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Exploring symmetry and asymmetry in evacuation dynamics: A comprehensive bibliometric and computational analysis

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Abstract. *This study presents a comprehensive bibliometric analysis of evacuation research, focusing on the integration of symmetry and asymmetry elements. By analyzing a dataset of scholarly papers from the ISI Web of Science database spanning 2000 to 2023, we reveal a sustained annual growth rate of 8.1% in academic interest. Key contributors, influential publications, and leading journals in the field are identified. The analysis highlights the importance of considering information symmetry/asymmetry, symmetric/asymmetric Hausdorff distance, evacuation layout symmetry/asymmetry, and symmetry-breaking behaviors of evacuees. We show that N-gram analysis techniques uncover various applications of symmetry and asymmetry in evacuation research, emphasizing their significance in addressing evacuation challenges and enhancing strategies.*

Keywords: evacuation, bibliometric analysis, network analysis, information symmetry, symmetry-breaking behavior.

JEL Classification: C88, C63, R58, R41.

1. Introduction

Evacuation research is an increasingly critical field, attracting considerable attention from both scholars and policymakers. This growing interest reflects the evolving dynamics of modern society, particularly the complexities of expanding urban environments that present new challenges for emergency management (Perry and Lindell, 2003; Kapucu, 2008). The urgency of efficient evacuation strategies has been underscored by natural disasters, industrial accidents, and unforeseen crises such as pandemics. In this context, the science of evacuating populations safely and efficiently has become more vital than ever.

The present study seeks to advance our understanding of evacuation research by providing a comprehensive overview of the field. However, what sets our approach apart is its emphasis on exploring evacuation dynamics through the lens of symmetry and asymmetry. This distinctive perspective uncovers deeper insights into evacuation behaviors, patterns, and underlying factors that may have been overlooked by traditional studies (Che et al., 2015). While symmetry and asymmetry are often examined in other scientific disciplines, their application to evacuation research is uniquely significant. Evacuation is not simply the movement of individuals out of a space in a uniform manner; it involves a complex interplay of factors such as information asymmetry, the geometry of the evacuation environment, and the varied behaviors exhibited by evacuees themselves. Understanding these elements is crucial for optimizing evacuation strategies and improving their effectiveness across diverse real-world scenarios (Cotfas et al., 2023; Delcea et al., 2020). To investigate this topic, we have employed a bibliometric approach - an increasingly valuable tool for analyzing the evolution of research fields. Bibliometric analysis allows us to trace the trajectory of evacuation research by examining key trends, influential authors, institutions, and journals, while also identifying shifts in terminology and conceptual focus (Delcea et al., 2023). Bibliometrics, with its inherent capabilities, offers valuable insights into key stakeholders, academic institution affiliations, influential publications, and leading journals in the field, while also highlighting common terminologies and their frequencies of use (Li et al., 2020; López Belmonte et al., 2020; Lou and Hung, 2023).

Our study draws upon the ISI Web of Science database, covering a period of more than two decades (2000–2023), and focuses specifically on publications related to evacuation that integrate symmetry and asymmetry elements. By leveraging this method, we can provide a detailed and nuanced view of how these elements have shaped the field. Our analysis reveals a compelling narrative, demonstrating a steady and substantial interest in evacuation research that incorporates symmetry and asymmetry. Notably, the data reveals an 8.1% annual growth rate in publications related to this niche, indicating the increasing recognition of its importance. This growth not only reflects the growing body of literature but also suggests that this unique angle is resonating with scholars and practitioners alike. Beyond quantitative analysis, our study provides an in-depth exploration of emerging trends, crucial keywords, and evolving research trajectories. By examining author collaboration networks, academic affiliations, and the global distribution of research, we offer new insights into how evacuation modeling, with a focus on symmetry and

asymmetry, is being applied worldwide. Additionally, our use of advanced computational techniques, such as n-gram analysis of titles, keywords, abstracts, and keyword-plus fields, reveals the diverse applications of these concepts within the evacuation domain.

The findings from our study significantly contribute to the broader discourse on evacuation research by integrating computational and bibliometric methods to investigate a previously underexplored dimension of the field. The study not only highlights the continued relevance of symmetry and asymmetry in evacuation scenarios but also offers a comprehensive review of globally cited documents, positioning our approach as a unique and valuable addition to existing literature.

2. Materials and Methods

For extracting the publications discussing the symmetry / asymmetry aspects to the field of evacuation, the Web of Science platform (WoS platform) was employed. The data collection is only applicable to papers published until the end of 2023. The bibliometric analysis has been conducted in accordance with the most recent works from the field which have considered the same analysis technique, but on a different topic – please consider the following works for similar bibliometric analysis on various topics (Gorski et al., 2023; Stefanis et al., 2023; Delcea and Cotfas, 2023; Fatma and Haleem, 2023). As suggested by Marin-Rodriguez et al. (Marín-Rodríguez et al., 2023), the bibliometric analysis incorporates two main parts: de identification of the dataset of articles from the evacuation area that take into account elements related to symmetry/asymmetry along with other elements that might derive from modeling such a complex situation (e.g. the occurrence of obstacles, evacuating with a friend, elevated floors, etc.), and the analysis of the extracted dataset. A similar approach is conducted by Anac et al. (Anaç et al., 2023).

Regarding the first part related to dataset extraction, a search action carried out on the WoS platform using a list of keywords that includes "evacuation" words like "evacuation" and "evacuations" as well as "symmetry"-related words like "symmetry", "asymmetry", "symmetric" and "asymmetric" on the papers' title, abstract, and keywords. This search is represented in the exploration steps 1 through 3 presented in Table 1. This method was chosen since a straightforward search using only the key words "evacuation" and "symmetry" would have produced a significant number of publications, the majority of which would not have been relevant to the chosen research area. This problem is brought about by the widespread use of the word "evacuation" and “symmetry” in several areas covered in scientific studies. As a result, 14 papers were identified as having both the searched keywords in the title, 202 papers had both the searched keywords in the abstract, and 9 papers in the keywords - Table 1. When searching for only one of the selected words, the result of the query amounts to a much larger number of papers, finding thousands more than when using both the keywords. A merging operation was performed in step 4 to create a total of 206 papers on evacuation research containing “symmetry” related words, because most of the papers contained the chosen keywords in more than one of the three sections of the article (title, abstract, or keywords).

Based on the language requirement, which specifies that the articles need to be written in English, 198 of these papers have been kept for analysis (please see step 5). Since most readers and researchers can easily understand English, this exclusion criterion has been used to eliminate papers written in languages other than English. Another exclusion criterion has been the document type. Only the papers designated as articles were kept for analysis. This action has the effect of bringing the number of papers down to 166 (step 6). Further, another exclusion criterion has been used (step 8) for the 162 papers. The publications that only discuss the subjects of evacuation were chosen based on this final criterion. The papers were chosen manually by reading their titles, abstracts, and keywords because the action couldn't be completed using the filtering tools provided by the WoS platform and we have observed that some of the papers included in the database, even though feature the use of evacuation specific keyword and symmetry / asymmetry specific keywords were not referring to the crowd evacuation but rather to other fields of study such as chemistry, biology or medicine (e.g. the gas particles evacuation). A total of 46 papers were retained for examination because of this action, and the results are reviewed and examined in the sections that follow. **Table 1** contains a list of the procedures required to extract the papers.

Table 1. *Queries used for extracting the database*

Exploration steps	Questions on Web of Science	Description	Query	Query number	Count
1	Title	Contains evacuation specific keyword	(TI=(evacuation)) OR TI=(evacuations)	#1	10,204
		Contains one of the symmetry / asymmetry specific keywords	(((TI=(symmetry)) OR TI=(asymmetry)) OR TI=(symmetric)) OR TI=(asymmetric)	#2	274,610
		Contains #1 and #2	#2 AND #1	#3	14
2	Abstract	Contains evacuation specific keyword	(AB=(evacuation)) OR AB=(evacuations)	#4	31,079
		Contains one of the symmetry / asymmetry specific keywords	((((AB=(symmetry)) OR AB=(asymmetry)) OR AB=(symmetric)) OR AB=(asymmetric)	#5	933,461
		Contains #4 and #5	#4 AND #5	#6	202
3	Keywords	Contains evacuation specific keyword	(AK=(evacuation)) OR AK=(evacuations)	#7	7370
		Contains one of the symmetry / asymmetry specific keywords	((((AK=(symmetry)) OR AK=(asymmetry)) OR AK=(symmetric)) OR AK=(asymmetric)	#8	151,840
		Contains #7 and #8	#7 AND #8	#9	9
4	Title/ Abstract/ Keywords	Contains evacuation specific keyword and one of the symmetry / asymmetry specific keywords	#3 OR #6 OR #9	#10	206
5	Language	Limit to English	(#10) AND LA=(English)	#11	198
6	Document Type	Limit to Article	(#11) AND DT=(Article)	#12	166
7	Publication year	Limit to 2023	(#12) NOT PY=(2024)	#13	162
8	Select the papers discussing evacuation and symmetry / asymmetry aspects	Limit to the papers dealing with evacuation and discussing aspects related to symmetry or asymmetry	Manually selected papers based on titles and abstracts	#14	46

For the dataset overview, a series of indicators have been discussed in accordance to other papers which have used the same analysis approach: the number of sources, papers' annual growth rate, number of authors, number of authors of single-authored document, co-authors per document, international co-authorship rate, number of authors' keywords, the average

years from publication, the average number of citations per document, the average citations per year per document, the number of references – all these on the purpose of having an overview over the selected papers. Sources analysis provides information related to the most relevant journals in terms of number of articles related to symmetry/asymmetry aspects, along with the sources located in the top peer according to Bradford's law, the most relevant journals form the point of view of H-index, and the growth of the number of papers for the top-ranked journals over time. Authors' analysis depicts the most prominent authors from both the number of authored papers and number of citations, discuss their affiliations, and their residence countries. Also, in this analysis a collaboration network is identified and discussed, along with the clusters of authors.

Papers analysis provides the list of top 10 most cited papers, along with their main indicators (total citations, total citations per year, normalized total citations per year indicator). In this analysis, a review of the top 5 most cited papers is provided along with information related to the main elements discussed in the paper, the type of data used, and theories considered. Besides these elements, a review of the symmetry / asymmetry elements is provided for all the papers included in the dataset. Words analysis discusses the top 10 n-grams (unigrams and bigrams) from various sections of the papers (e.g. title, abstract, authors' keywords). Based on these words and the evolution of the number of papers, a further analysis is conducted with the purpose of extracting the main themes that have occurred over time and their evolution. Mixed analysis connects the authors with their countries, with the journals in which they have published, or with their affiliations and keywords used for giving more insight on this area of research related to considering symmetry/asymmetry elements in evacuation problems.

As discussed in the previous section, evacuation is a complex process influenced by many different factors. In this study, we focus specifically on the role of symmetry and asymmetry in evacuation research. These aspects are particularly important because they can significantly affect the safety and efficiency of the evacuation process. By considering such factors, researchers can develop models that more accurately reflect real-world evacuation dynamics. A review of the selected literature also shows that many authors emphasize the importance of incorporating symmetry and asymmetry considerations when analyzing evacuation scenarios.

Bibliographic analysis, content analysis, visualization, and citation analysis have all been used to examine the data. Through the usage of the Biblioshiny program created by Aria and Cuccurullo from the Federico II University and University of Campania Luigi Vanvitelli, several visualizations have been carried out (Aria and Cuccurullo, 2017). This software was chosen as it offers a number of visually appealing graphics that demonstrate the links between the items under consideration. From a methodological point of view, the Bibliometrix package has been loaded in the RStudio console window using the *biblioshiny( )* command. However, the program has recently been used in numerous research projects that suggest author networks and paper analyses (Delcea and Cotfas, 2023; Zardari et al., 2023; Marín-Rodríguez et al., 2023).

3. Dataset Analysis

The following section includes a discussion that includes authors, sources and citations for the extracted publications in the field of evacuation.

3.1. Dataset Overview

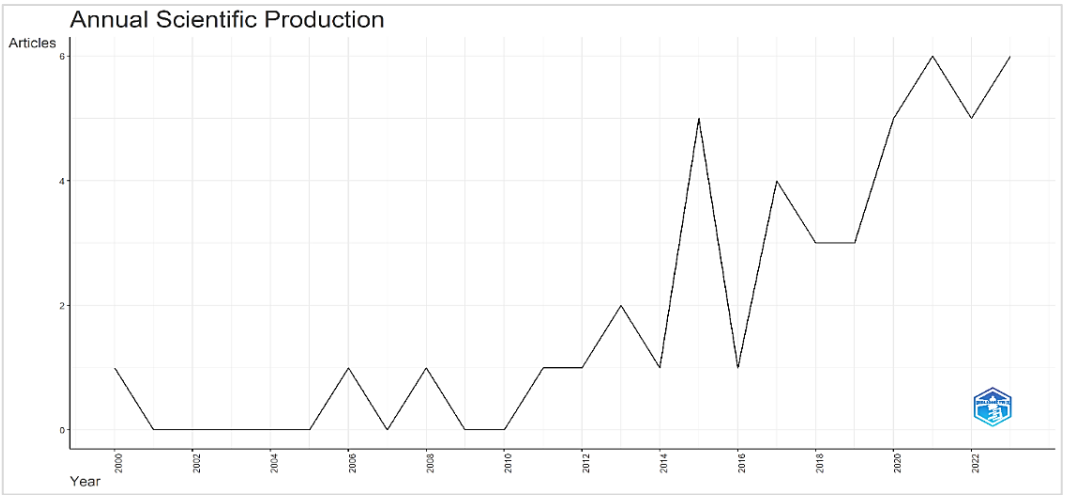
Table 2 provides the values for a set of variables and describe the characteristics of the data set made up of the 46 publications. The time period for the papers that have been published is 2000 to 2023, and the journals that the articles have been published in total 30 sources. Due to the low value for the average years from publication indicator, which is equal to 6.15 years, the majority of the publications included in the dataset are recent papers. According to the information in **Table 2**, the published articles have attracted more attention from the scientific community, as evidenced by an average of 21.89 citations per document.

Table 2. *Main information about data*

Indicator	Value
Timespan	2000:2023
Sources	30
Documents	46
Annual growth rate	8.1%
Authors	149
Authors of single-authored docs	3
Co-authors per document	3.52
International co-authorship	23.91%
Author's keywords	174
Average years from publication	6.15
Average citations per documents	21.89
References	1741

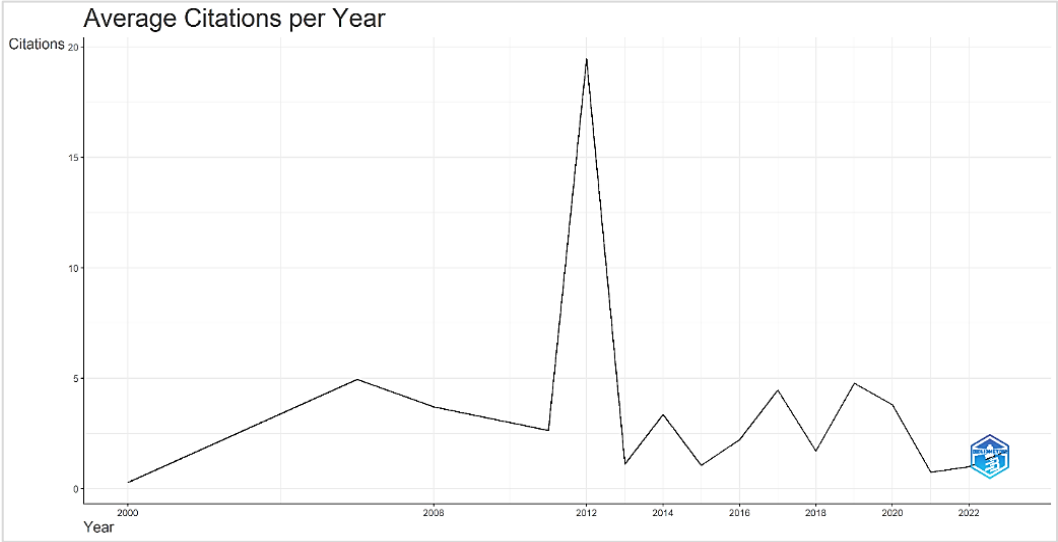
The annual scientific production has shown an increase in the number of papers, with an annual growth rate of 8.1%. This can be seen in **Figure 1**, reaching a number of 46, respectively 6 articles in year 2023. The first major spike was recorded in 2015, growing from 1 article per year, to a number of 5.

Figure 1. *Annual scientific production evolution*



The evolution of the average value of article citations has been between 3.7 and 4.95 since 2005, varying from year to year, indicating a good visibility of papers written in the field of evacuation research. Almost null values were recorded between 2000-2005. The year in which most references were made is 2012, when it reached a value of 19.46, a significant difference from other years (**Figure 2**).

Figure 2. *Annual average article citations per year evolution*



When using "keywords plus" in our analysis, we have reached a value of identified words (a number of 150) relatively lower than when using the authors' keywords, (174 occurrences). A total of 149 researchers have been uniquely identified. It can be said that the collaboration network among the authors of the papers written in the evacuation research area is predicted to be dense because the number of authors of single-authored documents is quite low in comparison to the number of extracted documents (3 versus 146). The fact that there is a comparable number of authors on multi-authored publications than there are overall (146 versus 149).

Table 3 presents key indicators of author collaboration within the scope of this study. The data reveals that out of the documents analyzed, only three were authored by a single individual, indicating a prevalent culture of collaboration in this research domain. On average, each author contributed to approximately 0.307 documents, highlighting the widespread involvement of multiple authors in each publication. Furthermore, the documents in the dataset had an average of 3.239 authors, showcasing the cooperative nature of scholarly work in the field. With an average of 3.52 co-authors per document, it's evident that many papers were the result of collective efforts. The collaboration index, calculated at 3.395, underscores the degree of cooperation among authors, emphasizing the importance of teamwork and shared expertise in advancing the study of evacuation incorporating symmetry/asymmetry elements.

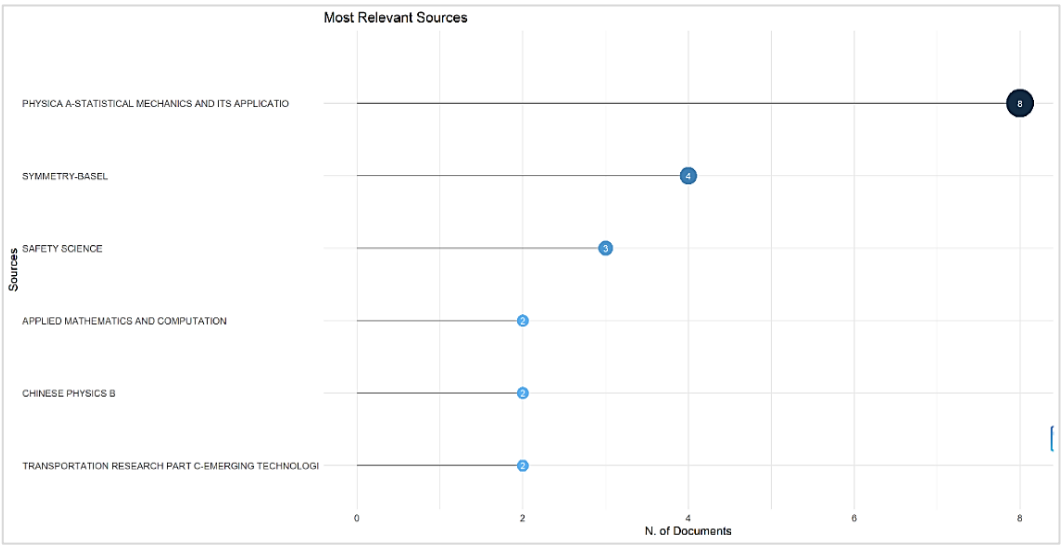
Table 3. *Authors collaboration*

Indicator	Value
Single-authored documents	3
Documents per author	0.307
Authors per document	3.239
Co-authors per documents	3.52
Collaboration index	3.395

3.2. Sources

When looking at the most relevant publications where the chosen papers have been published, it is clear that the journal "Physica A-Statistical Mechanics and its Applications", with 8 papers, is the top spot. Places second and third are close to each other, each having 4 and 3 papers published in the following journals: "Symmetry-Basel", and "Safety Science". The following place is held by three journals, each having 2 of the selected articles ("Applied Mathematics and Computation", "Transportation Research Part C-Emerging Technologies" and "Chinese Physics B"). This ranking can be seen as a graphical interpretation in **Figure 3**.

Figure 3. *Top 6 most relevant journals*



When applied to the chosen paper, Bradford's law places a total of four sources ("Physica A-Statistical Mechanics and its Applications", "Symmetry Basel", "Safety Science" and "Applied Mathematics and Computation") in zone 1 - please refer to **Figure 4**. The image illustrates the concept of "Core Sources" as defined by Bradford's Law, a principle in bibliometrics that describes the distribution of relevant literature across journals. The graph plots the number of articles against the logarithmic rank of sources, highlighting a steep decline in the number of articles as the rank increases. The shaded region represents the "Core Sources," which are a small subset of journals that publish the majority of relevant articles in a given field. This visualization underscores the idea that a few key journals dominate the dissemination of significant research, with diminishing returns observed in

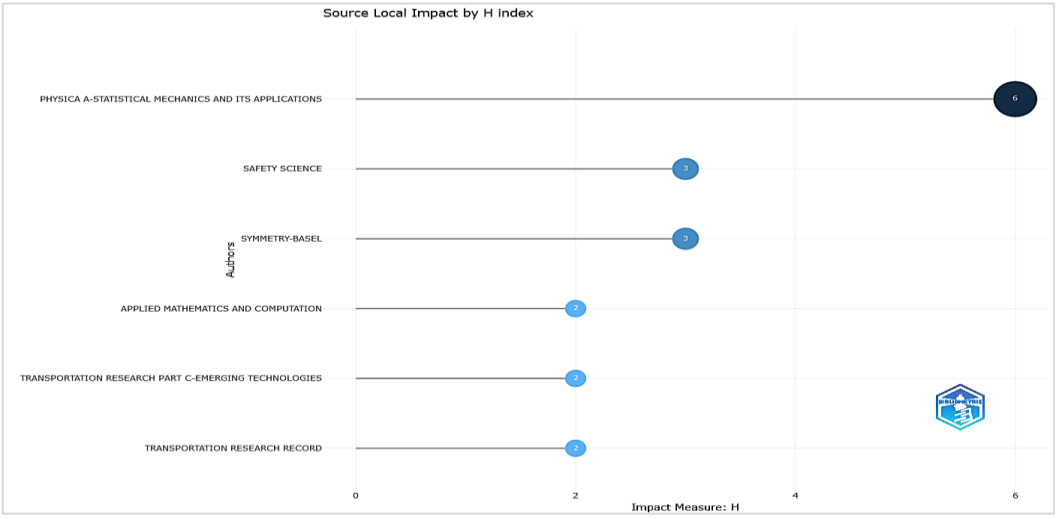
journals of lower rank. The graph effectively demonstrates the concentration of scholarly output, emphasizing the importance of identifying and focusing on these core sources for comprehensive literature reviews.

Figure 4. *Bradford's law on source clustering*



The H-index statistics have also been used to analyze the impact of the journals. This index, as known, is a measurement of the proportion of a journal's papers that have received H or more citations overall. Regarding the chosen articles, the journal “Physica A-Statistical Mechanics and its Applications” receives the greatest H-index score, with 6 works in the field of evacuation research, having received at least 6 citations (please see **Figure 5**). With H-index values ranging from 2 to 6, the journals designated as zone 1 according to Bradford's law are among the best (“Symmetry” and “Safety Science”).

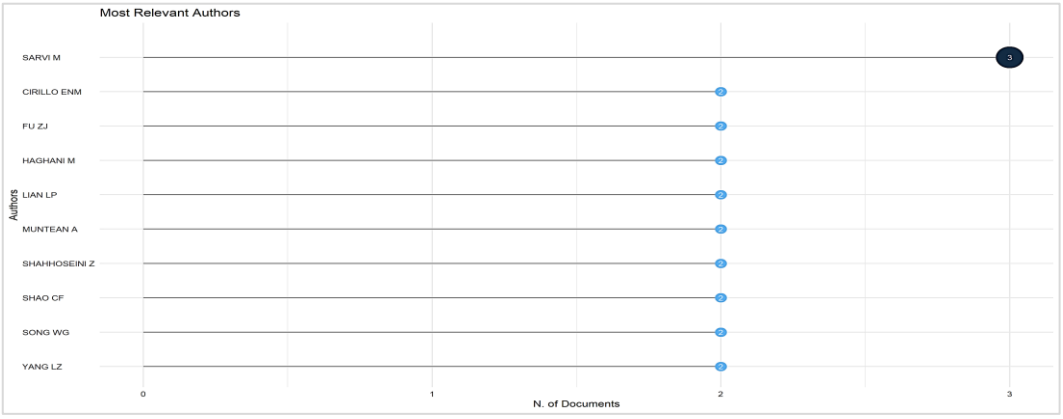
Figure 5. *Journals' impact based on H-index*



3.3. Authors

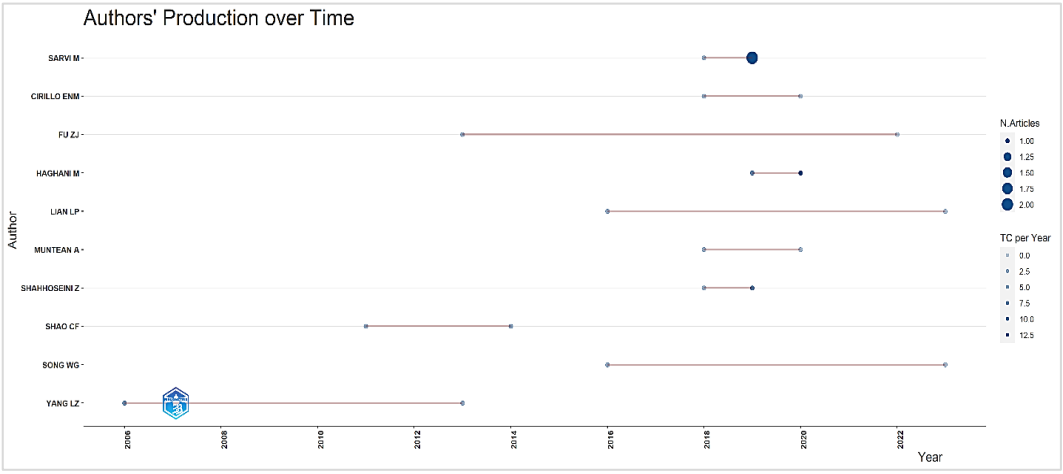
In the evacuation research field, the authors with the most prominent activity based on the number of published articles in this area can be seen in **Figure 6**. The author with the largest number of articles published in this research area is Sarvi M, counting 3 documents. Authors with fewer documents are Cirillo ENM, Fu ZJ, Haghani M, Lian LP, Muntean A, Shahhoseini Z, Shao CF, Song WG and Yang LZ, all having a number of 2 articles per author.

Figure 6. *Top-10 authors based on number of documents*



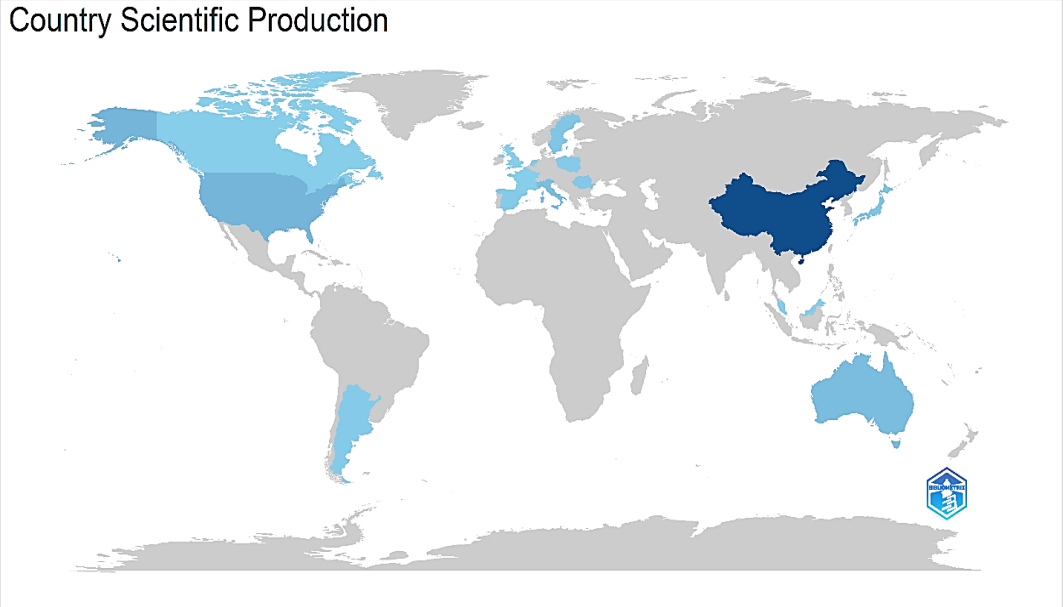
As for the most recent papers, the top 10 most prolific authors in terms of the number of documents they have published can be seen in **Figure 7**. Most of the articles have been published after 2018. Each dot signifies a published article, with the size of the dots corresponding to the number of articles produced in a given year. The brown horizontal lines indicate the span of an author's contributions over time. Additionally, the color intensity of the dots reflects the total citations per year, with darker shades indicating higher citation impact. Notably, Sarvi M and Cirillo ENM exhibit high-impact contributions, as indicated by the larger, darker blue dots around 2018. The graph provides insights into both the longevity and citation influence of key researchers in this domain.

Figure 7. *Top-10 authors' production over time*



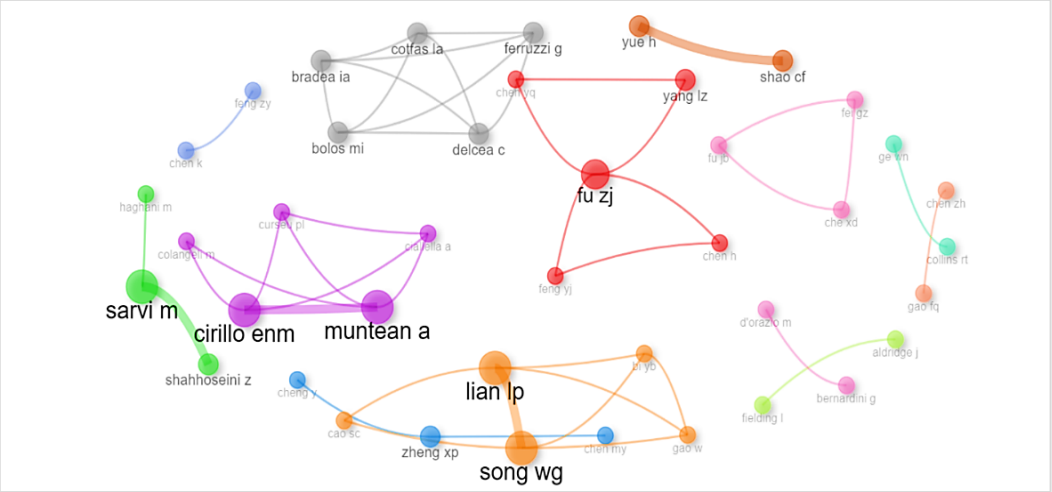
A map of global visualization makes it simple to see how each nation has contributed. The scientific contribution made by each author to the papers under consideration based on their home country is shown in **Figure 8**. The figure's colors are varied. From dark blue, denoting a significant contribution, as in the case of China, to grey, denoting a lack of publications in the fields of evacuation research. As a result of the trend established by scientific production, it can be seen that China has received 409 citations for the publications, which is the most of any nation. The following nation is USA with 274 citations, followed by Australia in close third with 227 citations.

Figure 8. *Scientific production based on country*



In **Figure 9** are presented the collaboration networks of the top 50 authors for the selected papers used in this study. This network visualization represents collaborative relationships among authors in the field of evacuation research involving symmetry and asymmetry. Each node corresponds to an author, with larger nodes indicating higher publication output and thicker connecting lines representing stronger co-authorship ties. The different colors signify distinct research clusters, highlighting groups of authors who frequently collaborate. Notably, Sarvi M, Cirillo ENM, and Muntean A form a tightly connected group (green), while Lian LP and Song WG (orange) also exhibit strong collaboration. Similarly, Fu ZJ (red) appears as a central figure in another major research cluster. This visualization provides insights into the structure of academic collaborations, identifying key contributors and research communities within the field.

Figure 9. *Top 50 authors collaboration network*



3.4. Analysis of Literature

In this part, we have chosen the top ten publications that have received the most citations and examined them from the perspective of the data that accompanied the papers.

3.4.1. Top 10 Most Cited Papers – Overview

Table 4 provides detailed information about the top ten most cited articles in the world, including the article's number of authors, area, total citations (TC), total citations per year (TCY), and normalized TC (NTC), which describes the number of citations for each author who cites the document.

Table 4. *Top 10 most global cited documents*

No.	Paper (First Author, Year, Journal, Reference)	Number of authors	Region	Total citations (TC)	Total citations per year (TCY)	Normalized TC (NTC)
1	Weina Ge, 2012, IEEE Transactions on Pattern Analysis and Machine Intelligence	3	USA	253	19.46	1.00
2	Zhao Daoliang, Yang Lizhong, 2006, Physica A: Statistical Mechanics and its Applications	3	China	94	4.95	1.00
3	Nirajan Shiwakoti, 2017, Safety Science	4	Australia	69	8.63	1.93
4	Milad Haghani, 2020, Safety Science	1	Australia	64	12.8	3.37
5	Ren-Yong Guo, 2008, Journal of Physics A: Mathematical and Theoretical	2	China	63	3.71	1.00
6	Zahra Shahhoseini, 2019, Transportation Research Part B: Methodological	2	Australia	45	7.50	1.57
7	Yue Hao, 2014, Chinese Physics B	4	China	37	3.36	1.00
8	Yue Hao, 2011, Physica A: Statistical Mechanics and its Applications	4	China	37	2.64	1.00
9	Huang Keke, 2016, Applied Mathematics and Computation	4	China	37	4.63	1.03
10	Milad Haghani, 2019, Safety Science	2	Australia	35	5.83	1.22

3.4.2. Top 5 Most Cited Papers – Review

The top ten most cited papers are reviewed briefly in the sections that follow, along with a brief synopsis of each work.

In the most cited article, "Vision-based Analysis of Small Groups in Pedestrian Crowds" by Weina Ge, Robert T. Collins, and R. Barry Ruback (Weina Ge et al., 2012), the authors introduce an innovative approach to automatically detect small groups within pedestrian crowds using state-of-the-art algorithms for pedestrian detection and multi-object tracking. Their method, based on hierarchical clustering and a generalized Hausdorff distance, demonstrates substantial statistical agreement with human-perceived group structures, providing a novel methodology for empirical studies of social behavior. This research not only advances the field of computer vision but also offers practical applications in crowd management, evacuation planning, and crowd simulation, with potential extensions exploring diverse social events and the incorporation of spatial group configurations into tracking algorithms.

The second raking article "Exit Dynamics of Occupant Evacuation in an Emergency" by Zhao Daoliang, Yang Lizhong, and Li Jian (Daoliang et al., 2006) presents a two-dimensional Cellular Automata model to simulate occupant evacuation dynamics. The study offers valuable insights into exit design for safety, emphasizing the importance of exit width exceeding a critical value and door separation being neither too small nor too large. It highlights that increasing exit width improves overall evacuation flow, and the optimal door separation remains consistent regardless of exit width. Additionally, the study underscores the importance of symmetry in exit layout for optimal performance in building design. Overall, this research contributes to a better understanding of occupant evacuation dynamics and provides guidance for performance-based building design considerations.

In the article "Likely Behaviors of Passengers Under Emergency Evacuation in Train Stations" by Nirajan Shiwakoti, Richard Tay, Peter Stasinopoulos, and Peter Jarrod Woolley (Shiwakoti et al., 2017), the authors investigate various aspects of passenger behavior during emergency evacuations in train stations. Through a survey of 1134 train passengers, the study reveals that passengers exhibit diverse behaviors, with a tendency toward reactive responses (waiting for instructions) rather than proactive ones (moving to exit independently) during emergencies. Furthermore, cooperative behavior (helping others) is more common than competitive behavior (pushing others), and while some symmetry-breaking behavior is observed (following others), it's not as pronounced as previous mathematical models assumed. Passengers also tend to avoid using escalators, lifts, and train tunnels during evacuations. The findings contribute valuable insights for developing mathematical models, emergency response strategies, training programs, and design solutions to enhance evacuation effectiveness in train stations. Overall, this research provides crucial insights into passenger behavior during emergency situations, particularly within complex and confined transport hubs.

In the article "Empirical Methods in Pedestrian, Crowd, and Evacuation Dynamics: Part II - Field Methods and Controversial Topics" by Milad Haghani (Haghani, 2020), the author

provides a comprehensive review of field data collection methods in pedestrian dynamics from April 2017 to July 2019. The article discusses the increasing popularity of field observations in natural settings for calibrating and validating simulation models. Additionally, the review identifies nine controversial topics in crowd dynamics, shedding light on recent experiments that challenge long-held assumptions. This article, notable for being single-authored, underscores the rapid growth in the field of pedestrian and evacuation dynamics, reflecting the expanding interest and research efforts in this area. It sets the stage for further investigation into and clarification of the inconsistencies surrounding these controversial topics in the years to come.

The fifth article "A Modified Floor Field Cellular Automata Model for Pedestrian Evacuation Simulation" by Ren-Yong Guo and Hai-Jun Huang (Guo and Huang, 2008) introduces an innovative approach to simulate pedestrian evacuations in high-density crowds. The authors address the asymmetric, accumulative, and transferable nature of pedestrian interactions by discretizing the evacuation space into smaller cells and considering individual inertia and forces imposed on others. Through numerical simulations, they explore the effects of pedestrian movement styles and model parameters on evacuation efficiency. The results reveal that unorganized movements and stronger push and bump interactions among pedestrians increase evacuation times. The modified model outperforms the original floor field model in terms of evacuation time, offering flexibility in adjusting parameters to match real-world scenarios. This research represents a promising development in understanding and optimizing pedestrian evacuation processes in various contexts, including buildings with multiple obstacles and multiple exits.

Table 5 provides information related to the elements considered from the evacuation research field, the type of data used in the analysis, the main purpose of the paper, the presence of a theoretical and/or practical application of the methodology, and the presence/absence of a hybrid approach, along with the name of the paper and a brief description based on the first author's name.

Table 5. *Brief summary of the content of top 5 most global cited documents*

No.	Paper (First Author, Year, Journal, Reference)	Title	Main elements	Data	Purpose	Hybrid approach / Theories considered
1	Weina Ge, 2012, IEEE Transactions on Pattern Analysis and Machine Intelligence	Vision-Based Analysis of Small Groups in Pedestrian Crowds	Detecting and tracking individuals	Field data	Automatically detection of small groups within pedestrian crowds	Algorithms for detecting pedestrians and multi-object tracking; hierarchical clustering; generalized Hausdorff distance
2	Zhao Daoliang, Yang Lizhong, 2006, Physica A: Statistical Mechanics and its Applications	Exit dynamics of occupant evacuation in an emergency	Exit design safety	Synthetic data	Simulation of occupant evacuation dynamics	Cellular Automata model
3	Nirajan Shiwakoti, 2017, Safety Science	Likely behaviors of passengers under emergency evacuation in train station	Analyzing passengers' behaviors	Survey	Investigation of various aspects of passenger behavior during emergency evacuations in train stations	-

No.	Paper (First Author, Year, Journal, Reference)	Title	Main elements	Data	Purpose	Hybrid approach / Theories considered
4	Milad Haghani, 2020, Safety Science	Empirical methods in pedestrian, crowd and evacuation dynamics: Part II. Field methods and controversial topics	Review of field data collection methods	Field data	Review of field data collection methods in pedestrian dynamics	-
5	Ren-Yong Guo, 2008, Journal of Physics A: Mathematical and Theoretical	A modified floor field cellular automata model for pedestrian evacuation simulation	Discretization of the evacuation space into smaller cells; consideration of individual inertia and forces imposed on others	Synthetic data	Simulation of pedestrian evacuations in high-density crowds	Numerical simulations

3.4.3. Symmetric/Asymmetric Elements Overview

In the context of articles pertaining to evacuation, an analysis of the inherent symmetry and asymmetry attributes within the selected papers has been conducted, with a focus on discerning the primary elements thereof. The outcomes of this scrutiny have been succinctly synthesized and are presented in Table 8. Upon initial inspection, it becomes evident that a substantial majority of the included articles emphasize the examination and discourse surrounding asymmetry considerations, with 33 out of the 40 papers explicitly addressing and delving into the subject of "asymmetry" in relation to the evacuation process. In contrast, a comparatively lesser proportion, specifically 16 out of the 40 papers, engage in discussions revolving around "symmetry"-related issues in the context of evacuations. Consequently, there emerges a subset of 9 papers that undertake a comprehensive examination of evacuation dynamics, concurrently exploring both symmetry and asymmetry facets.

Based on the categories presented in the final column of **Table 6**, three main themes emerge in the discussion of symmetry and asymmetry within evacuation research. The first and most common theme, addressed in 17 of the 40 selected papers, focuses on the symmetry or asymmetry of exit designs and layout configurations. Another important topic, explored in 8 papers, relates to the presence or absence of symmetry in evacuee behavior, including symmetry-breaking phenomena during evacuations. In addition, 6 papers examine the role of symmetric and asymmetric information in evacuation scenarios. Furthermore, within the remaining subset of papers, several distinctive and individualized themes are discerned. These include discussions on topics such as the utilization of Hausdorff distance as a means to simulate evacuation behavior, the occurrence of asymmetric flow patterns, and the assumption of asymmetric weight distributions within the simulation models, among others. For further elaboration on these specific themes, please refer to **Table 6**.

Table 6. *Summary of the symmetry/asymmetry content of the selected articles included in the analysis*

No.	Paper (First Author, Year, Journal, Reference)	Symmetry / Asymmetry Elements		Considered Symmetry / Asymmetry Elements and Brief Explanation
		Symmetry	Asymmetry	
1	Weina Ge, 2012, IEEE Transactions on Pattern Analysis and Machine Intelligence	✓		Small Groups in Pedestrian Crowds are discovered by bottom-up hierarchical clustering using a generalized Symmetric Hausdorff distance.
2	Zhao Daoliang,Yang Lizhong, 2006, Physica A: Statistical Mechanics and its Applications	✓		The exits' layouts are considered symmetrical.
3	Nirajan Shiwakoti, 2017, Safety Science	✓	✓	Trains passengers' behaviors considering various aspects, including symmetry breaking behavior, such as following other passengers, or symmetry behavior such as choose least crowded exit.
4	Milad Haghani, 2020, Safety Science		✓	Controversial topics discussion, including the symmetry breaking phenomenon
5	Ren-Yong Guo, 2008, Journal of Physics A: Mathematical and Theoretical		✓	Pedestrian evacuation considering a high-density crowd asymmetric interaction.
6	Zahra Shahhoseini, 2019, Transportation Research Part B: Methodological	✓	✓	Experimental scenarios for pedestrian crowd flows in shared spaces with symmetric and non-symmetric layouts.
7	Yue Hao, 2014, Chinese Physics B		✓	Exit selection in pedestrian evacuation is made by taking into account the asymmetry of exits or of pedestrian layout.
8	Yue Hao, 2011, Physica A: Statistical Mechanics and its Applications		✓	Pedestrian evacuation simulations for a room with asymmetrical exit layout.
9	Huang Keke, 2016, Applied Mathematics and Computation	✓	✓	Pedestrian evacuation from a room with symmetrically located exits; the occurrence of a symmetry breaking behavior.
10	Milad Haghani, 2019, Safety Science		✓	Symmetry breaking is observed in less substantial degrees of information uncertainty situations.
11	Zhijian Fu, 2013, Physica A: Statistical Mechanics and its Applications		✓	A cellular automata model, as an extension to the Asymmetric Simple Exclusion Process is considered.
12	Shujie Wang, 2016, Physica A: Statistical Mechanics and its Applications		✓	Ants demonstrate a symmetry breaking behavior when confronted with a stressful situation.
13	Hidalgo Rc, 2017, Physical Review E		✓	The use of spherocylindrical particles in evacuation simulation rather than the traditional symmetric disks.
14	Tomasz Gwizdalla, 2015, Physica A: Statistical Mechanics and its Applications		✓	Rooms with different asymmetries are considered when building the evacuation model.
15	Yuan-Kai Chung, 2017, Plos One		✓	Symmetry breaking study by considering heat-induced platform and ants.
16	Li Wang, 2020, Computers & Industrial Engineering		✓	Information asymmetry in evacuation planning.
17	Zahra Shahhoseini Z, 2018, Transportation Research Record: Journal of the Transportation Research Board	✓	✓	Symmetric layouts outperform the asymmetric counterparts in evacuation process.
18	Alessandro Ciallella, 2018, Mathematical Models and Methods in Applied Sciences	✓	✓	Asymmetry in the positioning of the obstacles with respect to the center of the corridor and a variation of simple symmetric random walk on the considered square lattice in the case of confined and darkened spaces.
19	Jonatan Gehandler, 2015, Fire Technology	✓		The one-dimensional symmetry of a tunnel in evacuation situation.
20	Xiaodong Che, 2015, Visual Computer		✓	Information asymmetry in evaluating evacuation plan.
21	ManWo Ng, 2015, Transportation Research Part C: Emerging Technologies	✓		The inclusion of an optional symmetry assumption in evacuation planning.
22	Huan-huan Tian, 2018, Physica A: Statistical Mechanics and its Applications		✓	Asymmetric rules for changing evacuees' strategies are considered.

No.	Paper (First Author, Year, Journal, Reference)	Symmetry / Asymmetry Elements		Considered Symmetry / Asymmetry Elements and Brief Explanation
		Symmetry	Asymmetry	
23	Camelia Delcea, 2020, Symmetry-Basel	✓	✓	Symmetric and asymmetric exits' impact on classroom and lecture halls evacuation.
24	Wenhan Wu, 2023, Tsinghua Science and Technology		✓	The state of the pedestrian parameters is affected by visual information, causing asymmetry in evacuees' acceleration behavior.
25	Rodrigo Martinez-Val, 2000, Journal of Aircraft		✓	The uneven longitudinal distribution of exits and lack of left to right symmetry in airplane evacuation impacts the difficulties in evacuation process.
26	Guofeng Ma, 2021, Advances in Civil Engineering	✓	✓	An even symmetry is determined to be more efficient than an asymmetric distribution of exits.
27	Gino J Lim, 2019, IISE Transactions	✓		Demand distribution (number of actual evacuees) is symmetric.
28	Fengqiang Gao, 2023, Applied Mathematics and Computation		✓	Asymmetric-exit evacuation is considered.
29	Emilio NM Cirillo, 2020, Mathematical Bioscience and Engineering	✓	✓	Symmetric random walk for the passive particles; asymmetric (drift guiding) for the active particles in pedestrian escape from an obscure room.
30	Razieh Khaksari, 2021, Symmetry-Basel		✓	Asymmetric smoke propagation in tunnel during contraflow traffic operations.
31	Zhenfei Wang, 2021, Symmetry-Basel	✓		Multi-exit symmetrical facilities are considered for pedestrian evacuation simulation.
32	Maha El-Metwally, 2015, Transportation Research Record: Journal of the Transportation Research Board		✓	Discussions related to crossing elimination when evacuation flow is asymmetric.
33	Junji Urata, 2021, Transportation Research Part C: Emerging Technologies		✓	The consideration of asymmetric weights of interaction in the evacuation departure choice.
34	Klaas Fiete Krutein, 2023, Transportation Research Part E: Logistics and Transportation Review		✓	Introduces a highly asymmetric Isolated Community Evacuation Problem.
35	Rongyong Zhao, 2021, IEEE Transactions on Intelligent Transportation Systems		✓	Asymmetric pedestrian merging layout is proposed for a T-shaped street junction.
36	Yan Mao, 2020, IEEE Access		✓	Asymmetric intimacy is considered when building the evacuation model.
37	Sikora W, 2013, Acta Physica Polonica A	✓	✓	Symmetry conditions of allowed space are considered. the times of evacuation and average presses acting on individuals during the evacuation are determined and compared for situations with and without symmetry considerations.
38	Atsuo Murata, 2023, Symmetry-Basel		✓	Information asymmetry is considered in delayed evacuation after disaster.
39	Li Y, 2021, Fresenius Environmental Bulletin	✓		Symmetrical inverse layout merger to the rescue path dynamic planning of refuge buildings.
40	Zhijian Fu, 2023, Physica A: Statistical Mechanics and its Applications		✓	Cellular automaton for pedestrian dynamics when asymmetry and bipedal features of rotation are considered.
41	Ming Zhang, 2023, Journal of Building Engineering	✓	✓	The influence of two typical crowd flow modes are used (symmetric split and asymmetric split)
42	Yang-Hui Hu, 2023, Chinese Physics B		✓	Asymmetric building and obstacles are used for simulations
43	Ken Chen, 2023, Physica A: Statistical Mechanics and its Applications	✓		A symmetric flip enlargement of the sample for aisle widths is used in the study
44	Enrico Q, 2023, Heritage	✓	✓	Large and symmetric squares used for evacuation simulations determine higher differences in evacuation indicators
45	Mengkai Liu, 2023, Fire	✓	✓	A symmetric building structure is studied in this paper with the asymmetry of the stairwell
46	Huaxian Wan, 2023, International Journal of Thermal Sciences		✓	A model for flame length of two asymmetric fires in a tunnel is developed

3.4.4. Words Analysis

In order to determine the methodologies that the authors employed in their articles or the scope of the applicability of their study, an analysis of the most frequently used words in the selected papers was conducted as follows in the section below. The keywords plus, authors' keywords, titles, and abstracts have all been used in the search.

Regarding the keywords plus, we have observed that the top-10 keywords refer to "simulation" (with 14 appearances), "dynamics" (with 14 appearances), "behavior" (11), "evacuation" (with 8), "flow" (with 7), "model" (with 6), "escape" (with 6), "pedestrian evacuation" (with 5) and "crowd" and "social force model" (with 4 appearances each). It is clear from **Table 7** that the majority of the top 10 keywords plus are related to the field of evacuation research.

Table 7. Top 10 most frequent words in keywords plus

Words	Occurrences
simulation	14
dynamics	14
behavior	11
evacuation	8
flow	7
model	6
escape	6
pedestrian evacuation	5
crowd	4
social force model	4

When using the authors' keywords, the situation from **Table 8** is somewhat different (please see **Table 7**). This time, the top 10 most frequent words are as follows: "evacuation" (with 8 appearances); "cellular automata", "crowd dynamics", "pedestrian dynamics", "crowd evacuation", "emergency evacuation" (with 4 appearances each); "pedestrian evacuation" (with 3 appearances); "analytical models", "dynamic parameters" and "crowd flow" (with 2 appearances each).

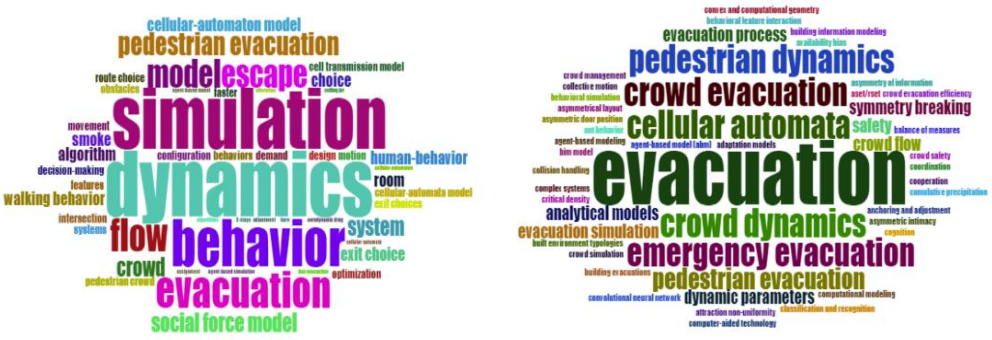
Table 8. Top 10 most frequent words in authors' keywords

Words	Occurrences
evacuation	8
cellular automata	4
crowd dynamics	4
pedestrian dynamics	4
crowd evacuation	4
emergency evacuation	4
pedestrian evacuation	3
analytical models	2
dynamic parameters	2
crowd flow	2

In **Figure 10**, two clusters are created inside the visualization: Cluster A, which concentrates on keywords plus, and Cluster B, which concentrates on authors' keywords. In the first cluster, A, which focuses on keywords plus, we can observe a Word Cloud formed of the most indicative words such as "simulation", "dynamics", "behavior", "evacuation", ""model", "flow", "escape", "crowd", "pedestrian evacuation" and so on (please see the left side of Figure 16 for more information). These words and phrases

capture the key ideas and topics that have emerged from this study. The second word cluster, B, that focuses on authors' keywords, has a Word Cloud formed of the following: "evacuation", "cellular automata", "crowd dynamics", "pedestrian dynamics", "pedestrian evacuation", "crowd evacuation", "emergency evacuation", "symmetry breaking" and so forth (please refer Figure 16, right side for more).

Figure 10. *Top 50 words based on keywords plus (A) and authors' keywords (B)*



(A) Top 50 words based on keywords plus

(B) Top 50 words based on authors' keywords

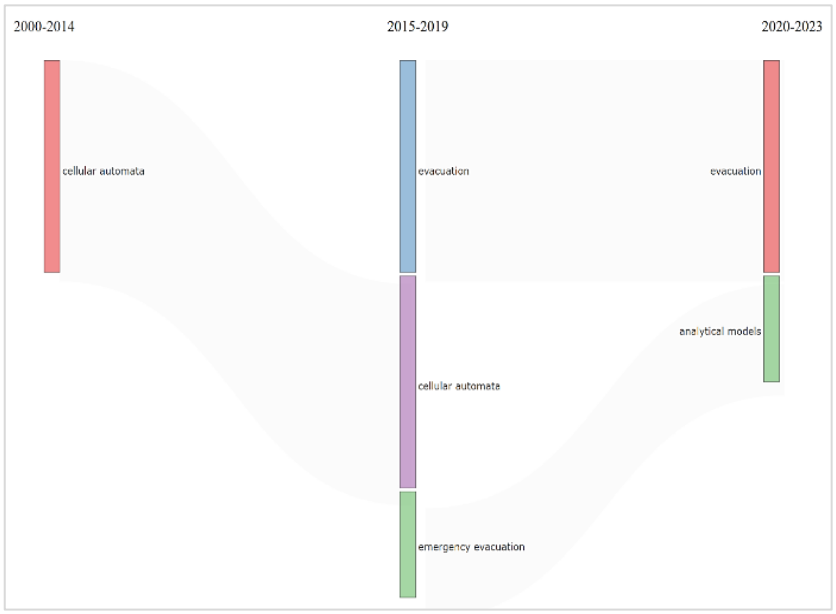
Table 9 provides valuable insights into the recurring bigrams found in both the abstracts and titles of scholarly works related to evacuation research. In the realm of abstracts, it is evident that phrases such as "evacuation time" and "evacuation efficiency" stand out, occurring 21 and 16 times, respectively. These bigrams underline the crucial importance of enhancing evacuation procedures for better safety and efficiency. Additionally, "crowd evacuation" and "refuge building" appear prominently, demonstrating a keen interest in addressing the challenges posed by evacuating large groups of people, particularly within refuge structures. Meanwhile, in the titles, bigrams like "cellular automaton" and "crowd evacuation" hold prominence, indicating the significance of computational models and crowd dynamics in the study of evacuation. The prevalence of bigrams like "evacuation planning" and "pedestrian evacuation" highlights the multifaceted nature of research in this field, which encompasses both strategic planning and individual-level behaviors. These recurring bigrams not only reflect the current research trends but also serve as valuable pointers for understanding the key themes and concepts driving scholarly discourse in evacuation research.

Table 9. *Top 10 most frequent bigrams in abstracts and titles*

Bigrams in abstracts	Occurrences	Bigrams in titles	Occurrences
evacuation time	21	crowd evacuation	4
evacuation efficiency	16	cellular automaton	3
crowd evacuation	10	evacuation planning	3
evacuation process	9	field cellular	3
refuge building	9	floor field	3
exit selection	8	pedestrian evacuation	3
symmetry breaking	8	cellular automata	2
flame length	7	evacuation model	2
exit width	7	emergency evacuation	2
experimental results	7	evacuation behavior	2

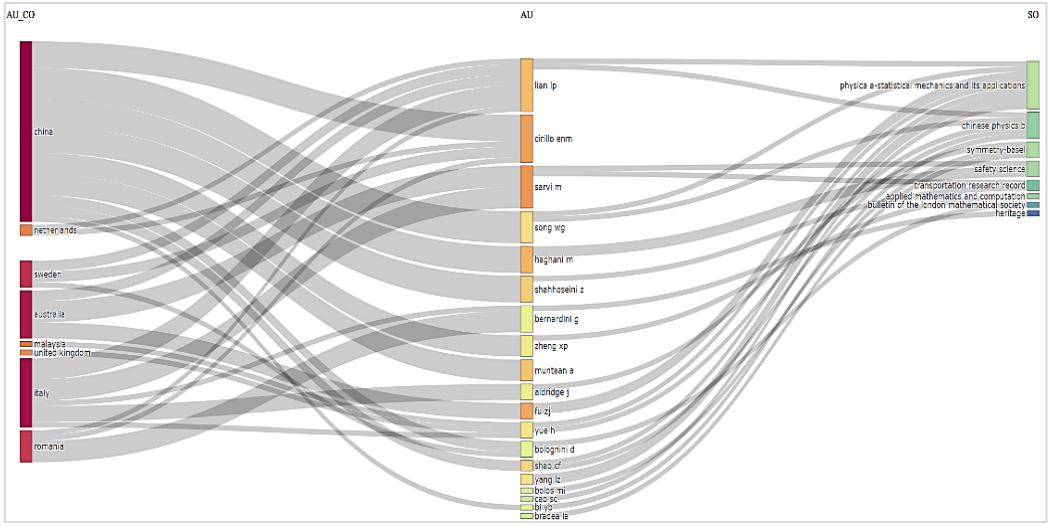
Considering the entire time-period, the use of cellular automata for both the 2000-2014 and 2015-2019 periods is highlighted in **Figure 11**, while the general evacuation theme emerges from the 2015-2019 and continues in the 2020-2023 period. Overall, the image illustrates a progression from a singular focus on cellular automata to a broader exploration of evacuation dynamics and analytical modeling, reflecting the evolving interests and methodologies in the research community over time.

Figure 11. *Thematic evolution*



3.5. Mixed Analysis

Figure 12. *Three-fields plot: countries (left), authors (middle), journals (right)*



As the importance of the evacuation research field has grown in recent years, it is crucial to investigate the complex connections between authors, journals, and nations while examining scholarly publications. Three-fold plots, like the one in **Figure 12**, are used to depict these complex interactions.

The triadic arrangement provides insights into the working relationships between authors from various nations and their connections to particular journals. Sweden, Italy, and Romania are the top three nations in terms of collaborations in **Figure 12**, which highlights their active participation in global research projects. The fact that "Physica A-Statistical Mechanics and its Applications" stands out as the main venue for publishing these collaborative works highlights the journal's crucial role in fostering international research collaborations.

4. Limitations

While emphasizing the incorporation of symmetry and asymmetry features, this analysis aims to find the most relevant publications within the fields of evacuation research. However, it is important to recognize some inherent limits that constrain the scope of this study.

First off, the only publications included in our analysis are those found in ISI Web of Science-indexed journals. As a result, it excludes information that could be found in research papers or conference proceedings that are available in other databases, like Scopus or PubMed. This restriction might unintentionally leave out important contributions from these alternate sources. Secondly, due to linguistic restrictions, we could only review papers that were written in English. Therefore, despite their potential value, papers written in other languages were not included in our study. In addition to the previously mentioned constraints, it's essential to acknowledge another limitation regarding the specific time period selected for this analysis, spanning from 2000 to 2023. This period has been a result of the selection keywords used in the paper, of the linguistic restriction and of the selected database. By considering other databases, keywords, types of paper and language, it is possible that someone could identify some papers before the year 2000.

As shown in **Table 1**, a predefined list of terms related to our subject of interest (“evacuation” and “symmetry” / “asymmetry”) further defined the scope of our study. It's possible that this selected list of keywords unintentionally left out relevant publications that use other languages or cover related subfields.

We understand that various software packages may give unique perspectives and insights, thus while we used the Biblioshiny library inside the R programming language to help our study, our findings are constrained by the particular tools used.

5. Conclusions

Research in evacuation has evolved significantly since the year 2000, reflecting the growing complexity of urban environments and the increasing need for efficient emergency response strategies. Our study employed the well-established ISI Web of Science database (WoS platform) to gather and analyze the most influential authors, journals, and publications within this domain from 2000 to 2023. By leveraging advanced bibliometric techniques available in the Biblioshiny library, we were able to systematically examine key research trends and contributions over this period.

This investigation involved a comprehensive analysis of publication trends, identifying leading nations and prolific re-searchers, assessing the impact of individual papers, and mapping citation networks across journals, countries, and authors. Notably, we highlighted the top five most-cited papers that have played a pivotal role in shaping the field. This in-depth examination not only facilitated a better understanding of the evolution of evacuation research but also provided valuable insights into the diverse methodologies employed and their real-world applications. The findings reinforce the growing importance of evacuation modeling, especially in the context of increasing global risks, including natural disasters, industrial accidents, and large-scale public events.

To present our key findings effectively, we utilized a variety of graphical representations, including Collaboration Networks, Word Clouds, Thematic Maps, and Collaboration Maps. These visual tools offered a clearer perspective on the research landscape, shedding light on emerging trends and influential works. Additionally, recent advancements in crowd simulation and evacuation modeling have significantly enriched this field. For instance, Sun et al. (2024) introduced a novel multi-agent deep reinforcement learning approach to enhance crowd cooperation for formation maintenance and collision avoidance, providing valuable insights into realistic crowd behaviors under emergency conditions. Furthermore, Khan and Deng (2024) conducted an extensive survey on agent-based crowd simulation, identifying critical factors influencing heterogeneous behavior, thus improving our under-standing of individual and collective movement dynamics (Khan, 4993).

In addition to these contributions, agent-based simulation techniques continue to play a crucial role in advancing evacuation research. Recent studies have integrated hierarchical agent models with physics-based character control to enhance the realism of evacuation scenarios, allowing for more accurate predictions of crowd behavior in dynamic environments. Similarly, knowledge-driven dynamic perception models have been introduced to refine scene simulations, improving both decision-making accuracy and evacuation efficiency. These advancements highlight the growing sophistication of computational models and their potential to enhance real-world evacuation planning and emergency preparedness.

Given the rapid advancements in this field, we recommend that future research broaden its scope by incorporating additional databases such as Scopus and other relevant public repositories. Expanding the analysis to include conference proceedings alongside journal

publications would also provide a more comprehensive view of the evolving research landscape. Furthermore, integrating interdisciplinary approaches - such as artificial intelligence, virtual reality, and real-time sensor data - may further enhance the effectiveness and applicability of evacuation models.

Ultimately, evacuation research remains an exciting and continuously evolving domain, driven by its critical real-world implications. As global urbanization accelerates and new challenges emerge, this field will undoubtedly continue to capture the interest of academics and practitioners worldwide. The ongoing advancements in simulation technologies and data-driven methodologies will further strengthen our ability to design safer, more efficient evacuation strategies for the future.

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References

Anaç, M., Gumusburun Ayalp, G. and Erdayandi, K. (2023). Prefabricated Construction Risks: A Holistic Exploration through Advanced Bibliometric Tool and Content Analysis. *Sustainability*, 15, 11916, <doi:10.3390/su151511916>

Aria, M. and Cuccurullo, C. (2017). Bibliometrix: An R-Tool for Comprehensive Science Mapping Analysis. *Journal of Informetrics*, 11, 959–975, <doi:10.1016/j.joi.2017.08.007>

Che, X., Niu, Y., Shui, B., Fu, J., Fei, G., Goswami, P. and Zhang, Y. (2015). A Novel Simulation Framework Based on Information Asymmetry to Evaluate Evacuation Plan. *Vis Comput*, 31, 853–861, <doi:10.1007/s00371-015-1119-6>

Chen, K., Li, F., Ji, Q., You, Q., and Feng, Z. (2023). Emergency Evacuation Behaviour Characteristics Classification of Aircraft Cabin Passengers Based on Deep Learning Network Model SMCNN-LSTM. *Physica A: Statistical Mechanics and its Applications*, <10.1016/j.physa.2023.129097>

Chung, Y.-K. and Lin, C.-C. (2017). Heat-Induced Symmetry Breaking in Ant (Hymenoptera: Formicidae) Escape Behavior. *PLoS ONE*, 12, e0173642, <doi:10.1371/journal.pone. 0173642>

Ciallella, A., Cirillo, E.N.M., Curşeu, P.L. and Muntean, A. (2018). Free to Move or Trapped in Your Group: Mathematical Modeling of Information Overload and Coordination in Crowded Populations. *Math. Models Methods Appl. Sci.*, 28, 1831–1856, <doi:10.1142/S02182025 18400079>

Cirillo, E.N.M., Colangeli, M., Muntean, A. and Thieu, T.K.T. (2020). A Lattice Model for Active-Passive Pedestrian Dynamics: A Quest for Drafting Effects. *Mathematical Biosciences and Engineering*, 17, 460–477, <doi:10.3934/mbe.2020025>

Cotfas, L.-A., Delcea, C., Iancu, L.-D., Ioanas, C., and Ponsiglione, C. (2023). Large Event Halls Evacuation Using an Agent-Based Modeling Approach. *IEEE Access*, 10, 49359–49384, <doi:10.1109/ACCESS.2023.3172285>

Daoliang, Z., Lizhong, Y., and Jian, L. (2006). Exit Dynamics of Occupant Evacuation in an Emergency. *Physica A: Statistical Mechanics and its Applications*, 363, 501–511, <doi:10.1016/j.physa.2005.08.012>

Delcea, C., and Cotfas, L.-A. (2023). "Hybrid Approaches Featuring Grey Systems Theory." In *Advancements of Grey Systems Theory in Economics and Social Sciences*; Series on Grey System; Springer Nature Singapore: Singapore, 281–333 ISBN 978-981-19993-1-4.

Delcea, C., and Cotfas, L.-A (2023). "State of the Art in Grey Systems Research in Economics and Social Sciences." In *Advancements of Grey Systems Theory in Economics and Social Sciences;* Series on Grey System; Springer Nature Singapore: Singapore, 1–44 ISBN 978-981-19993-1-4.

Delcea, C., Cotfas, L.-A., Bradea, I.-A., Boloș, M.-I., and Ferruzzi, G. (2020). Investigating the Exits' Symmetry Impact on the Evacuation Process of Classrooms and Lecture Halls: An Agent-Based Modeling Approach. *Symmetry*, 12, 627, <doi:10.3390/sym12040627>

Delcea, C., Cotfas, L.-A., Craciun, L., and Molanescu, A.G. (2020). An Agent-Based Modeling Approach to Collaborative Classrooms Evacuation Process. *Safety Science*, 121, 414–429, <doi:10.1016/j.ssci.2019.09.026>

Delcea, C., Javed, S.A., Florescu, M.-S., Ioanas, C., and Cotfas, L.-A. (2023). 35 Years of Grey System Theory in Economics and Education. *K*, <doi:10.1108/K-08-2023-1416>

El-Metwally, M., and Murray-Tuite, P. (2015). Selecting Four-Leg Intersections for Crossing Elimination in Evacuations. *Transportation Research Record*, 2532, 141–153, <doi:10.3141/2532-16>

Fatma, N., and Haleem, A. (2023). Exploring the Nexus of Eco-Innovation and Sustainable Development: A Bibliometric Review and Analysis. *Sustainability*, 15, 12281, <doi:10.3390/su151612281>

Fu, Z., Xiong, X., Luo, L., Yang, Y., Feng, Y., and Chen, H. (2023). Influence of Rotation on Pedestrian Flow Considering Bipedal Features: Modeling Using a Fine Discrete Floor Field Cellular Automaton. *Physica A: Statistical Mechanics and its Applications*, 605, 128027, <doi:10.1016/j.physa.2023.128027>

Fu, Z., Yang, L., Chen, Y., Zhu, K., and Zhu, S. (2013). The Effect of Individual Tendency on Crowd Evacuation Efficiency under Inhomogeneous Exit Attraction Using a Static Field Modified FFCA Model. *Physica A: Statistical Mechanics and its Applications*, 392, 6090–6099, <doi:10.1016/j.physa.2013.07.062>

Gao, F., Yan, Y., Chen, Z., Zheng, L., and Ren, H. (2023). Effect of Density Control in Partially Observable Asymmetric-Exit Evacuation under Guidance: Strategic Suggestion under Time Delay. *Applied Mathematics and Computation*, 418, 126838, <doi:10.1016/j.amc.2021.126838>

Gehandler, J., Eymann, L., and Regeffe, M. (2015). Limit-Based Fire Hazard Model for Evaluating Tunnel Life Safety. *Fire Technol*, 51, 585–614, <doi:10.1007/s10694-014-0406-5>

Gorski, A.-T., Ranf, E.-D., Badea, D., Halmaghi, E.-E., and Gorski, H. (2023). Education for Sustainability – Some Bibliometric Insights. *Sustainability*, 15, 14916, <doi:10.3390/su152014916>

Guo, R.-Y., and Huang, H.-J. (2008). A Modified Floor Field Cellular Automata Model for Pedestrian Evacuation Simulation. *J. Phys. A: Math. Theor.*, 41, 385104, <doi:10.1088/1751-8113/41/38/385104>

Gwizdałła, T.M. (2015). Some Properties of the Floor Field Cellular Automata Evacuation Model. *Physica A: Statistical Mechanics and its Applications*, 419, 718–728, <doi:10.1016/j.physa.2014.10.070>

Haghani, M. (2020). Empirical Methods in Pedestrian, Crowd and Evacuation Dynamics: Part II. *Field Methods and Controversial Topics. Safety Science*, 129, 104760, <doi:10.1016/j.ssci.2020.104760>

Haghani, M., and Sarvi, M. (2019). 'Herding' in Direction Choice-Making during Collective Escape of Crowds: How Likely Is It and What Moderates It? *Safety Science*, 115, 362–375, <doi:10.1016/j.ssci.2019.02.034>

Hidalgo, R.C., Parisi, D.R., and Zuriguel, I. (2017). Simulating Competitive Egress of Noncircular Pedestrians. *Phys. Rev. E*, 95, 042319, <doi:10.1103/PhysRevE.95.042319>

Hu, Y., Bi, Y., Zhang, J., Lian, L., Song, W., and Gao, W. (2023). Effect of a Static Pedestrian as an Exit Obstable on Evacuation. *Chinese Physics B*, 32, 018901, <10.1088/1674-1056/ac9605>

Huang, K., Zheng, X., Cheng, Y., and Yang, Y. (2017). Behavior-Based Cellular Automaton Model for Pedestrian Dynamics. *Applied Mathematics and Computation*, 292, 417–424, <doi:10.1016/j.amc.2016.07.002>

Kapucu, N. (2008). Planning for Disasters and Responding to Catastrophes: Error of the Third Type in Disaster Policy and Planning. *IJPP*, 3, 313, <doi:10.1504/IJPP.2008.020985>

Khaksari, R., Harun, Z., Fielding, L., and Aldridge, J. (2021). Numerical Simulation of the Evacuation Process in a Tunnel during Contraflow Traffic Operations. *Symmetry*, 13, 2392, <doi:10.3390/sym13122392>

Khan, S., and Deng, Z. (4993). Agent-based crowd simulation: an in-depth survey of determining factors for heterogeneous behavior. *Vis Comput 40*, –5004, <https://doi.org/10.1007/s00371-024-03503-2>

Krutein, K.F., and Goodchild, A. (2023). The Isolated Community Evacuation Problem with Mixed Integer Programming. *Transportation Research Part E: Logistics and Transportation Review*, 161, 102710, <doi:10.1016/j.tre.2023.102710>

Li, B., Xu, Z., Zavadskas, E.K., Antuchevičienė, J., and Turskis, Z. (2020). A Bibliometric Analysis of Symmetry (2009–2019). *Symmetry*, 12, 1304, <doi:10.3390/sym12081304>

Li, Y., and Liu, P. (2021). A Novel Dynamic Planning Method for Rescue Routes of Refuge Buildings in Response to Geological Environmental Disasters Based on Spatial Layout Theory. *Fresenius Environ. Bull.*, 30, 8491–8497.

Lim, G.J., Rungta, M., and Davishan, A. (2019). A Robust Chance Constraint Programming Approach for Evacuation Planning under Uncertain Demand Distribution. *IISE Transactions*, 51, 589–604, <doi:10.1080/24725854.2018.1533675>

Liu, M., and Wang, G. (2023). Indoor Fire Simulation in Low-Rise Teaching Buildings Based on BIM–FDS. *Fire*, 6(5), 203, <10.3390/fire6050203>

Lou, T.-F., and Hung, W.-H. (2023). Revival of Classical Algorithms: A Bibliometric Study on the Trends of Neural Networks and Genetic Algorithms. *Symmetry*, 15, 325, <doi:10.3390/sym15020325>

López Belmonte, J., Segura-Robles, A., Moreno-Guerrero, A.-J., and Parra-González, M.E. (2020). Machine Learning and Big Data in the Impact Literature. *A Bibliometric Review with Scientific Mapping in Web of Science. Symmetry*, 12, 495, <doi:10.3390/sym12040495>

Ma, G., Wang, Y., and Jiang, S. (2021). Optimization of Building Exit Layout: Combining Exit Decisions of Evacuees. *Advances in Civil Engineering*, 2021, 1–16, <doi:10.1155/2021/6622661>

Mao, Y., Fan, Z., Mao, H., and He, W. (2020). Asymmetric Intimacy Based Positive Emotions Contagion Peer Public Safety Evacuation Behavior. *IEEE Access*, 8, 185253–185265, <doi:10.1109/ACCESS.2020.3030339>

Martinez-Val, R., and Hedo, J.M. (2000). Analysis of Evacuation Strategies for Design and Certification of Transport Airplanes. *Journal of Aircraft*, 37, 440–447, <doi:10.2514/2.2617>

Marín-Rodríguez, N.J., González-Ruiz, J.D., and Botero Botero, S. (2023). Dynamic Co-Movements among Oil Prices and Financial Assets: A Scientometric Analysis. *Sustainability*, 14, 12796, <doi:10.3390/su141912796>

Marín-Rodríguez, N.J., González-Ruiz, J.D., and Valencia-Arias, A. (2023). Incorporating Green Bonds into Portfolio Investments: Recent Trends and Further Research. *Sustainability*, 15, 14897, <doi:10.3390/su152014897>

Murata, A., Doi, T., Hasegawa, R., and Karwowski, W. (2021). Delayed Evacuation after a Disaster Because of Irrational Prediction of the Future Cumulative Precipitation Time Series under Asymmetry of Information. *Symmetry*, 14, 6, <doi:10.3390/sym14010006>

Ng, M., and Lin, D.-Y. (2015). Sharp Probability Inequalities for Reliable Evacuation Planning. *Transportation Research Part C: Emerging Technologies*, 60, 161–168, <doi:10.1016/j.trc.2015.08.003>

Perry, R.W., and Lindell, M.K. (2003). Preparedness for Emergency Response: Guidelines for the Emergency Planning Process. *Disasters*, 27, 336–350, <doi:10.1111/j.0361-3666.2003.00237.x>

Quagliarini, E., Bernardini, G., and D'Orazio, M. (2023). How Could Increasing Temperature Scenarios Alter the Risk of Terrorist Acts in Different Historical Squares? A Simulation-Based Approach in Typological Italian Squares. *Heritage*, 6(7), 5151-5186, <10.3390/heritage6070274>

Shahhoseini, Z., and Sarvi, M. (2018). Traffic Flow of Merging Pedestrian Crowds: How Architectural Design Affects Collective Movement Efficiency. *Transportation Research Record*, 2672, 121–132, <doi:10.1177/0361198118796714>

Shahhoseini, Z., and Sarvi, M. (2019). Pedestrian Crowd Flows in Shared Spaces: Investigating the Impact of Geometry Based on Micro and Macro Scale Measures. *Transportation Research Part B: Methodological*, 122, 57–87, <doi:10.1016/j.trb.2019.01.019>

Shiwakoti, N., Tay, R., Stasinopoulos, P., and Woolley, P.J. (2017). Likely Behaviours of Passengers under Emergency Evacuation in Train Station. *Safety Science*, 91, 40–48, <doi:10.1016/j.ssci.2016.07.017>

Sikora, W., and Malinowski, J. (2013). Crowd Behavior as an Example of the Evolution of a Complex System - Evacuation Models Proposal Based on the Symmetry Analysis Approach. *Acta Phys. Pol. A*, 124, 1005–1012.

Stefanis, C., Giorgi, E., Tselemponis, G., Voidarou, C., Skoufos, I., Tzora, A., Tsigalou, C., Kourkoutas, Y., Constantinidis, T.C., and Bezirtzoglou, E. (2023). Terroir in View of Bibliometrics. *Stats*, 6, 956–979, <doi:10.3390/stats6040060>

Sun, L., Yan, J., and Qiu, Y. et al. (2024). The crowd cooperation approach for formation maintenance and collision avoidance using multi-agent deep reinforcement learning, Vis Comput. <https://doi.org/10.1007/s00371-024-03647-1>

Tang, K., Zhang, J, Shen, Y., Li, C., and He, G. (2024), KDPM: Knowledge-driven dynamic perception model for evacuation scene simulation, *Computer Animation & Virtual Worlds*, Volume 35, Issue 3, <https://doi.org/10.1002/cav.2279>

Tian, H., Wei, Y., Dong, L., Xue, Y., and Zheng, R. (2018). Resolution of Conflicts in Cellular Automaton Evacuation Model with the Game-Theory. *Physica A: Statistical Mechanics and its Applications*, 503, 991–1006, <doi:10.1016/j.physa.2018.08.140>

Urata, J., and Hato, E. (2021). Dynamics of Local Interactions and Evacuation Behaviors in a Social Network. *Transportation Research Part C: Emerging Technologies*, 125, 103056, <doi:10.1016/j.trc.2021.103056>

Wan, H., Xiao, Y., Wei, S., Zhang, Y., and Oka, T. (2023). Experimental study on multiple fire hazards in a naturally ventilated tunnel: Assessment of the flame interaction and extension of two unequal fires. *International Journal of Thermal Sciences*, 187, 108209, <10.1016/ j.ijthermalsci.2023.108209>

Wang, L. (2020). A Two-Stage Stochastic Programming Framework for Evacuation Planning in Disaster Responses. *Computers & Industrial Engineering*, 145, 106458, <doi:10.1016/j.cie. 2020.106458>

Wang, S., Cao, S., Wang, Q., Lian, L., and Song, W. (2016). Effect of Exit Locations on Ants Escaping a Two-Exit Room Stressed with Repellent. *Physica A: Statistical Mechanics and its Applications*, 457, 239–254, <doi:10.1016/j.physa.2016.03.083>

Wang, Z., Zhang, C., Wang, J., Zheng, Z., and Li, L. (2021). Research on Path Planning Algorithm for Crowd Evacuation. *Symmetry*, 13, 1339, <doi:10.3390/sym13081339>

Weina, Ge., Collins, R.T., and Ruback, R.B. (2012). Vision-Based Analysis of Small Groups in Pedestrian Crowds. *IEEE Trans. Pattern Anal. Mach. Intell.*, 34, 1003–1016, <doi:10.1109/TPAMI.2011.176>

WoS Web of Science Available online: <webofknowledge.com> [accessed on 5 May 2026].

Wu, W., Chen, M., Li, J., Liu, B., Wang, X., and Zheng, X. (2023). Visual Information Based Social Force Model for Crowd Evacuation. *Tsinghua Sci. Technol.*, 27, 619–629, <doi:10.26599/TST.2021.9010023>

Ye, J., Liu, Z., Liu, T, Wu, Y., and Wang, Y. (2024). Crowd evacuation simulation based on hierarchical agent model and physics-based character control, *Computer Animation & Virtual Worlds*, Volume 35, Issue 3, <https://doi.org/10.1002/cav.2263>

Yue, H., Guan, H., Shao, C., and Zhang, X. (2011). Simulation of Pedestrian Evacuation with Asymmetrical Exits Layout. *Physica A: Statistical Mechanics and its Applications*, 390, 198–207, <doi:10.1016/j.physa.2010.10.003>

Yue, H., Zhang, B.-Y., Shao, C.-F., and Xing, Y. (2014). Exit Selection Strategy in Pedestrian Evacuation Simulation with Multi-Exits. *Chinese Phys. B*, 23, 050512, <doi:10.1088/1674-1056/23/5/050512>

Zardari, S., Alam, S., Al Salem, H.A., Al Reshan, M.S., Shaikh, A., Malik, A.F.K., Masood Ur Rehman, M., and Mouratidis, H. (2023). A Comprehensive Bibliometric Assessment on Software Testing (2016–2021). *Electronics*, 11, 1984, <doi:10.3390/electronics11131984>

Zhang, M., Xu, R., Siu, M., and Luo, X. (2023). Human Decision Change in Crowd Evacuation: A Virtual Reality-Based Study. *Journal of Building Engineering*, 68, 106041, <10.1016/j.jobe.2023.106041>

Zhao, R., Liu, Q., Hu, Q., Dong, D., Li, C., and Ma, Y. (2021). Lyapunov-Based Crowd Stability Analysis for Asymmetric Pedestrian Merging Layout at T-Shaped Street Junction. *IEEE Trans. Intell. Transport. Syst.*, 22, 6833–6842, <doi:10.1109/TITS.2020.2995275>