to provide new research ideas, research technology aims to apply scientific knowledge to the practical targets of human life or, as it is sometimes phrased, to change and manipulate the human environment (Knowles, 2014). At present, the industrial transformation led by the IoT, Intelligent Manufacturing, and Intelligent Control is profoundly affecting the future of the global industrial layout. Information exchange, intelligence, and environmental sustainability are rapidly penetrating the field of Evacuation Science, promoting the emergence of new application forms and cooperation forms of SC approaches. In the field of AI, for example, a computer is beginning to understand human behaviour patterns and trying to model human risk perception during evacuation (Peterson Joshua et al., 2021). Other emerging AI technologies, such as unsupervised learning, sequential learning, spatio-temporal neural network, and reinforcement learning, provide intelligent evacuation technology solutions for crowd management. Intelligent evacuation management systems cover the aspects of crowd monitoring, crowd disaster prediction, evacuation modelling, and evacuation path guidelines. SC approaches play a vital role in the design and deployment of intelligent evacuation applications pertaining to crowd control management (Ibrahim et al., 2016; Jiang et al., 2022). However, the effectiveness of current AI technology depends to a large extent on the performance of computer hardware and algorithms, and solving mass evacuation problems may require considerable energy consumption. In addition, when using AI technology and analyzing data, the privacy issue will inevitably arise (Alguliyev et al., 2019). Interpretability of DL is an issue worth exploring as well. Therefore, the strengths and weaknesses of AI should be analyzed appropriately. Hence, it is necessary to improve information exchange, intelligence, and environmental sustainability in order to deploy AI technologies with their full potential in the field of SC applications for emergency evacuation.

The trend of new technology convergence is a System Engineering challenge. Future research should also focus on hardware development and platform building, such as new sensor technologies, new IoT technologies, new data collection technologies, new simulation platforms, and new efficient solvers (Golpîra et al., 2021; Molka-Danielsen et al., 2018). In addition, it is important to note that rapid advances in BIM (Gath-Morad et al., 2022; Naticchia et al., 2020), Digital Twin, and Extended Reality (Pirch et al., 2021) allow researchers to generate complex, realistic large-scale evacuation scenarios while still ensuring that researchers are able to collect behavioural data and observe crowd dynamics with great experimental control (Safikhani et al., 2022). New technologies and their convergence provide a huge development opportunity for the Evacuation Science discipline in terms of future perception, human–computer interaction, efficient algorithms, low-cost simulations, and intelligent evacuation modelling (Lorusso et al., 2022). At the same time, more attention is needed to ethical debates about new technologies to find a balance among the realism level, reliability, validity level of simulation experiments, and representativeness of the virtual environment (Feng et al., 2021a).

5. Conclusions

The main purpose of this literature survey was to present a comprehensive review of the emergency evacuation studies that rely on soft computing techniques. The rationale behind the selection of the survey is the increasing occurrence of natural and manmade hazards around the globe and the urgent need for new methods that can be used for effective emergency evacuation planning. To achieve the study objectives, by identifying and critically analyzing the current research trends and future outlook, a total of 778 documents published from 2000 to 2020 were selected from the core database of Web of Science and analyzed using the CiteSpace and VOSviewer software packages. This review paper's contributions are: 1) integrating a scientometric analysis with a critical review to produce an objective quantitative visualization, 2) highlighting research distribution characteristics that will help scholars identify the dynamic temporal development and visualization of collaborative networks among academic groups along with the connection of multidisciplinary knowledge domains, and 3) presenting future research directions by reviewing and synthesizing hundreds of recent publications.

The following are the main findings identified for each research question:

RQ1: Different soft computing approaches were applied for different emergency evacuation types. In general, for the two emergency evacuation taxonomies considered (i.e., evacuation scenarios and evacuation causes), Neuron Computing and Evolutionary Computing were identified to be the most widely used.

RQ2: There was a considerable increase in publications over the past 20 years during the three development stages: (1) initial generation stage (before 2006); (2) initial growth stage (2006–2011); and (3) rapid development stage (2012 to now).

RQ3: The most contributing countries and institutions are mainly distributed in the Asia-Pacific region and the Western developed countries. China and the U.S. are the core countries of the two main groups in the national cooperation network with researchers from four total major research groups.

RQ4: A total of 42 disciplines were identified in the selected publications, mainly distributed in Computer Science, Engineering, Transportation Science, and Management Science. Computer Science and Artificial Intelligence were found to be popular in all the development stages. In addition, advanced engineering technologies link the wide application and implementation of Soft Computing to emergency evacuation studies.

RQ5: Three current research hotspot clusters were identified through the keyword co-occurrence analysis, namely crowd modelling, evacuation simulation, and emergency evacuation optimization. Optimization is one of the most popular keywords with the highest co-occurrence frequency in this field. In addition, three important frontiers were identified based on the keyword timeline view analysis: multiple topic interactions, man–machine collaboration, and new technology convergence.

Table A1
Summarized presentation of benchmark studies.

Reference	Type of document	Research axis	Case Study/ Simulation	Emergency evacuation		Soft computing approaches					Another method (s)
				Evacuation scenarios	Evacuation causes	FZ	NC	EC	RS	NC&EC	
(Liu et al., 2020)	Article	Emergency evacuation	Database in the WOS	All	All	–	–	–	–	–	Bibliometrics analysis
(Gerakakis et al., 2019)	Article	Crowd dynamics	Agent-Based Modelling and Simulation	BE	EE	√					CA
(Sharbini et al., 2021)	Review	An evacuation simulation model with SC optimization	Related literature	All	All	√	√	√	√	√	Systematic literature review
(Alam and Habib, 2021)	Article	Evacuation planning and optimization	Buses that Halifax Peninsula owns	MTE	EE			√			Dynamic Programming
(Luh et al., 2012)	Article	Evacuating behaviour analysis	Agent-Based Modelling and Simulation	BE	MDE		√				Dynamic Programming
(Şahin et al., 2019)	Article	Evacuation planning	Agent-Based Modelling and Simulation	BE	EE	√					Multi-agent systems
(Mei and Xie, 2019)	Article	Evacuation strategy	Metro station	BE	EE	√					TOPSIS
(Ibrahim et al., 2016)	Review	Intelligent evacuation	video and nonvideo data	All	All	√	√	√	√	√	Systematic literature review
(Ghasemi et al., 2019)	Article	Evacuation planning	District 1 of Tehran	MTE	NDE			√			Epsilon constraint method
(Dulebenets et al., 2020)	Article	Evacuation planning	Broward County, Florida, US	MTE	NDE					√	Multi-objective optimization
(Li et al., 2019a)	Article	Evacuation planning	A hypothetical three-story building, a cruise ship	BE	EE			√			Network flow model
Reference	Type of document	Research axis	Case Study/ Simulation	Emergency evacuation		Soft computing approaches					Another method (s)
				evacuation scenarios	evacuation causes	FZ	NC	EC	RS	NC&EC	
(Li et al., 2019b)	Article	Evacuation management systems	Nuclear power plant	BE	MDE	√					An interactive two-step algorithm (Huang and Cao, 2011)
(Zhang et al., 2021a)	Article	Motion prediction	Public places	LSE	EE					√	Cyber-physical systems
(Rabbani et al., 2018)	Article	Evacuation planning	Hospital	BE	MDE			√			robust possibilistic programming
(Shen et al., 2019)	Article	Crowd counting	ShanghaiTech dataset (Zhou et al., 2015) and others	LSE	EE		√				–
(Wen et al., 2019)	Proceedings Paper	Motion prediction	Changsha metro, China	BE	EE	√					–
(Peng et al., 2019)	Article	Evacuation planning	a large public building in Nanjing, China	BE	EE					√	BIM
(Krasko and Rebennack, 2017)	Article	Evacuation planning	2009 Jesusita wildfire	MTE	NDE				√		Decision-dependent stochastic programming
(Afshar and Haghani, 2008)	Article	Evacuation planning	Ocean City, Maryland, US	MTE	HDE				√		A mesoscopic traffic simulator

Note: building evacuation (BE), large-scale evacuation (LSE), mixed traffic evacuation (MTE), natural disaster evacuation (NDE), manmade disaster evacuation (MDE), hybrid disasters evacuation (HDE), evacuation experiments (EE), and others (OTE); fuzzy computing (FZ), rough set theory (RS), neuron computing (NC), evolutionary computing (EC).

In the following years, researchers most likely will develop more Soft Computing techniques for emergency evacuation that will contribute to more effective planning and intelligent evacuation management. Our findings can serve as a guideline for a design framework that incorporates the elements of evacuation and hybrid Soft Computing approaches to advance Evacuation Science in the long term. However, although the keyword co-occurrence analysis can reflect the current research framework to some extent, it lacks quantitative research methods in the aspect of future outlook identification. Ideally, the aforementioned limitation can be addressed in future research.

CRediT authorship contribution statement

Benbu Liang: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **C. Natalie van der Wal:** Methodology, Writing – original draft, Writing – review & editing, Supervision. **Kefan Xie:** Writing – review & editing, Supervision, Conceptualization. **Yun Chen:** Writing – review & editing, Project administration, Funding acquisition. **Frances M.T. Brazier:** Writing – review & editing, Supervision, Methodology. **Maxim A. Dulebenets:** Writing – review & editing, Validation, Supervision. **Zimei Liu:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Searching terms in the WOS database

(TS=(“evacuation” OR “evacuating” OR “crowd evacuation” OR “safety evacuation” OR “emergency evacuation” OR “pedestrian evacuation” OR “human evacuation” OR “fire evacuation” OR “tsunami evacuation” OR “evacuation management” OR “evacuation plan*” OR “crowd disaster” OR “stampede*” OR “trampling*” OR “crowd turbulence” OR “evacuation model*” OR “crowd model*” OR “crowd behavio*” OR “pedestrian flow” OR “evacuat* behavio*” OR “evacuation routes” OR “tunnel escape” OR “escape route” OR “emergency exit”)).

AND

(TS= (“soft computing” OR “evolutionary computing” OR “fuzzy computing” OR “neuron computing” OR “optimization” OR “rough set theory” OR “fuzzy system*” OR “artificial neuro-fuzzy inference system” OR “fuzzy logic” OR “fuzzy set*” OR “theory of possibility” OR “expert system” OR “neuron model” OR “neural network” OR “knowledge retrieval” OR “knowledge management” OR “neurocomputing” OR “deep learning” OR “machine learning” OR “image processing” OR “computer vision” OR “system dynamics” OR “petri nets” OR “virtual reality” OR “vr” OR “augmented reality” OR “ar” OR “knowledge retrieval” OR “knowledge management” OR “natural language” OR “ensemble learning” OR “active learning” OR “ai” OR “swarm intelligence” OR “metaheuristics” OR “multi optimization” OR “many-objective optimization” OR “genetic algorithm” OR “ga” OR “heuristic model*” OR “heuristic algorithm” OR “particle swarm algorithm” OR “pso” OR “ant colony algorithm” OR “aco” OR “artificial life” OR “chaos theory” OR “rough set” OR “probabilistic reasoning” OR “bayes*” OR “rough-fuzzy set*” OR “fuzzy-rough set*”)).

Appendix B

See Table A1.

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