Resilience and safety of civil engineering systems and communities: A bibliometric analysis for mapping the state-of-the-art

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Resilience and safety of civil engineering systems and communities: A bibliometric analysis for mapping the state-of-the-art

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ABSTRACT

The interest in the concept of resilience has been growing consistently over the past few years to study the functionality and behavior of systems against natural and man-made hazards. Yet a comprehensive, updated review of methods and frameworks to assess and improve the resilience and safety of civil engineering systems and communities is lacking. In this paper, a bibliometric and visualization method is implemented to explore the status of resilience research in civil engineering applications by analyzing journal papers published from 1996 to 2020. The concept of resilience and safety is investigated through eight subject categories identified by the authors in the literature: recovery time strategies and downtime, critical infrastructures, probabilistic approaches, fuzzy logic approaches, structural health monitoring, health care facilities, emergency management and decision-making, community and urban resilience. Results show that resilience research has increased rapidly since its introduction, most notably in the past seven years. The analysis identifies two main research approaches: frameworks and conceptual models, and case study based. The latter is the most adopted methodology by the analyzed works. In terms of geographical distribution, most of them have been carried out in the USA, the United Kingdom, China, and Italy. The authors' keywords analysis reveals that recovery strategies, critical infrastructures, vulnerability, and community resilience and safety have attracted prominent attention in the past decade. Finally, we conclude that further multidisciplinary research is needed to model multi-hazard scenarios and cascading effects, to collect data, and to define new performance metrics.

1. Introduction

Resilience was first used to describe property of materials and to explain why some materials were able to accommodate severe loads without breaking (Hollnagel et al., 2006). In the 1970s, Holling (Holling, 1973) referred to the resilience of an ecosystem as its ability to absorb changes and still exist. Over the last few years, the topic has spread into several fields such as ecology, management, economics, social sciences, and engineering (World Economic Forum and Report, 2023). Therefore, the term "resilience" is broadly used to describe several aspects, such as "the capacity to manage with connected systems, to degrade gracefully and to improve the ability to cope with future risks" (Yang, 2023). Some of the most common definitions of resilience in various fields are reported in Table 1.

In engineering, the concept of resilience is related to the capacity of a system to "withstand stress, survive, adapt and bounce back from a crisis or disaster and rapidly move on" (Wagner and Breil, 2013). Bruneau et al. (Bruneau, 2003) defined resilience as "the ability of organizations and communities to mitigate hazards, contain the effects of disasters, and carry out recovery strategies to mitigate the effects of further earthquakes". Resilience engineering is a paradigm for improving safety avoiding failures and losses, as well as responding appropriately after an event (Leveson, 2006). Engineering systems are highly correlated with safety management in terms of their resilience when facing a crisis or disasters (Yang, 2023). Defining resilience assessment approaches can be useful for managers of industrial and construction safety, as it could help monitor and improve the resilience and performance of engineering systems. To ensure adequate safety conditions, systems and communities must be resilient in terms of avoiding failures and losses, while responding appropriately after a hazard. In the civil engineering field, most of the studies on resilience quantification are aimed at mitigation and recovery strategies of physical systems. For instance, Liu et al. (Liu et al., 2017) developed a framework to combine dynamic modeling with resilience analysis for two interconnected critical infrastructures. A

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Table 1
Literature definitions of resilience concept in different fields.

Terminology	Definition	Sources
Organizational resilience	Ability to face disruptions and unanticipated events through the strategic operational management of internal and external shocks.Ability to bounce back to the original state from a disruption.	(Annarelli and Nonino, 2016) (Sheffi and Rice, 2005)
Resilience engineering	Ability of a system to adapt and absorb changes and disruptions. Ability of a system to prevent and withstand any hazards and recover to normal functionality.	(Hollnagel et al., 2006) (Ouyang, 2014)
Economic resilience	Ability to recover, to withstand, to adapt, and to avoid the potential losses maintaining.The capacity to allocate resources efficiently.	(Rose and Liao, 2005) (Martin, 2012)
Social resilience	Capacity to cope with stress, significant change, or risk.The process of adaptation despite challenging circumstances.	(Greene et al., 2002) (Masten et al., 1990)

conceptual model in which the concept of resilience is correlated to the concept of recovery is presented by Miles and Chang (2006). In their work, the relationships between a community's business, lifeline networks, and neighborhood are investigated. Regarding the resilience of urban communities, a quantitative method is represented by the PEOPLES framework (Cimellaro, 2016). It consists of seven dimensions, highlighting the multidisciplinary nature of the topic (Renschler, 2010). Recently, probabilistic, and fuzzy approaches have been introduced to estimate the recovery time and the resilience of buildings and infrastructures after a seismic event (De Iuliis, 2019; De Iuliis, 2019; Hosseini and Barker, 2016; Yodo and Wang, 2016). Moreover, Zhang et al. (Zhang et al., 2018) described a strategy for enhancing structural resilience through the implementation of structural health monitoring (SHM) technologies into civil infrastructures.

The abovementioned works demonstrate a great variety of applications related, making a systematic analysis of the literature in the civil engineering domain essential. Among the available review techniques, bibliometric analysis is a widely used tool. It is a quantitative approach that enables the exploration of a given field's development while revealing emerging trends (Li, 2022; Zeng and Li, 2022). Several reviews have been conducted on resilience (Santamaria-Ariza, 2023; Li, 2023; Yu, 2023). For instance, Meerow et al. (Meerow et al., 2016) focused on resilience related to industrial ecology. A year later, a critical review of some qualitative and quantitative frameworks was provided by Ceré et al. (Ceré et al., 2017). Sirsant et al. (Sirsant et al., 2023) presented a bibliometric analysis and scoping review of reliability assessment tools for managing and designing Water Distribution Networks (WDNs). Fraccascia et al. (Fraccascia et al., 2018) reviewed the state-of-the-art of complex systems resilience in different fields through bibliometric tools. However, these review articles focus on specific systems or aspects of resilience and safety. For example, Ellis et al. (Ellis, 2019) combined scoping review and bibliometric analysis of the literature on resilient health care. Similarly, Luo et al. (Luo, 2022) used a bibliometrics approach to analyze the literature on construction safety. They pointed out differences between developed and developing countries as well as new trends on the use of artificial intelligence and digital technologies. While construction safety partly contributes to the overall resilience of buildings and infrastructures, this study targets a wide spectrum of resilience enhancing features, designs, interventions, and quantification methodologies related to civil engineering systems and urban communities. Existing review articles on resilience focus on the resilience definition, measurement, and optimization methods in a specific research domain, such as transportation network, risk management, natural hazards, etc. There are still some questions to be solved in the field of civil engineering resilience: 1) What are the research hotspots in this field? 2) Which journals, articles, and authors are influential in the identified research hotspots? 3) Which country and institution are the most active contributor? The answers to these questions are fundamental to provide comprehensive insights for the newcomers to this field, which will help them to decide where to focus their research. To identify the evolution of this field, there is a need for bibliometric analysis.

To the knowledge of the authors, such comprehensive and detailed review that embraces several research sub-areas related to resilience and safety in civil engineering through a bibliometric visual analysis, is still missing in the literature. This paper aims at filling this void by (i) tracing the resilience development in eight prevailing research domains within civil engineering applications, (ii) identifying the influential journals, articles, keywords, and scholars in the domain of resilience and safety of civil infrastructure systems, (iii) analyzing the citation and co-citation network of the publications and their interdependency, (iv) discussing the limitations or gaps of existing research in the resilience and safety domain; and (v) enabling readers to identify future trends. This review-based study introduces the science mapping approach into the domain of resilience and safety in civil engineering field and provides recommendations for future-research.

The remainder of this paper is structured as follows. Section 2 introduces the data source and bibliometric methodology. Section 3 illustrates the results and their classification, including historical analysis, the geographical distribution of the research works, the author keyword, co-authorship, and co-citation analyses. Finally, section 4 discusses the findings and identifies possible directions for future research.

2. Literature review methodology

The study is based on bibliometric research conducted in March 2021. The expected results of conducting the bibliometric analysis proposed in this work can be replicated by implementing the steps presented in Fig. 1.

The systematic review's starting point is the definition of the field of study, i.e., safety and resilience in civil engineering. Subsequently, five steps are followed: (1) choosing the databases to cover relevant literature in the field; (2) defining inclusion and exclusion criteria and selecting publications based on them; (3); collecting and extracting bibliometric data; (4) performing quantitative data analysis through visualization bibliometric maps; (5) presentation and discussion of the results. The first step is the definition of scientific research platforms to be investigated for mining scientific data. The analyzed publications were retrieved from Web of Science (WoS), a widely used database. WoS is an academic citation indexing and search service of Thomson Reuters' Web of Knowledge that covers journals, conference papers, websites, and patents (Reuters, 2012). According to Clarivate (Analiytics. Clarivate Analytics., 2022), "Web of Science (WoS) is the world's most powerful search engine, delivering your library with best-in-class publication and citation data for confident discovery, access, and assessment". WoS was chosen as the primary and only database since (i) it has a remarkable multidisciplinary nature, which is particularly useful to gather information about the state of the art; (ii) it covers highly rated journals and an extensive collection of scientific publications; and (iii) it provides several publication and citation data for reliable discovery and bibliometric analyses. Once the scientific platform to be used was established, the search criteria of the publications had to be defined. Generally, the main search criteria applied in the bibliometric analysis are specific terms to the field of study, area of knowledge, publication type, and language. To identify resilience in civil engineering applications, keyword searches within the titles, keywords, and abstracts of the different research outputs have been applied.

Looking at the literature, eight prevailing research domains were identified: (1) *recovery time and downtime*, (2) *critical infrastructures*, (3) *structural health monitoring*, (4) *probabilistic approaches*, (5) *fuzzy logic approaches*, (6) *health care facilities*, (7) *emergency management and*

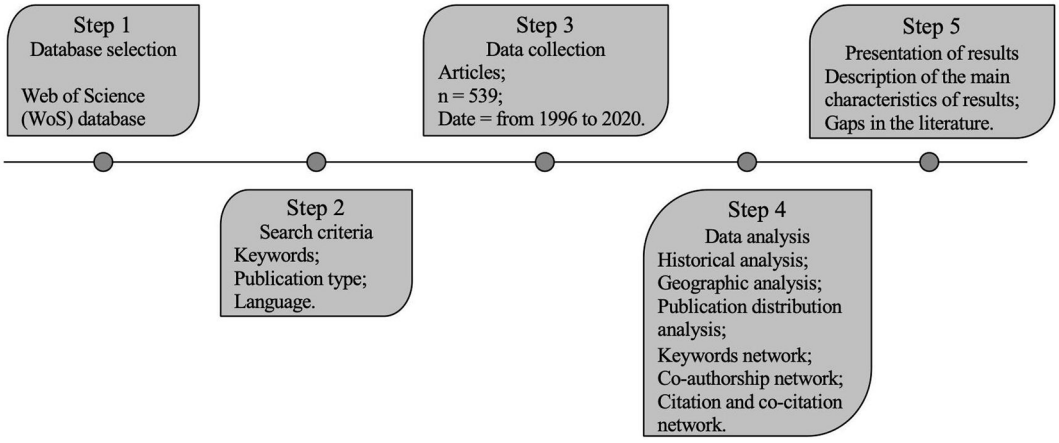

Fig. 1. Steps of the bibliometric analysis for mapping the state-of-the-art.

decision-making, (8) *community and urban resilience*. The fuzzy logic approach was considered as it is a key technique in the resilience and downtime assessment of buildings and infrastructures, and it has several applications in safety science. Generally, it is an approach that can be exploited for risk assessment, including the identification of risks accounting for human factors and errors. Table 2 shows the keyword search for each sub-category identified by the authors.

Despite the word "safety" per se was not included in the search criteria, we believe the concept of resilience is inherently related to the concept of safety. Indeed, as mentioned in the Introduction section, one of the main purposes of assessing the resilience of an asset or a community is to make sure that they can prevent, be prepared or adapt to changing conditions and external disruptions to maintain their properties and functionalities.

No inferior year limit was applied when performing the search. However, the oldest article, according to the keywords, was from 1996. Thus, research articles were extracted from a period of 1996–2020. We decided to include articles until 2020 to have a sufficient citation base and terms of comparison for the most recent ones. Considering the latest articles published after 2020 could mean putting them at the bottom of the citation rank. In the search process, only journal articles that have been cited and published in English were selected. Furthermore, those papers having titles and abstracts where the word resilience does not appear among the keywords were omitted. A very strict and generally limiting way of categorizing publications was applied in this work to accurately reflect the dissemination of resilience in civil engineering applications in academic research. Despite the strict criteria, post-processing of the literature was still necessary to exclude insufficiently relevant papers (e.g., papers where resilience was not the main topic but only mentioned as a suggestion for future works, papers where the word resilience was among keywords, but they did not fully address the topic). All the papers including titles and abstracts were read and analyzed and the selection was refined by removing non-resilience-related works. After these steps, 539 papers were selected as constituting the final database.

Table 2
Search criteria.

Research field	Keywords used
Recovery time and Downtime	resilience AND downtime AND "recovery time*" AND restoration
Community and Urban resilience	resilience AND communit*AND urban
Critical infrastructures	resilience AND infrastructure* AND network*
Structural Health Monitoring	resilience AND "structural monitoring"
Fuzzy Logic approach	resilience AND "fuzzy logic"
Probabilistic approach	resilience AND probabilistic
Emergency Management and Decision-Making	resilience AND emergency AND manage* AND "decision-mak*"
Health Care Facilities	resilience AND hospital* AND "health facilit*"

Fig. 2 illustrates the PRISMA diagram reporting the number of articles (n) after applying the inclusion and exclusion criteria in all the steps of the search process.

All the bibliographic records were exported into a text file (delimited tabs) to be used later. The full record and cited references include bibliometric parameters such as publication information on the title, author (s), year of publication, abstract, source title (i.e., journal name), affiliation, author's keywords, language, and the number of citations. Since only one database was used, there were no duplicates.

The data from the database was analyzed to identify the general trends in resilience research in civil engineering applications. That is, the exported records were used for different analyses: (i) historical analysis was conducted to understand the temporal trend of resilience research in civil engineering; (ii) geographical distribution analysis was carried out to analyze the research output in different countries and leading institutions using the authors' affiliations as the criterion to locate them; (iii) publication distribution analysis was investigated to highlight the most popular journals, the most cited records along with the corresponding authors in the realm of resilience research, and finally (iv) keywords analysis was performed for the author's keywords to understand the nature, links, and concepts used by the author(s). The analyzed database was imported into VOS-viewer 1.6.14 software to build visualization networks of major co-occurrence keywords and create easily readable figures. VOSviewer software offers an effective overview of the results by developing two-dimensional networks based on co-authorship, citation, co-citation, and co-occurrence of keywords, authors, and countries to determine relationships between them (Van Nunen, 2018; Cancino, 2017; Gall et al., 2015).

As mentioned before, the proposed bibliometric analysis was limited to eight sub-categories. Each abovementioned sub-research area was analyzed separately. That is, for each of them, detailed analyses were performed to highlight the core journals and countries involved in the research, and identify the core literature, i.e., the articles with the highest number of citations. Furthermore, co-authorship analysis was carried out to discover the key research groups and the relationships among them, as well as the relationships among countries involved in the research. Then, citation and co-citation networks were built including all the analyzed papers to discover the most important and influential articles, which are being cited together, in driving the research on resilience in the civil engineering field.

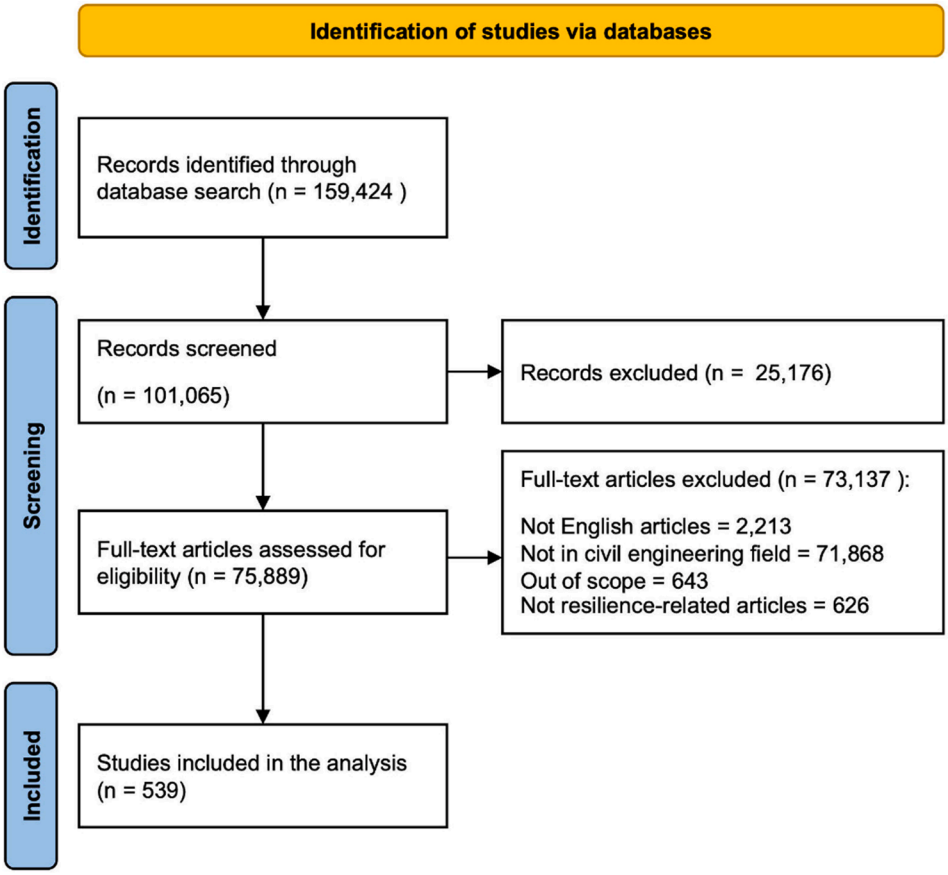

Fig. 2. PRISMA flowchart for bibliometric analysis of resilience in the civil engineering field.

3. Results and discussion

3.1. Historical analysis

The annual number of publications is considered an important indicator to evaluate the increase of interest in a particular topic. Results showed an increasing number of studies on the concept of resilience applied to civil engineering. From the search the first publications date back to 1996. Fig. 3 shows the annual number of published papers with a steady increase after 2011 and was contributed by the major industrialized countries (USA, UK, Italy, China, etc.). According to the extracted database, the first study that used the concept of resilience in civil engineering was published by Fox and Suidan (Fox and Suidan, 1996). Most of the research, roughly 60 %, was published during 2013–2018. This means a growing knowledge accumulation and research interest of the scientific community. Fig. 4 shows the total number of citations for all the publications found in the considered set. An exponential positive trend can be observed for this measure. Since 2012, more than 200 citations per year have been gained by the analyzed papers. Thus, from this year, the interest in resilience applied to civil engineering applications started growing significantly.

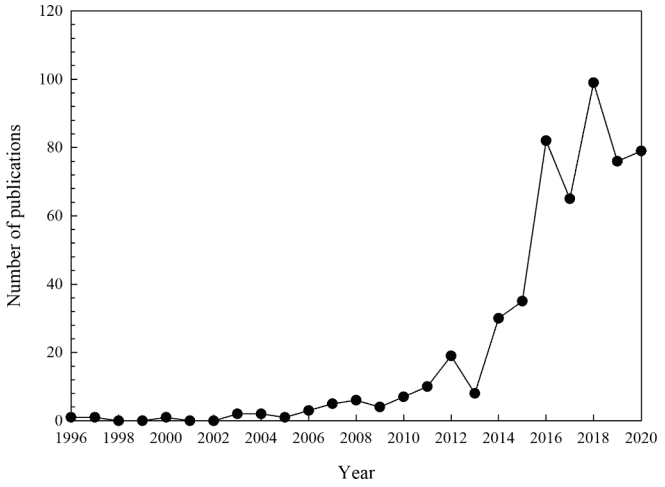

Fig. 3. Number of published papers on resilience in civil engineering applications (1996–2020).

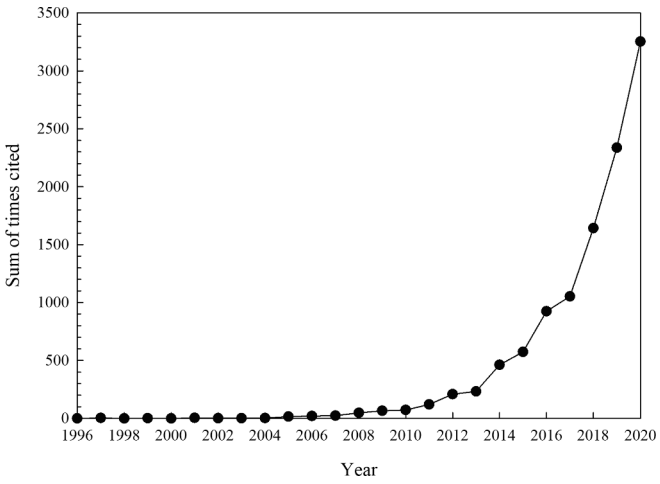

Fig. 4. Sum of times cited by year (1996–2020).

3.2. Number of publications by countries and institutes

The 539 papers analyzed were published in 52 different countries worldwide (Fig. 5). A mapping approach was implemented to graphically represent the number of publications by countries, using authors' affiliation in the records as the criterion to locate them. The most productive country in this regard is the USA with 307 cited publications (corresponding to 57 %) followed by UK, Italy, China, and Australia with 63, 56, 54, and 27 cited publications, respectively. Few to no authors come from Central Asia, the Middle East, and Africa. Therefore, the map indicates a polarization between Western and Eastern countries. However, it should be noted that in those areas research published in non-English languages might have been done.

The universities that are leaders among the top 5 most productive research countries are presented in Table 3, where the number of cited publications along with the corresponding percentage of the total research output are listed. The research organization with the largest number of author affiliations in the cited resilience papers represents the leading institution for the country.

As mentioned before, the USA is overall the most prolific country in civil engineering resilience research, but its top institution – the University of California – is responsible for only 13 % of the total research output in the country. This indicates that a larger number of American research organizations have focused on the concept of resilience applied to civil engineering studies. A similar observation can be made for China and Australia, where the shares of the respective leading organizations are below 20 %.

Table 3
Leading institutes in the top 5 most productive countries (1996–2021).

Rank	Country	No. of publications	Most productive institute	Percentage
1	USA	40	University of California	13.03 %
2	UK	14	University of Exeter	22.22 %
3	ITALY	18	Polytechnic University of Turin	32.14 %
4	CHINA	10	The Hong Kong Polytechnic University	18.52 %
5	AUSTRALIA	5	The University of Melbourne	18.52 %

Table 4
Top 10 journals with the largest number of publications (1996–2020).

Rank	Journal	Year of first publication	No. of articles
1	Natural Hazards Review	1986	38
2	Journal of Infrastructure Systems	1995	34
3	Journal of Structural Engineering	1955	33
4	Engineering Structures	1970	26
5	Earthquake Spectra	1984	25
6	Transportation Research Record	1974	25
7	Sustainable and Resilient Infrastructure	2016	22
8	Journal of Risk and Uncertainty in Engineering Systems	2015	20
9	Water Resources Management	1987	20
10	Structure and Infrastructure Engineering	2007	19

3.3. Number of publications by journals

This section aims at analyzing the most popular journals in the realm of resilience research in the civil engineering field, the highly cited articles on the topic, and the authorship. The analysis examines the 539 academic articles published in 94 journals and authored by 1,431 researchers. Table 4 lists the top 10 journals where the selected articles were published. The top journal with 38 cited papers in resilience in civil engineering is *Natural Hazards Review,* published by the American Society of Civil Engineers (ASCE). This is followed by the *Journal of Infrastructure Systems* (34 articles) and the *Journal of Structural Engineering* (33 articles). Furthermore, the actual number of citations that each cited resilience article has gained was investigated. The top 10 articles with the most citations, their authors, publication year, and publishing journals are presented in Table 5. The most prominent contributor in the area is Professor M. Bruneau, who co-authored 4 of the top 10 cited papers. Similarly, Professors G.P. Cimellaro (Italy) and A. Reinhorn (USA) have also achieved excellent recognition, with their names appearing two and three times in the top 10 list.

The trends in the 5 journals with the greatest number of articles are illustrated in Fig. 6. A correlation in trends between the analyzed journals was observed. The overall number of articles published in these journals increased with ups and downs, showing a significant increase in the interval 2016–2019.

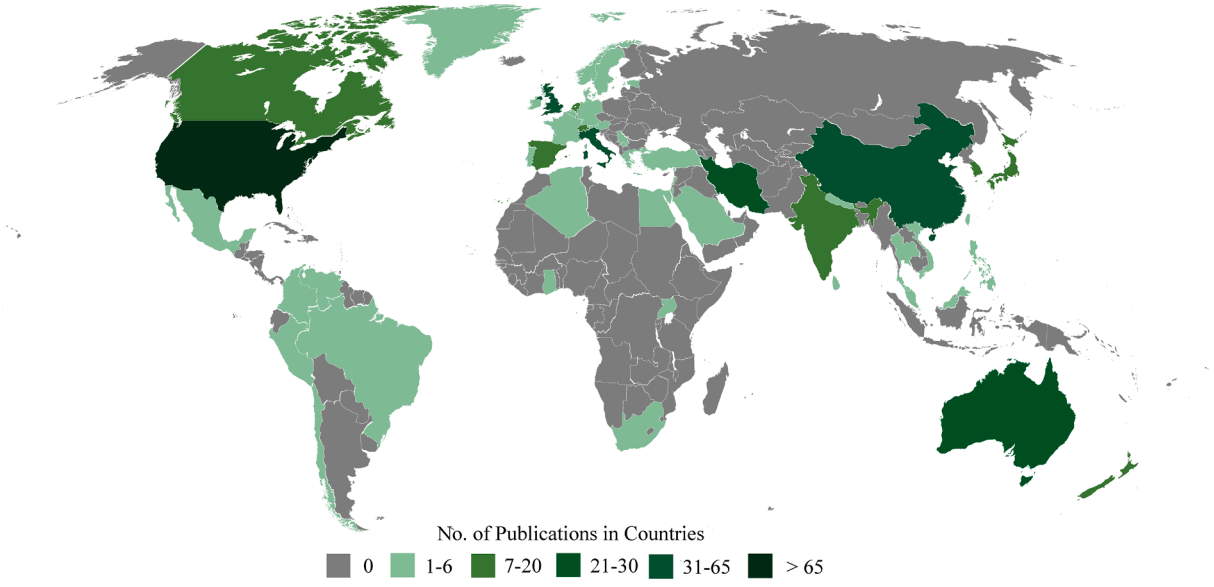

Fig. 5. Distribution of publications by country.

Table 5
Top 10 articles with most citations (1996–2020).

Rank	Title	Year	Author(s)	No. of citations	Journal
1	A framework to quantitatively assess and enhance the seismic resilience of communities	2003	Bruneau, M; Chang, SE; Eguchi, RT; et al	1,490	Earthquake Spectra
2	Urban Hazard Mitigation: Creating Resilient Cities	2003	Godschalk, David R.	534	Natural Hazards Review
3	Framework for analytical quantification of disaster resilience	2010	Cimellaro, Gian Paolo; Reinhorn, Andrei M; Bruneau, Michel	479	Engineering Structures
4	Multiobjective genetic algorithms for design of water distribution networks	2004	Prasad, TD; Park, NS	323	Journal of Water Resources Planning and Management
5	A three-stage resilience analysis framework for urban infrastructure systems	2012	Ouyang, Min; Duenas-Osorio, Leonardo; Min, Xing	306	Structural Safety
6	Measuring improvements in the disaster resilience of communities	2004	Chang, SE; Shinozuka, M	283	Earthquake Spectra
7	Seismic resilience of a hospital system	2010	Cimellaro, Gian Paolo; Reinhorn, Andrei M; Bruneau, Michel	218	Structure and Infrastructure Engineering
8	Exploring the concept of seismic resilience for acute care facilities	2007	Bruneau, Michel; Reinhorn, Andrei	195	Earthquake Spectra
9	Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach	2014	Bocchini, Paolo; Frangopol, Dan M; Ummenhofer, Thomas; et al.	180	Journal of Infrastructure Systems
10	Multi-dimensional hurricane resilience assessment of electric power systems	2014	Ouyang, Min; Duenas-Osorio, Leonardo	178	Structural Safety

3.4. Author keywords analysis

Keyword analysis reveals the exact context of resilience studies in the civil engineering area. VOSviewer software was used to construct a visualization map to picture the linkages and co-occurrence of chosen keywords by studied authors (Van Eck and Waltman, 2013). In the map, each keyword is represented by a circle whose diameter represents the number of links with other keywords. Hence, a larger circle means more links with other keywords. The thickness of the line between two or more circles represents the frequency of co-occurrence of the keywords together. Furthermore, the distance between two nodes reflects the strength of the relation between them.

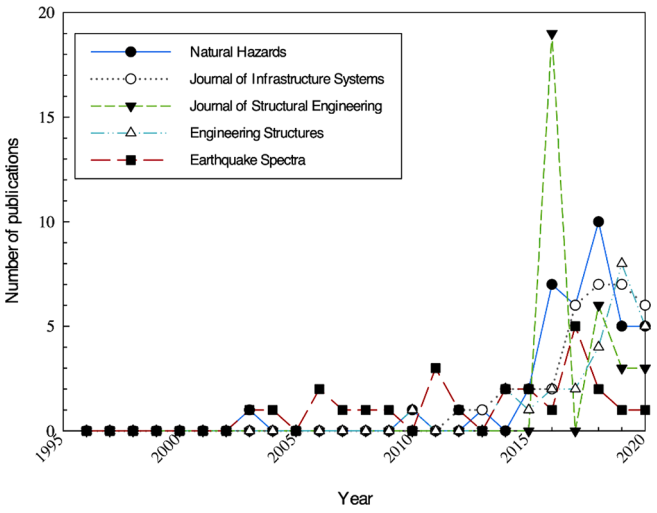

Fig. 6. The growth trends of the top 5 journals.

Fig. 7 shows the major keywords used in resilience studies in the civil engineering area. The figure represents instances where the co-occurrence of a keyword is at least 5 times. Only 61 out of a total of 1,453 authors' keywords met the threshold covering the studied interval, which equals 4.13 %. VOSviewer divided the keywords of resilience-related publications into 6 clusters. Common keywords revealed are "community resilience", "sustainability", "recovery", "climate change", and "earthquake".

Table 6 lists the 10 most frequently used author keywords along with their occurrences in the analyzed publications and total link strength with other keywords. The keyword "resilience" has the highest frequency, equal to 147. Other keywords with a high frequency include "community resilience" (37), "sustainability" (24), and "recovery" (22). The total link strength of a node is the sum of the link strengths of such node over all the other nodes and it can be used to indicate the relationships among two nodes (Pinto et al., 2014). For example, the node "resilience" presents thicker lines with "recovery" (14), "infrastructure" (10), "sustainability" (10), and "vulnerability" (10). These are the nodes whose link strengths are greater or equal to 10. The relationship between "resilience" and "recovery" (link strength of 14) implies the close integration of recovery programs within the resilience estimation. By performing a timeline analysis, it can be noted that before 2013 little research was done on resilience in civil engineering applications and the keywords of that period are concentrated on "water distribution systems", "disasters", "water supply", "fragility", and "hospital". After 2013, research began to increase and keywords started including additional aspects.

3.5. Analysis of each sub-category

3.5.1. Resilience, recovery time and Downtime

Between 1996 and 2020, 159 papers were published in 43 journals (Fig. 8). Considering the top five journals in terms of number of publications, *Journal of Structural Engineering* (IF 2.45, H-index 146) published 15 papers (9.43 % of the published papers), *Journal of Infrastructure Systems* (IF 1.82, H-index 64) and *Natural Hazards Review* (IF 2.06, H-index 52) published 14 papers each (8.85 %), *Earthquake Spectra* (IF 2.47, H-index 86) published 12 papers (7.54 %), *Engineering Structures* (IF 4.38, H-index 128), and *Transportation Research Record* (IF 1.18, H-index 107) published 11 papers each (6.91 %).

Fig. 8 shows that the number of papers published by year increased over time with a peak in 2020 (30 papers). Records in this sub-category gained in total 4546 citations, and on average, each paper was cited

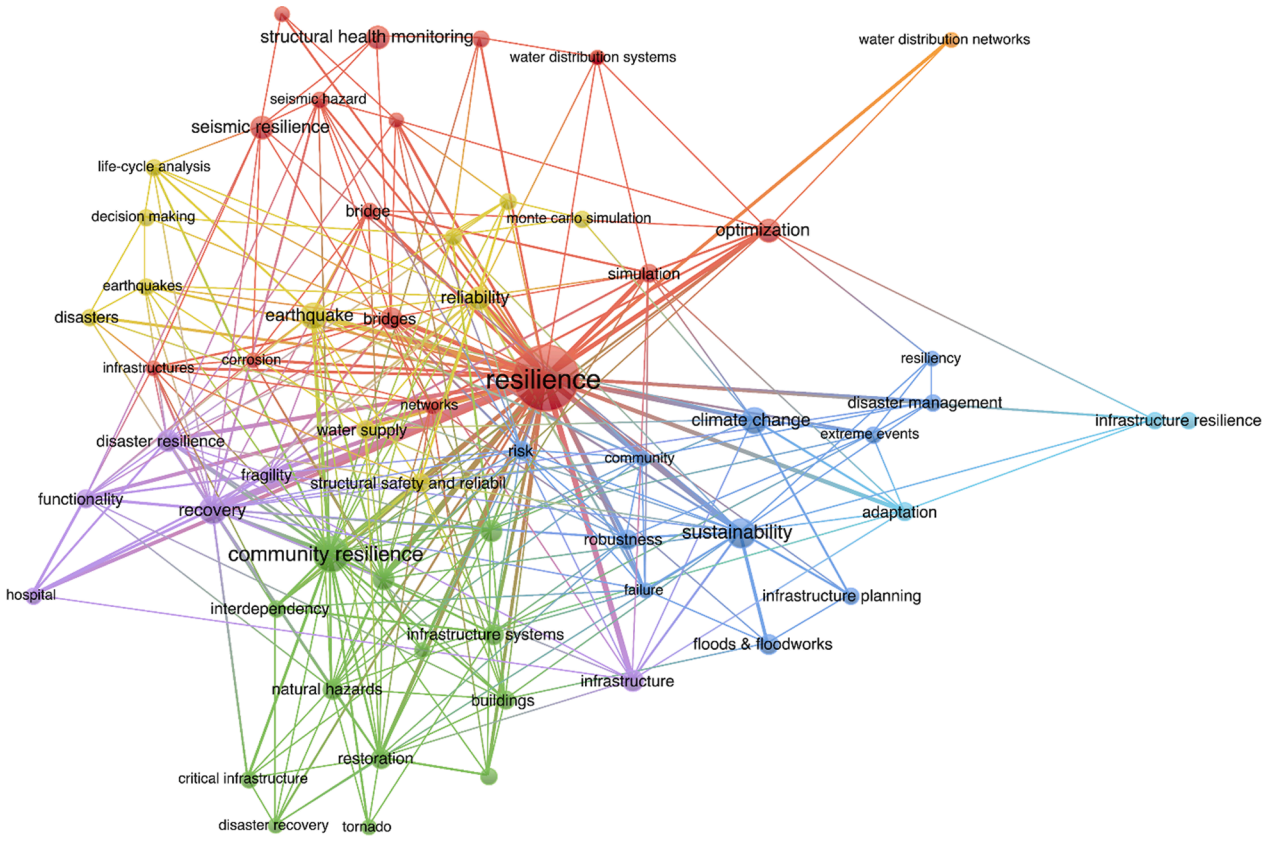

Fig. 7. Map of Civil Engineering resilience of author's keywords (5 co-occurrence criteria with 61 keywords).

Table 6
Top 10 most frequency of author keywords, 1996–2020.

Rank	Author Keywords	Occurrences	Total link strength
1	Resilience	147	220
2	Community resilience	37	50
3	Sustainability	24	36
4	Recovery	22	58
5	Earthquake	18	31
6	Climate change	18	18
7	Reliability	13	29
8	Optimization	13	21
9	Vulnerability	12	32
10	Bridges	12	27

28.59 times. Overall, the selected papers were authored by 424 researchers. Fig. 9 presents the co-authorship map illustrating the largest set of connected items, where each node corresponds to one researcher and two nodes are linked if the corresponding researchers co-authored at least one paper. In the figure, the size of the node is proportional to the number of authored papers. In particular, the map highlights 8 main research groups spread worldwide. It also shows that the most noteworthy researchers in the scientific community are Gian Paolo Cimellaro (Polytechnic University of Turin), John van de Lindt (Colorado State University), Michel Bruneau (University of Buffalo), Henry V. Burton (University of California), You Dong (The Hong Kong Polytechnic University), Yi Li (University of British Columbia), Paolo Gardoni (University of Illinois), and Leonardo Duenas-Osorio (Rice University). These researchers present scientific productivity higher than the average (larger size of the node) and they cooperated in a larger number of research groups (larger number of links). From the figure, it is also possible to notice that the research is fragmented, because of the high number of research groups without any interaction among them. Most of the authors published only one paper each on this area, suggesting that additional works are yet to be developed.

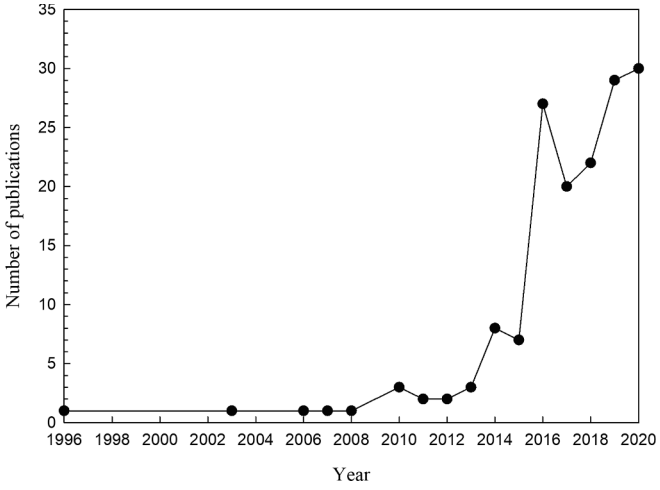

Fig. 8. Number of papers published by year (1996–2020).

The countries involved in the research and the collaborative relationships among them are indicated in Fig. 10. Each node represents a country, and the size of the node is proportional to the number of papers written by at least one researcher of that country. The countries involved are 25: USA (105 papers), Italy (19), People's Republic of China (13), England (10), Canada (9), New Zealand (9), Australia (7), Iran (6), Japan (3), France (2), Greece (2), India (2), Netherlands (2), South Korea (2), Spain (2), Switzerland (2), Taiwan (2), Brazil (1), Colombia (1), Egypt (1), Nepal (1), Philippines (1), Portugal (1), Sweden (1), and Vietnam (1). From the figure, it is highlighted that the USA plays a primary role in this research area, given both the number of papers

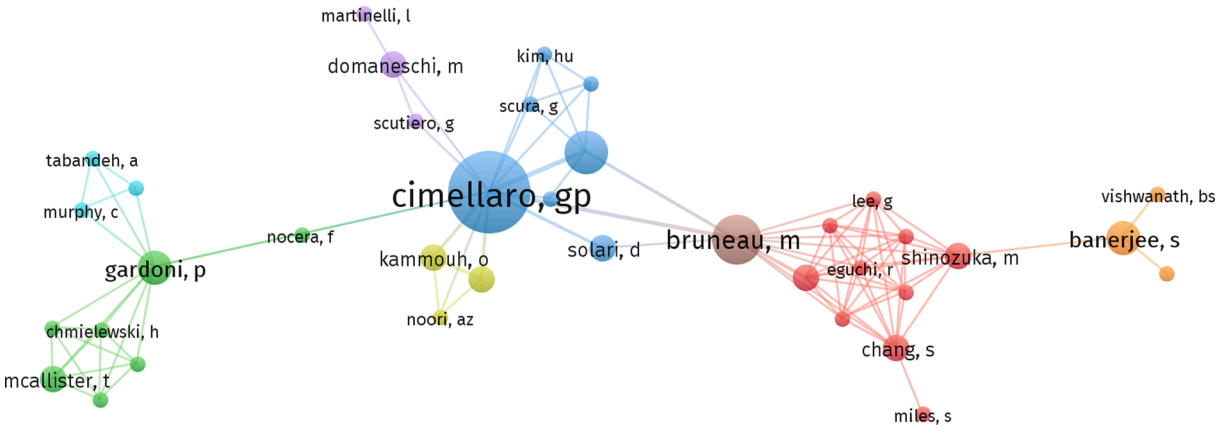

Fig. 9. Co-authorship map for papers belonging to research area "Recovery time and Downtime".

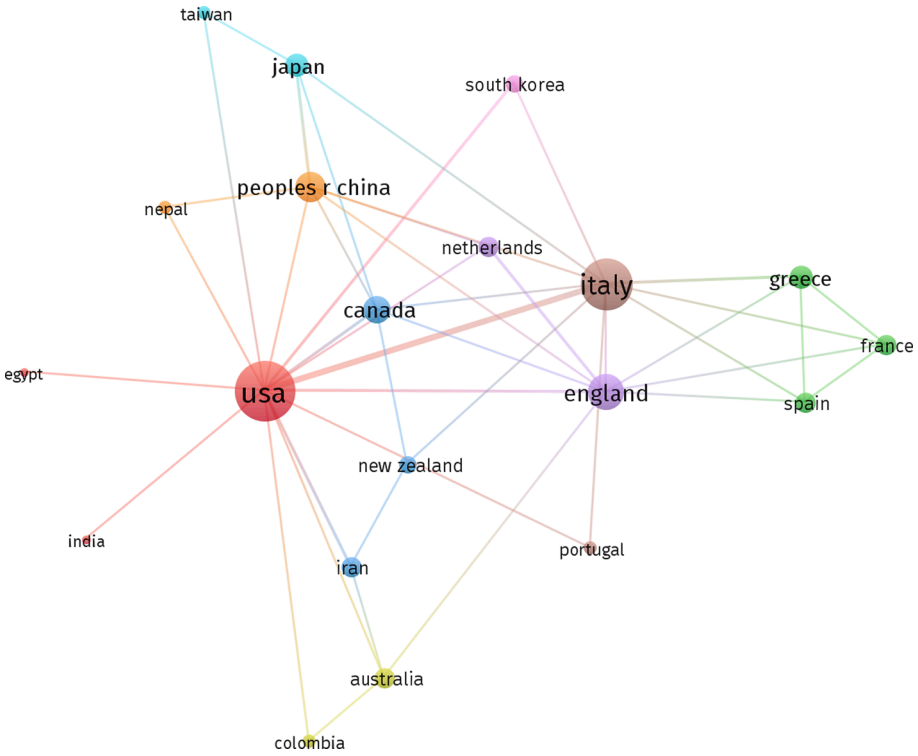

Fig. 10. Relationships among countries concerning papers belonging to the research area "Recovery time and Downtime".

published and the cooperation with other foreign researchers.

As representative of the core literature, the innovative contributions of the five papers with the highest number of citations are here highlighted. Bruneau et al. (Bruneau, 2003) (1495 citations, 78.68 citations per year) developed a conceptual framework for defining and measuring seismic resilience to establish needs and priorities. Quantitative measures are included within the framework: robustness, rapidity, resourcefulness, and redundancy. The goals are to determine the resiliency of different units of systems and to develop resiliency targets that can be adaptable for the analysis of various systems. Cimellaro et al. (Cimellaro et al., 2010) (481 citations, 40.08 citations per year) and Cimellaro et al. (Cimellaro et al., 2010) (219 citations, 18.25 citations per year) presented a comprehensive model to quantify disaster resilience of systems by combining loss estimation and recovery models. The work aimed at providing a framework for quantitative definition of resilience using an analytical function that fits both technical and organizational issues. Bruneau and Reinhorn (Bruneau and Reinhorn, 2007) (196 citations, 13.07 citations per year) explored the concept of resilience for both physical and social systems and proposed a methodology to quantify resilience providing a comprehensive understanding of damage, response, and recovery. Although quantification of resilience was first approached from the societal context, engineering tools could be integrated into decision support tools that are necessary for the formulation of resilience strategies. Miles and Chang (Miles and Chang, 2006) (120 citations, 7.5 citations per year) presented a comprehensive conceptual model of community recovery and listed the main relationships between a community's households, businesses, lifeline networks, and neighborhoods after an earthquake occurs. A prototype computer model of community recovery was developed and integrated with a graphical user interface to set out the foundations for implementing robust recovery models.

3.5.2. *Resilience and critical infrastructures*

Fig. 11 shows the number of papers published by year (2004–2020).

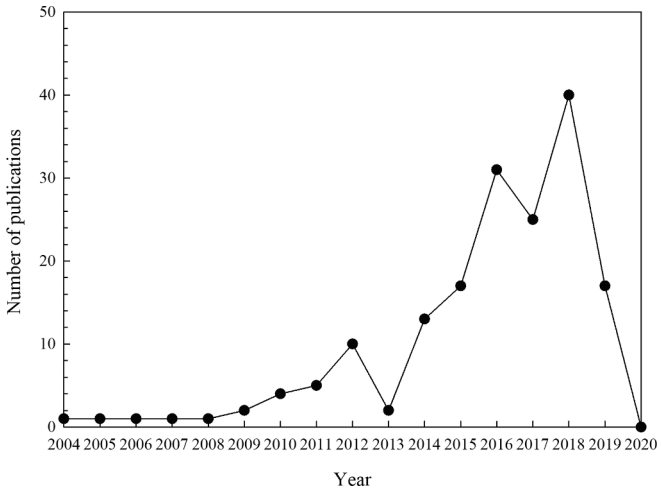

Fig. 11. Number of papers published by year (2004–2020).

Between 2004 and 2020, 193 papers were published in 50 different journals. Within the top five journals, *Journal of Infrastructure Systems* (IF 2.46, H-index 64) published 17 papers (8.80 %), *Journal of Water Resources Planning and Management* (IF 2.71, H-index 93), *Transportation Research Record* (IF 1.18, H-index 107), and *Water Resources Management* (IF 3.13, H-index 91) published 12 papers each (6.21 %), and *Sustainable and Resilient Infrastructure* published 11 papers (5.69 %).

As the figure shows, the number of papers increased rapidly, peaking in 2018 (40 papers). Records in this research area gained in total 4409 citations, and on average, each paper was cited 22.48 times. The selected papers were authored by 544 researchers. Fig. 12 shows the co-authorship map, indicating interactions among 52 authors. In particular, the figure highlights 9 main research groups worldwide. The most relevant researchers in the scientific community are Dan M. Frangopol (Lehigh University), Mitsuyoshi Akiyama (Waseda University), Paolo Bocchini (Lehigh University), Leonardo Duenas-Osorio (Rice University), Fabio Biondini (Polytechnic University of Milan), Therese P. McAllister (National Institute of Standards and Technology), and Guantgtao Fu (University of Exeter).

The contributing countries involved in the research and the relationships among them are presented in Fig. 13. 32 countries contributed to the research: USA (103 papers), England (29), People's Republic of China (23), Italy (16), Iran (14), Australia (13), India (6), Canada (5), Netherlands (5), South Korea (5), Japan (4), New Zealand (4), France (3), Singapore (3), Denmark (2), Germany (2), Greece (2), Spain (2), Uganda (2), Venezuela (2), Austria (1), Egypt (1), Ireland (1), Mexico (1), Nepal (1), Norway (1), Saudi Arabia (1), South Africa (1), Sweden (1), Taiwan (1), and Vietnam (1). From Fig. 13, it can be observed the central role played by the USA, which cooperates with almost all the other countries. Scant collaborative relationships among the others can be noticed.

As representative of the core literature, the innovative contributions of the five papers with the highest number of citations are here highlighted. Prasad and Park (Prasad and Park, 2004) (323 citations, 17.94 citations per year) applied a multi-objective genetic algorithm approach to the design of a water distribution network aiming at minimizing the network cost and maximizing a reliability measure. The method produced a set of Pareto-optimal solutions in the search space of cost and network resilience, which was introduced as a new reliability measure. Ouyang et al. (Ouyang et al., 2012) (306 citations, 30.60 citations per year) proposed a new multi-stage framework to analyze infrastructure resilience. Different resilience-based improvement strategies were highlighted, and appropriate measures of resilience were identified to be combined for setting an expected annual resilience metric. One of the main novelty of the framework is that it accounts for both single hazards and concurrent multiple hazards. Bocchini et al. (Bocchini, 2014) (181 citations, 22.63 citations per year) proposed a unified approach that uses the concepts of probability of occurrence and risk to address resilience and sustainability of the civil infrastructure simultaneously and quantitatively. This paper was a first conceptual attempt to provide a unified perspective suggesting that the combination of both resilience and sustainability infrastructure concepts provides a truly comprehensive assessment of the quality of the infrastructure. Ouyang and Duenas-Osorio (Ouyang and Duenas-Osorio, 2014) (178 citations, 22.25 citations per year) introduced a probabilistic modeling approach for quantifying the hurricane resilience of contemporary electric power systems. The approach included multi-dimensional technical, social, organizational, and economic resilience. The novelty of the work is the introduction of a resilience framework for infrastructure systems, which is not only adequate for single and multiple hazards, but also for quantifying potential future resilience with the consideration of system evolution. Farmani et al. (Farmani et al., 2005) (177 citations, 10.41 citations per year) investigated the application of multi-objective evolutionary algorithms (MOEAs) to the identification of the pay-off characteristic between total cost and resilience index (a surrogate measure for network reliability) of a water distribution system through the "Anytown" network used as an example.

3.5.3. Resilience and Structural health monitoring

Between 2007 and 2020, 23 papers were published in 20 different journals. Within the top five journals, *Structural Control Health Monitoring* (IF 4.14, H-index 55) published 3 papers (11.54 % of the published

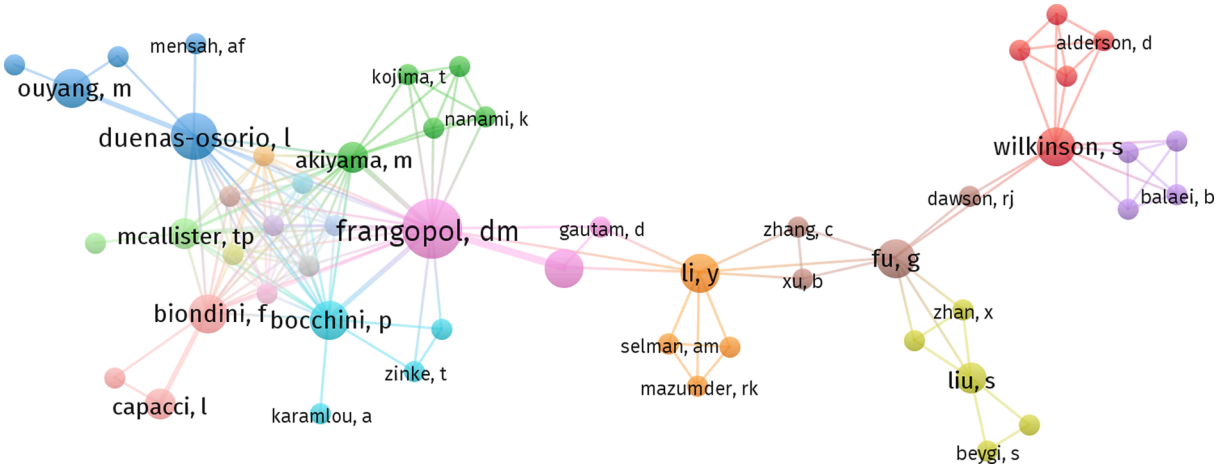

Fig. 12. Co-authorship map for papers belonging to research area "Infrastructure systems".

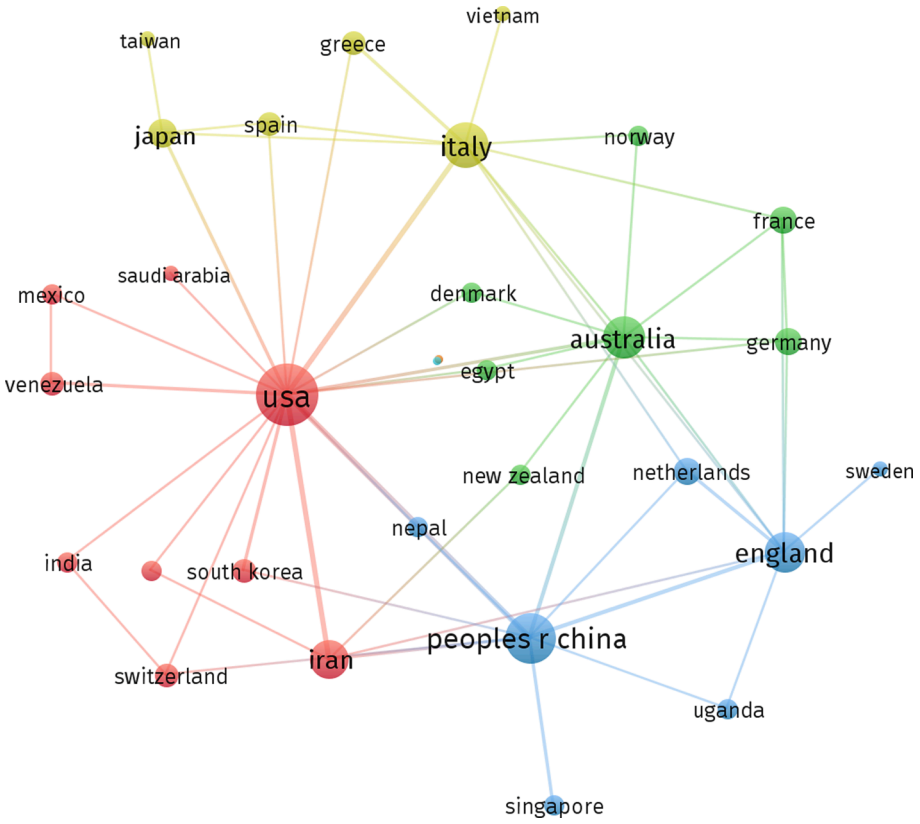

Fig. 13. Relationships among countries regarding papers belonging to the research area "Infrastructure systems".

papers), *Construction and Building Materials* (IF 5.14, H-index 147), *Engineering Structures* (IF 4.38, H-index 128), *Journal of Civil Structural Health Monitoring* (IF 2.70, H-index 23), and *Tunnelling and Underground Space Technology* (IF 5.37, H-index 86) published 2 papers each (7.69 %).

The number of papers increased since 2014 with its ups and downs, reaching a peak in 2019 (7 papers). Publications in this research area obtained in total 206 citations, and on average, each record was cited 7.29 times. The analyzed papers were authored by 92 researchers. The largest set of connections among the authors consists of 12 items. The leading researcher in the scientific community is Giovanni Fabbrocino (University of Molise). Interactions among the other researchers contributing were pointed out, as each of them wrote only one paper. 12 countries over the world are included in the research: USA (12 papers), Italy (6), England (3), Spain (2), Switzerland (2), Australia (1), Egypt (1), France (1), Japan (1), Malta (1), People's Republic of China (1), and South Korea (1). The USA played a central role in this research area, mainly collaborating with four other countries.

The innovative contributions of the five papers with the highest number of citations are here briefly presented. Elsaid and Seracino (Elsaid and Seracino, 2014) (36 citations, 4.50 citations per year) illustrated for the first time the use of horizontally displaced mode shapes and the calculated change in the dynamic flexibility features to identify scour from the response of the bridge superstructure. This research may be considered one of the first attempts to show that the horizontally displaced mode shapes are sensitive to scour due to its large impact on the flexural stiffness of piles. Naser and Kodur (Naser and Kodur, 2018) (18 citations, 4.50 citations per year) proposed a coupled sensing-structural approach to monitoring the vulnerability of critical infrastructure in real-time. This approach suggests that IoT technology can institute a platform to enable more resilient design of new and existing critical infrastructures. The proposed concept for cognitive infrastructure aims at monitoring key response parameters to locate impacts and consequences of a disaster and to raise occupants' and first responders' awareness during a disaster. Cavalagli et al. (Cavalagli, 2019) (12 citations, 4 citations per year) proposed an innovative and multidisciplinary methodology for evaluating construction materials' degradation in historical masonry buildings, providing a risk mapping accounting for interactions between climate change effects and structural damage. Such an impact contributes to materials degradation and structural safety in historical constructions, which are more vulnerable compared to recent designs. Sajedi and Liang (Sajedi and Liang, 2020) (11 citations, 5.50 citations per year) proposed an innovative data-driven framework for the identification, in nearly real time, of the existence, probable location, and severity of damage in buildings depending on the hazard uncertainty. The framework consisted of cumulative intensity-based damage features and Support Vector Machines (SVMs). Hardy et al. (Hardy, 2016) (9 citations, 1.50 citations per year) developed and characterized a new type of Carbon Nanofiber High-Performance Fiber-Reinforced Cementitious Composite (CNF-HPFRCC) to offer high resilience in several applications. The findings of the study are beneficial to the development of self-sensing and nano reinforced HPFRCCs applied in structural and transportation systems.

3.5.4. Resilience and probabilistic approach

Between 2007 and 2020, 104 studies were published in 44 journals (see Fig. 14). Within the top five journals, *Engineering Structures* (IF 4.38, H-index 128) published 14 papers (13.34 %), *Journal of Structural Engineering* (IF 2.45, H-index 138) published 9 papers (8.57 %), *Structure and Infrastructure Engineering* (IF 3.33, H-index 41) published 8 papers (7.62 %), *Earthquake Engineering and Structural Dynamics* (IF 4.43, H-index 115), *Sustainable and Resilient Infrastructure* published 7 papers (6.66 %), and *Journal of Risk and Uncertainty in Engineering Systems* (IF 1.86, H-index 12) published 6 papers (5.71 %).

As shown in Fig. 14, the number of papers published between 2000 and 2020 reached a peak in 2018, when 22 publications were published.

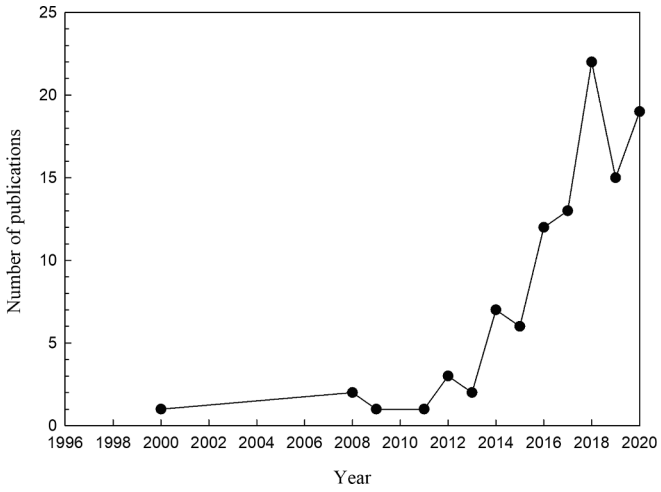

Fig. 14. Number of papers published by year (2000–2020).

The examined papers in this research area reached in total 1668 citations, and on average, each item was cited 15.89 times. The researchers contributing to the assessment of resilience through probabilistic approaches were 293. The analysis pointed out three main research groups and the most relevant researchers. In particular, the main contributing authors are Paolo Gardoni (University of Illinois), Gian Paolo Cimellaro (Polytechnic University of Turin), Omar Kammouh (Delft University of Technology), Armin Tabandeh (University of Illinois), and John van de Lindt (Colorado State University). Compared to the other researchers working on this research area, who published only one paper each, the mentioned researchers cooperated in a larger number of research groups (larger number of links). This means that the research is fragmented, due to the high number of research groups without any interaction among them.

Fig. 15 illustrates the collaborative relationships among the 27 countries involved in the research area. The country with the largest number of papers written by at least one researcher of that country in cooperation with other foreign researchers is the USA (61 papers), followed by Italy (15), People's Republic of China (13), Spain (6), Australia (5), Canada (5), Iran (5), England (4), Colombia (3), Netherlands (3), France (2), Germany (2), Japan (2), Singapore (2), South Korea (2), Belgium (1), Bermuda (1), Chile (1), Denmark (1), India (1), Ireland (1), Mexico (1), Peru (1), Portugal (1), Saudi Arabia (1), Taiwan (1), and Turkey (1).

The innovative contributions of the five papers with the highest number of citations are here briefly presented. Ouyang and Duenas-Osorio (Ouyang and Duenas-Osorio, 2014) (178 citations, 22.25 citations per year) introduced a probabilistic modeling approach for quantifying the hurricane resilience of contemporary electric power systems. The novelty of the work is the introduction of a resilience framework for infrastructure systems, which is not only adequate for single and multiple hazards, but also for quantifying potential future resilience with the consideration of system evolution. Decò et al. (Decò et al., 2013) (92 citations, 10 citations per year) proposed a probabilistic approach for the pre-event assessment of the seismic resilience of bridges, accounting for uncertainties associated with expected damage, the restoration process, and rebuilding/rehabilitation costs. The innovative aim of this work was to evaluate resilience for assisting decision-makers in planning pre-event activities. Dong and Frangopol (Dong and Frangopol, 2015) (88 citations,12.57 citations per year) presented a framework for probabilistic seismic performance assessment of highway bridges subjected to mainshock and aftershocks (MSAS). The paper aimed to not only quantify the seismic vulnerability of bridges but also to integrate the resilience performance indicator within a seismic risk assessment process under MSAS sequences through a probabilistic framework. Guidotti et al. (Guidotti, 2016) (84 citations, 14 citations per year) introduced a unified theoretical methodology for modeling dependent/interdependent infrastructure networks and incorporated it in a six-step probabilistic procedure to evaluate their resilience. The probabilistic procedure captured the direct physical damage, cascading effects due to interdependencies, loss of network functionality and allowed quantification of the effects of damage on network functionality. Tian and De Wilde (Tian and De Wilde, 2011) (74 citations, 6.73 citations per year) tackled the uncertainties and sensitivities in the prediction of the thermal performance of buildings under climate change. The approach propagated uncertainties in climate change predictions and those related to interventions.

3.5.5. *Resilience and fuzzy logic approach*

Six papers were published between 2008 and 2018, each of them in a

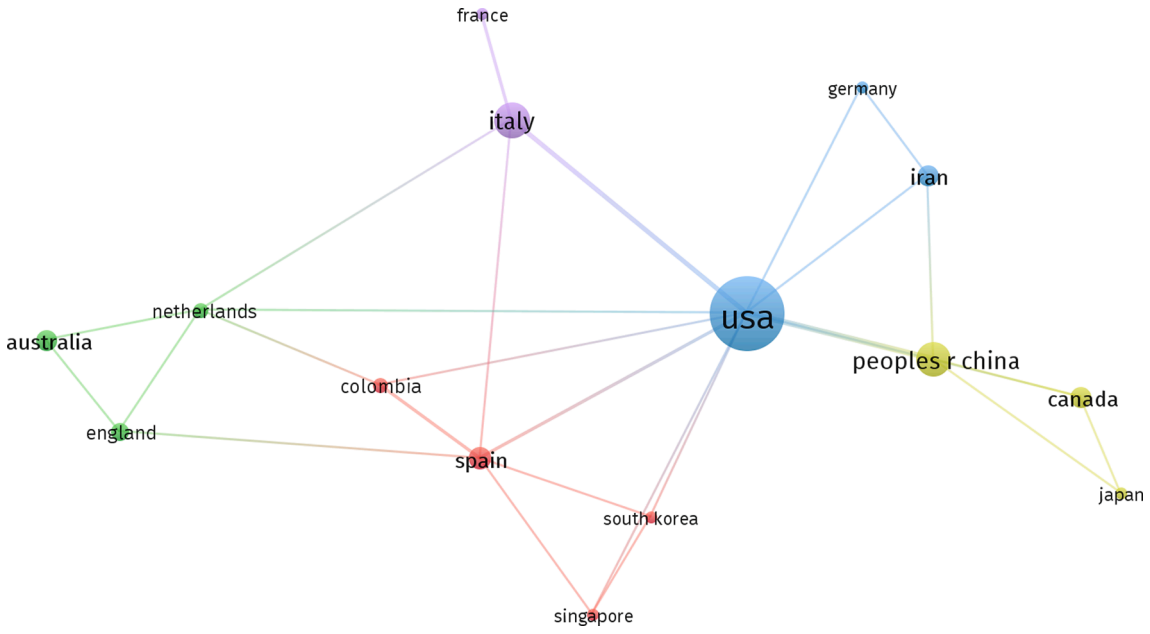

Fig. 15. Relationships among countries concerning papers of the research area "Probabilistic approach".

different journal. This means that core journals for this research area do not exist, and the topic has not been fully explored yet. Papers in this area gained 155 citations; on average, each paper was cited 25.83 times. Research in this field is highly fragmented; 6 research groups were found, composed of up to 5 researchers, without any interaction among them. Each of the 19 researchers wrote one paper, meaning that a reference point for the research does not exist. The research involved 6 countries over the world: Iran (3 papers), the USA (2), Canada (1), England (1), Italy (1), and the People's Republic of China (1). In the following paragraph, the main contribution of the papers with the highest number of citations is presented.

Safavi et al. (Safavi et al., 2015) (46 citations, 6.57 citations per year) proposed an expert knowledge and data-based model to evaluate near future conditions of complex water systems considering the water management policies and climate change conditions. The proposed scenario analysis benefits Artificial Neural Networks (ANN) and Fuzzy Inference System (FIS) to account for future climate change conditions in case of limited data availability. John et al. (John, 2016) (40 citations, 6.67 citations per year) proposed a modeling approach based on the Fuzzy Bayesian Network (FBN) to represent the uncertainty in results for modeling in support of decision making and to optimize the performance effectiveness of seaport operations. The use of FBN allows the influencing variables to be represented in a hierarchical structure for collaborative design and modelling of the system and evaluating the relative influence of each influencing variable. The procedure highlighted how both quantitative and qualitative datasets can be integrated in a flexible manner. Tesfamariam and Saatcioglu (Tesfamariam and Saatcioglu, 2008) (34 citations, 2.43 citations per year) proposed a risk-based evaluation technique to quantify seismic assessment and develop a ranking scheme for reinforced concrete buildings. Fuzzy set theory is implemented to handle vagueness uncertainty because of subjective walk-down survey, while fuzzy rule base modeling is used to incorporate decision-maker's knowledge in combining the input parameters. Kammouh et al. (Kammouh, 2018) (16 citations, 4 citations per year) introduced an indicator-based method to evaluate the resilience of communities based on the PEOPLES framework. PEOPLES framework is a multi-layered framework that defines community resilience using seven dimensions. Knowledge-based fuzzy modeling is implemented to evaluate quantitatively the PEOPLES indicators through descriptive knowledge rather than deterministic data including the uncertainty of the analysis.

3.5.6. Resilience and Health care facilities

In this sub-category, 19 records were published between 2007 and 2020 in 15 journals: 4 of them published 2 papers (10.526 %) (*Building and Environment,* IF 4.97, H-index 124; *Earthquake Spectra,* IF 2.47, H-index 86; *Energy and Buildings*, IF 4.86, H-index 184; and *Engineering Structures*, IF 4.38, H-index 128, while the remaining 11 published 1 paper each (5.26 %). The number of papers published between 2007 and 2020 peaked in 2016 and 2019 when 3 studies were published. The analyzed records in this research area achieved in total 1275 citations, and on average, each item was cited 67.11 times. The evaluation of resilience of health care facilities and emergency departments was studied by 42 researchers. 10 different research groups over the world and the most relevant researchers in the scientific community were identified. That is, the authors who mainly contribute are Gian Paolo Cimellaro (Polytechnic University of Turin), Kevin John Lomas (Loughborough University), Michel Bruneau (University of Buffalo), Rangaraj Giridharan (Bharathidasan University), and Andrei M. Reinhorn (University of Buffalo). The research involved 10 countries: the USA (10 papers), England (5), Italy (5), People's Republic of China (2), Australia (1), Iran (1), Netherlands (1), New Zealand (1), Spain (1), and Thailand (1). However, scant cooperation exists among these countries.

The innovative contributions of the five papers with the highest number of citations are here briefly presented. Cimellaro et al. (Cimellaro et al., 2010) (498 citations, 41.50 citations per year) provided a quantitative framework for the definition of disaster resilience using an analytical function that may fit both technical and organizational issues. The quantification of resilience is determined through dimensionless analytical functions related to the variation of functionality during a period of interest, including losses and recovery time. Cimellaro et al. (Cimellaro et al., 2010) (226 citations, 18.83 citations per year) presented a regional loss estimation study that evaluates the economic losses of six hospital buildings within the city of Memphis, Tennessee. The study successfully integrated the information from different fields (engineering, economics, operations, etc.) into a single function. Bruneau and Reinhorn (Bruneau and Reinhorn, 2007) (199 citations, 13.27 citations per year) explored both physical and social systems and proposed a methodology to quantify resilience providing a comprehensive understanding of damage, response, and recovery. Lomas and Giridharan (Lomas and Giridharan, 2012) (76 citations, 7.60 citations per year) and Lomas and Ji (Lomas and Ji, 2009) (57 citations, 4.38 citations per year) evaluated the thermal resilience to climate change of hospital wards illustrating how field measurement, thermal modeling, and generation of current and future extreme weather years can be used in the resilience assessment.

3.5.7. Resilience and emergency management and decision-making

In this sub-category, 46 records were published between 1997 and 2020 in 24 journals. Within the top five journals, *Natural hazards review* (IF 2.06, H-index 52) published 5 papers (10.87 %), *Journal of Infrastructure Systems* (IF 2.46, H-index 64) and *Water Resources Management* (IF 3.13, H-index 91) published 4 papers (8.696 %), finally *Journal of Risk and Uncertainty in Engineering System* (IF 1.31, H-index 17) and *Journal of Hydro informatics* (IF 2.37, H-index 50) published 3 papers (6.522 %). Records published between 1997 and 2020 reached a peak in 2018 when 10 journal papers were published. The analyzed publications in this research area achieved in total of 558 citations, and on average, each item was cited 12.13 times. Furthermore, the sum of citations has increased since 2013. The estimation of resilience in the emergency management and decision-making research area is carried out by 175 researchers. Fig. 16 shows the co-authorship map, illustrating that research is highly fragmented; 40 research groups were found, composed of up to 12 researchers, without any interaction among them. Furthermore, a reference point for the research does not exist. That is, 9 researchers wrote 2 papers each, and the other authors only wrote one paper. The research involved 21 countries all over the world. The most productive country is the USA with 27 papers (i.e., 58.69 %) followed by England (6 papers), Italy and the People's Republic of China (5 papers), Canada and South Korea (4 papers). The central role is again played by the USA, which cooperates with almost all the other countries. Little collaborative relationships among the other countries can be noticed. In the following paragraph, the main contribution of the papers with the highest number of citations is presented.

Bodoque et al. (Bodoque, 2016) (50 citations, 8.33 citations per year) presented a methodological approach to analyze flood hazard and social vulnerability. The analysis of flash flood risk was carried out through hydrological and hydraulic models, hazardousness mapping, social exposure, and vulnerability analysis. Lounis and McAllister (Lounis and McAllister, 2016) (48 citations, 8 citations per year) presented a framework for risk-informed decision-making for the lifecycle performance of infrastructure facilities that accounts for the concept of sustainability and resilience. An innovative risk-informed decision-making approach was applied, and resilience performance goals were evaluated for design alternatives. Zanuttigh et al. (Zanuttigh, 2014) (45 citations, 5.63 citations per year) proposed an open-source Spatial Decision Support System within the THESEUS Project to help decision-makers prioritize proper strategies to reduce coastal risks and improve resilience. The main novelty of the tool is that it allows performing a coastal risk assessment analyzing the effects of several combinations of engineering, social, economic, and ecologically based mitigation options, across short, medium, and long-term scenarios. Chang et al. (Chang, 2012) (39

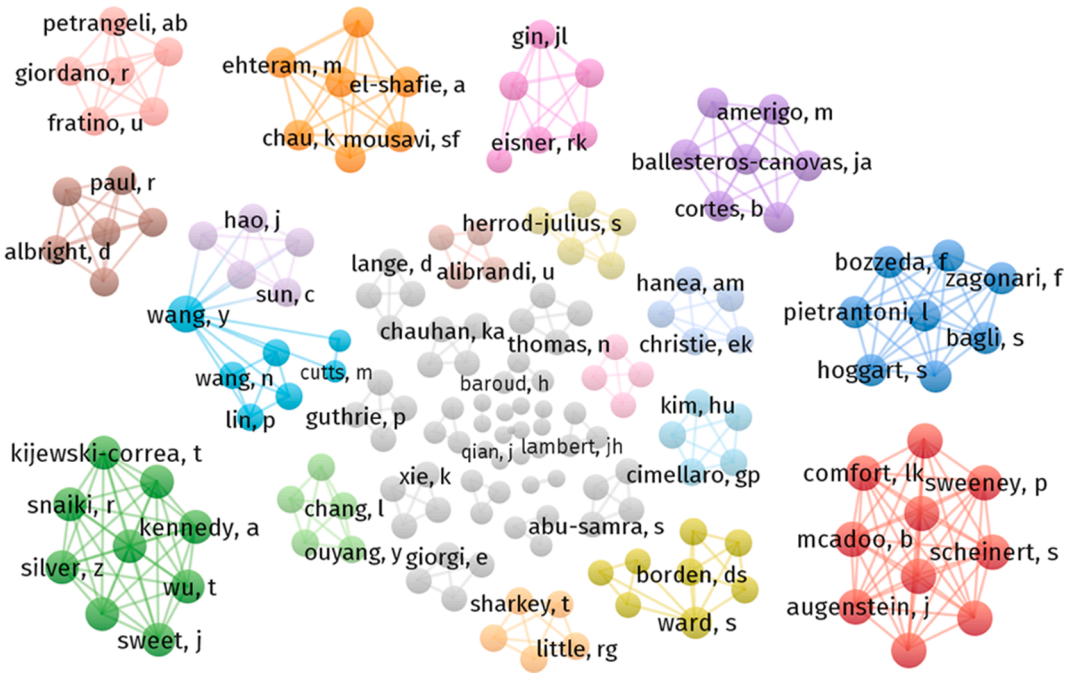

Fig. 16. Co-authorship map for publications of the research area "Emergency management and decision-making".

citations, 3.90 citations per year) described an efficient stochastic programming optimization framework for decision-making on bridge network seismic retrofit prioritization, which has been computationally challenging in literature. Monte Carlo simulation was applied to address the uncertainties involved in the structural damage and demonstrate its potential for the planning and maintenance of realistic highway networks. Ayyub (Ayyub, 2015) (38 citations, 5.43 citations per year) introduced a new resilience definition that considers reliability and risk as key relevant metrics. Existing metrics were reviewed, and simplified ones were proposed for sound decision-making tools in multi-hazard environments.

3.5.8. Community and urban resilience

137 papers were published between 2003 and 2020 in 40 journals. Within the top five journals, *Natural hazards review* (IF 2.06, H-index 52) published 21 papers (15.32 %), *Earthquake Spectra* (IF 2.47, H-index 86) published 14 papers (10.21 %), *Journal of Structural Engineering* (IF 2.45, H-index 138) published 11 papers (8.02 %), *Structural Safety* (IF 4.52, H-index 93) and *Sustainable and Resilient Infrastructure* published 10 papers (7.29 %). Papers in this research area gained a total of 4,207 citations, and on average, each paper was cited 30.71 times. The analyzed papers were authored by 376 researchers. Fig. 17 illustrates the co-authorship map, highlighting the largest set of connected items that consist of 6 main research groups spread worldwide. It also shows that the most relevant researchers in the scientific community are John van de Lindt (Colorado State University), Yingjun Wang (South China University of Technology), Hussam Mahmoud (Colorado State University), Peihui Lin (Zhejiang University), Maria Koliu (Texas A&M University System), R. Bruce Ellingwood (Tsinghua University), and Naiyu Wang (Zhejiang University). In addition to a productivity higher than the average, these authors cooperated in a larger number of research groups. The countries involved are 31. The most productive ones are the USA (90 papers), Italy

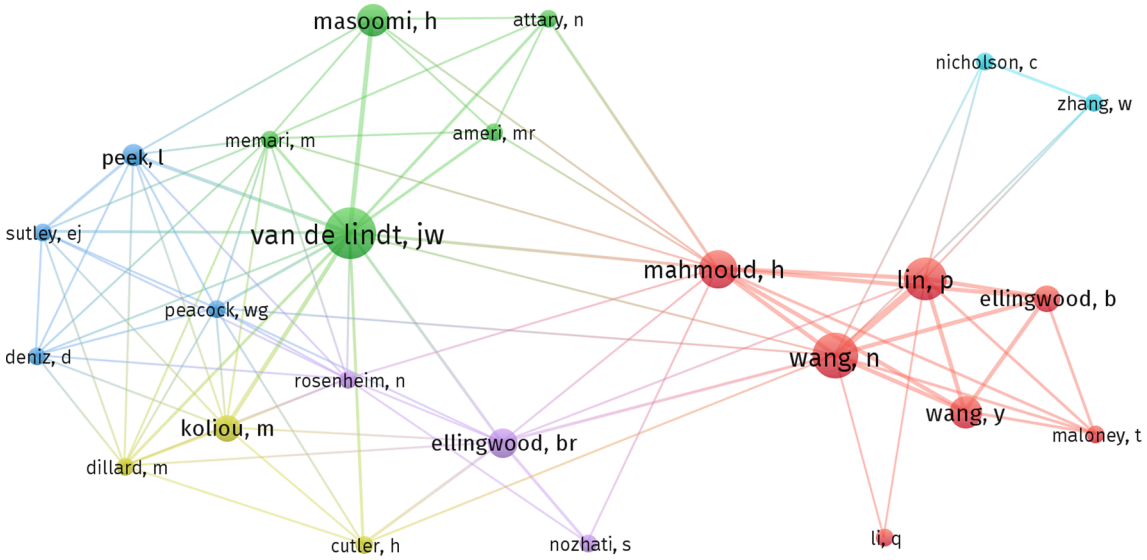

Fig. 17. Co-authorship map for publications of the research area "Community and Urban Resilience".

(16), England (10), the People's Republic of China (9), and New Zealand (5). The figure highlights the relevant role played by the USA in this research area, for both the number of papers and cooperation with many foreign researchers.

The innovative contributions of the five papers with the highest number of citations are here briefly presented. Bruneau et al. (Bruneau, 2003) (1543 citations, 81.21 citations per year) developed a framework for defining and measuring seismic resilience to establish the needs and priorities of communities. The goal of this work is to integrate resilience measures into the four dimensions of community resilience – technical, organizational, social, and economic – that can be adapted to quantify measures of resilience for different types of systems exposed to both natural and man-made disasters. Godschalk (Godschalk, 2003) (549 citations, 28.89 citations per year) proposed a novel strategy to mitigate urban hazards and create resilient cities. Hazard mitigation practice and resilient city concepts are reviewed, and the relationships among resilience and terrorist attacks are considered in this work. Chang and Shinozuka (Chang and Shinozuka, 2004) (289 citations, 16.06 citations per year) developed and applied quantitative measures to demonstrate the concept of disaster resilience. This paper proposed measures that relate expected losses in future hazards to the community's seismic performance objectives and compared two seismic retrofit strategies to improve community resilience. Lee et al. (Lee et al., 2013) (133 citations, 14.78 citations per year) developed a survey tool that organizations can use to identify the strengths and weaknesses of their communities and to evaluate the effectiveness of their strategies. In this work, a new model of organizational resilience was developed where resilience is a function of adaptive capacity and planning. Miles and Chang (Miles and Chang, 2006) presented a comprehensive conceptual model of community recovery and listed the main relationships between a community's households, businesses, lifeline networks, and neighborhoods after an earthquake occurs. A prototypal digital model was developed and integrated with a graphical user interface to set out the foundations for developing robust models of community recovery.

3.6. Citation and co-citation analysis

In this section, a citation network of the 539 analyzed papers is presented. The citation network allows (i) understanding the relative importance of the most cited papers in the field, and (ii) understanding how papers are grouped in terms of citation patterns. The largest set of citation networks among the papers belonging to the analyzed database with at least 20 citations is shown in Fig. 18. In the citation network, each node depicts one paper, while links among papers determine citations among them. The network consists of 302 links. The most cited papers are Bruneau et al. (Bruneau, 2003) (1492 citations), Godschalk (Godschalk, 2003) (534 citations), Cimellaro et al. (Cimellaro et al., 2010) (479 citations), Prasad and Park (Prasad and Park, 2004) (323 citations), and Ouyang et al. (Ouyang et al., 2012) (306 citations) (see Table 5). These papers belong to *Community and Urban Resilience*, *Critical infrastructures*, and *Health care facilities* research areas and are the most influential for the study of resilience in civil engineering applications.

Co-citation analysis provides information about the most influential works that are being cited together. That is, a co-citation network evaluates quantitively publications based on their scientific and intellectual relationship by defining how often two or more studies have been cited together (Meerow et al., 2016). Since it is not possible to conduct a co-citation analysis of the whole database due to the high number of citations, the co-citation network of the references was constructed with a minimum of 20 citations which resulted in 27 studies (Fig. 19). The size of the node presents the normalized number of citations received by the articles and the thickness of the lines represents the strength of co-citation ties. The link and proximity between the two articles identify the co-citation relationship between them. For example, in Fig. 19, the line between Bruneau et al. (Bruneau, 2003) and Chang and Shinozuka (Chang and Shinozuka, 2004) is thick, indicating a strong co-citation relationship between the 2 articles (i.e., they are often cited together). Each node was labeled by the first author and publication year of the record. If a set of articles is co-cited very often, this implies that such articles most likely share common ideas. The clusters of articles determine what is termed a "structural knowledge group" that represents the central themes and intellectual structures of a field (Pilkington and Meredith, 2009; Leydesdorff and Vaughan, 2006). As it is shown in Fig. 19; Bruneau et al. (Bruneau, 2003) is not only the most frequently cited study but also one of the most frequently co-cited with other references. The most commonly cited co-reference is Cimellaro et al. (Cimellaro et al., 2010); Ouyang et al. (Ouyang et al., 2012), and Chang and Shinozuka (Chang and Shinozuka, 2004) (which are also listed as the top cited works in Table 5).

Interestingly, it was found that papers belonging to a given sub-

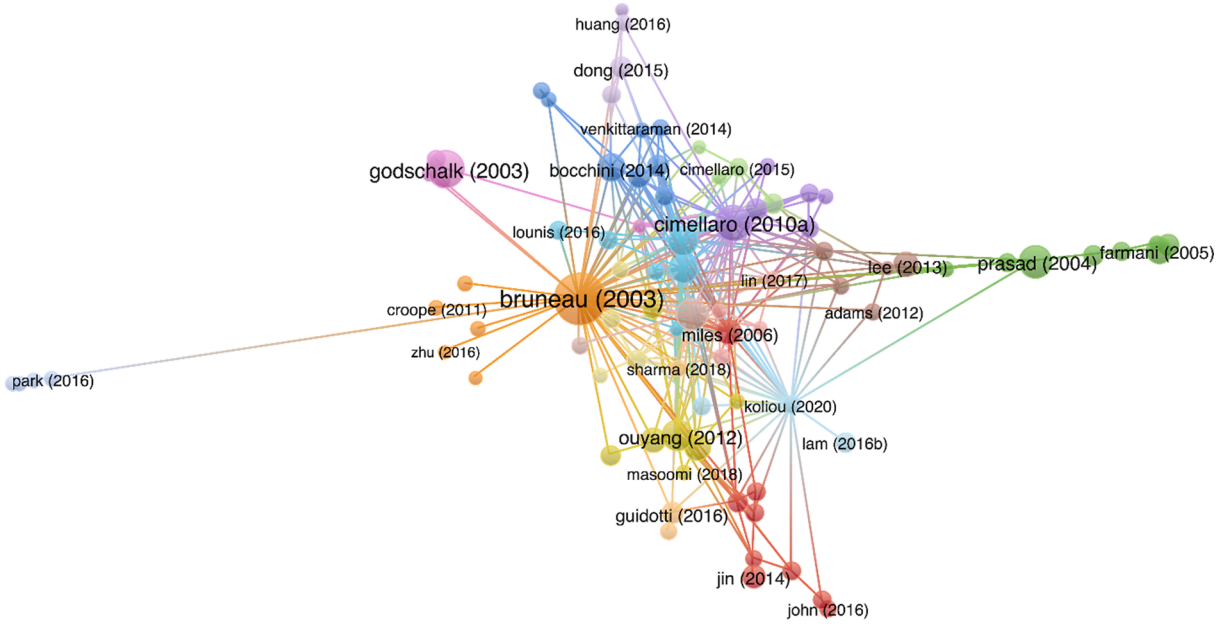

Fig. 18. Citation network among the papers belonging to the analyzed database (with at least 20 citations).

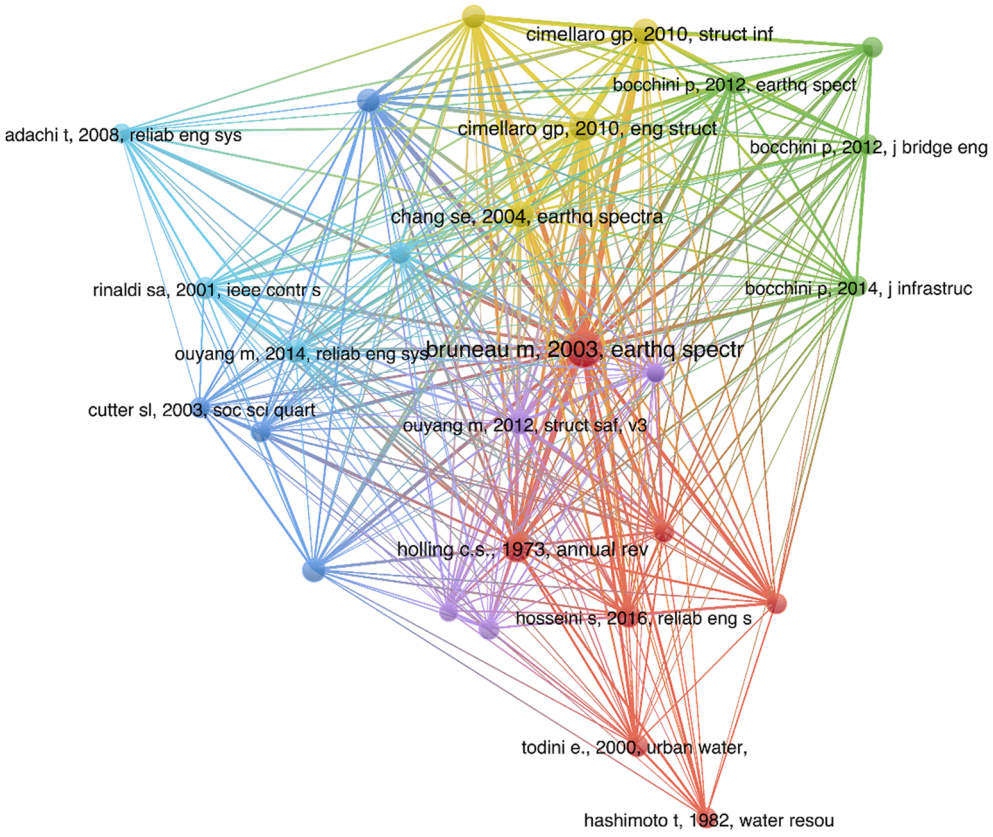

Fig. 19. Co-citation analysis of highly cited references (with a minimum of 20 citations).

research area tend to cite papers belonging to the same area. This means that the research fields are still isolated with little integration.

4. Discussion and future trend analysis

The number of contributions found in the literature and analyzed in this study confirms an increasing interest in the topic of resilience in the field of civil engineering. A comparison among the proposed 8 research sub-categories was made and the main results are summarized in Table 7. From the table it is evident that *Recovery time and Downtime*, *Critical infrastructures*, *Probabilistic approach*, and *Community and Urban resilience* are the fields where resilience gained the most attention. That is, both the number of papers published, and the number of citations increased over time. *Structural health monitoring*, *Fuzzy Logic approach*, *Health care facilities*, and *Emergency management and decision-making* are quite recent areas of interest, yet the number of citations is significant. In all research areas, except in the implementation of fuzzy logic methods, the USA plays a prominent role.

Section 3.5 highlighted the most relevant contributions in the 8 identified sub-categories. The analysis identified two primary research approaches, i.e., (i) frameworks and conceptual models and (ii) case study based. Conceptual models are mainly employed to provide new notions, definitions, and aspects of resilience and theoretically identify the drivers of resilience. On the other hand, case studies are used to show the applicability of conceptual models, and to confirm the relationships between drivers and resilience. Overall, the case study approach is the most adopted methodology by the selected papers. This result points out an interesting trend which is implementing concrete applications of resilience assessment methods and resilience-enhancing strategies. This was an aspect that was missing in many of the early studies on the topic. Case study-based approaches are also useful as they can provide real examples and quantitative data for other researchers to test and validate their theories. Nonetheless, the authors believe that developing new conceptual models is still essential to include missing elements that contribute to making the built environment and communities safer and more resilient.

4.1. Gaps and future trends

Based on the reviewed literature, the following gaps and future research trends relevant both to the academic and professional communities have been identified.

Table 7
Summary of the main features for each sub-research area.

Research sub-areas	Papers	Interval time	Journals	Citations	Authors	Prominent country
Recovery time and Downtime	159	1996–2020	43	4769	425	USA
Critical infrastructures	193	2004–2020	50	4592	544	USA
Structural health monitoring	23	2007–2020	25	146	84	USA
Probabilistic approach	105	2000–2020	44	1755	293	USA
Fuzzy Logic approach	6	2008–2018	6	163	19	IRAN
Health care facilities	19	2007–2020	15	1283	42	USA
Emergency management and Decision-making	46	1997–2020	25	560	175	USA
Community and Urban resilience	137	2003–2020	40	4236	376	USA

- While several studies have assessed resilience in civil engineering applications against specific hazards, far less attention has been directed toward resilience assessment in multi-hazard scenarios. It is crucial to define new effective strategies to recover from and respond to multiple disruptions.
- Another shortcoming noted from the bibliometric analysis is that the available models focused either on resilience enhancement or restoration separately. Nonetheless, resilience and restoration measures are interrelated and should be both considered within the same model.
- Since the measurement of resilience is a core research topic, one of the main limitations pointed out by the analysis is the lack of common standards and easy-to-implement resilience metrics, which hinders their integration into management plans. In addition, social, organizational, and economic resilience indicators need to be further addressed to provide a more comprehensive resilience assessment.
- A future research trend concerns the definition of new parameters as performance-level metrics, such as the availability of critical facilities, the number of people served, or the level of economic activities.
- Future research should combine qualitative judgments and quantitative metrics to define resilience by considering the interactions among different aspects. More effort is also needed in extending current tools to model different interdependencies to understand and minimize the cascading effects in large-scale civil engineering systems. Interdependency should be further supported by multidisciplinary approaches to evaluate interdependent resilience. For instance, it could be useful to combine data sources and mathematical models to develop multidisciplinary estimation techniques and early warning systems for predicting disruptions.
- Additional studies are needed to develop strategies for collecting complete and accurate information about communities and the built environment. Data acquisition regarding a system's performance and condition assessment is essential for resilience planning. Many available resilience assessment methods are challenging to implement due to information scarcity, especially during hazards. Having reliable datasets with real-time information during failure events can be considered significant to ensure the efficacy of the resilience methodologies.
- Finally, weather-related research should gain more attention in the future, as climate change disruptions are likely to increase in number and severity.

4.2. Implications for research, practice, and society

This paper is expected to be impactful to (i) junior researchers to draw attention toward open challenges in civil engineering resilience and safety, (ii) senior researchers to provide a multidisciplinary research agenda developing new collaborations, and (iii) practitioners to recognize potential applications leading to concrete actions toward safe and resilient civil engineering systems and communities. Further research on the highlighted trends and gaps could lead to new policies for the management of critical infrastructures and design codes that include quantitative resilience principles. Consequently, this would have a direct impact on society who will be safer while interacting with the built environment, suffer less frequent service interruptions, and see economic and human losses decreasing even in case of severe disruptive events that involve different hazards and cascading effects.

4.3. Limitations

Although some interesting results have been obtained through the bibliometric and visualization analyses of resilience-related publications, the following limitations should be acknowledged. The database extracted from WoS only retrieves articles and journals based on selected keywords and written in English. Considering only results in English is a common practice as the most read and top journals are published in English. The analysis conducted in this work shows that a small percentage of papers are published in other languages compared to the ones published in English (i.e., 0.3 % in German, 0.8 % in Spanish, and 0.3 % in French). Therefore, language bias might exist in the analyses as the publications counted in this paper do not include all publications about resilience and safety in the worldwide literature. There are certainly other scholarly papers published in other languages and pertaining to other online repositories that are making their contribution to this area, and this study is not trying to undermine the work done by these researchers by any means. Considering other studies published in other languages could also change the geographical distribution and relevance of countries. However, the involvement of developing countries remains a crucial point for developing new, impactful research.

Moreover, only journal articles were included. We did not specifically search for PhD theses, available for instance through ProQuest, nor for books. This is because the outcomes of relevant PhD theses are typically published in scientific journals. Overall, peer-reviewed articles are best suited for the keyword analysis, as books and book chapters often do not include keywords, and particularly citation network analysis (De Bellis, 2009). In some cases, authors prefer to cite a whole book instead of single chapters, which implies that the number of citations of single chapters are not representative of their relevance.

Another choice that was made in this review was to consider publications up to 2020 to have a window of time large enough for them to be cited. Considering newer studies could have potentially showed further research trends, but it would have not been possible to assess their relevance in the citation network analysis.

Furthermore, the publications selected in this study are only those containing "resilience" either in their title, abstracts, and keywords, abstracts while publications based on possible synonyms, such as resistance, reliability, and robustness, or antonyms, such as vulnerability, are neglected. The keywords of suitable article selection were based on the identification of the most relevant research categories related to the resilience assessment, since the resilience is the priority of this article. Regarding the eight items reported as prevailing research domains, it is not possible to exclude that research works concerning safety and resilience of civil engineering systems can be grouped in slightly different or additional categories.

Finally, as the topics of safety and resilience are becoming increasingly popular among the general public, the use of 'altmetrics' (e.g., social media) in future bibliometric reviews might bring additional insights and be useful to evaluate the social impact. All these limitations are worth considering in the future.

5. Conclusions

This paper presented a bibliometric literature review of publications retrieved from WoS regarding the topics of resilience and safety in civil engineering systems and communities. The selected studies were structured into eight research sub-categories and analyzed to identify the major contributing organizations, researchers, and journals, as well as gaps, trends, and key knowledge of resilience related to civil engineering applications. The following conclusions were drawn from this study:

1. The number of publications on resilience applied to civil engineering have increased by almost 10 times over the last 10 years, meaning that there is a great number of journals, institutions, and countries involved in this research field.
2. The geographical analyses revealed that research is distributed among several countries worldwide. However, a clear disparity has been observed among developed and developing countries. Industrialized countries such as the USA, China, the UK, and Italy dominate in terms of both article and citation count.
3. Overall, 539 research articles in 94 journals authored by 1,431 researchers were included. Among the proposed eight sub-categories,

research has mainly focused on *community and urban resilience*, *critical infrastructure*, *probabilistic approach*, and *recovery time and downtime*. A lower number of papers is related to the other sub-categories highlighting possible gaps in the literature. Moreover, in the sub-categories of *Fuzzy Logic approach*, *Structural Health Monitoring*, and *Emergency management and decision-making*, research is highly fragmented and carried out by several isolated research groups. This represents a strong limitation for the development of new studies in these research areas that could benefit from the collaboration of research groups from different locations and organizations.

4. From the bibliometric analysis it was evident that both the number of published papers and the number of citations increased over time, suggesting that new research is actively being worked on. All outputs were published in various journals. The ones with the largest number of publications are *Natural Hazards Review*, *Journal of Infrastructure Systems*, and *Journal of Structural Engineering*. This indicates that the choice of a journal is not a limiting factor for the researchers willing to publish on these topics. It is also worth noting that journals that were once focusing on specific aspects of civil engineering have been broadening their scope to include resilience and safety of civil engineering systems and communities.
5. From the analysis of the distribution of author keywords, it could be concluded that the research on community resilience, safety, sustainability, recovery, and infrastructure has attracted more attention so far. These are probably the most representative topics of the frontiers of resilience and safety. Furthermore, many author keywords emerged after the year 2013, showing a growing interest in resilience research probably due to the increasing number and impact of natural and man-made hazards.

In summary, the literature review pointed out a constant growing interest towards the topics of safety and resilience of civil engineering systems and communities both from researchers and scientific journals. Some categories are still under-researched and there is potential for future growth and meaningful impacts. However, there is a need for collaboration among research groups and institutions, as well as involvement of developing countries.

Despite the current work provides a comprehensive review that was missing in the field of civil engineering applications, this work presents some shortcomings as detailed in section 4.3. The main limitations are that the database was extracted from WoS and only English publications were considered. Other databases and types of publications, such as MSc and PhD theses, books, and book chapters, were not included.

The contribution of this paper to the existing literature is to propose a quantitative and accurate mapping of the knowledge of resilience in the civil engineering field through bibliometric techniques. Compared to other traditional literature reviews, the bibliometric method can be used as a tool to help researchers and public authorities learn more about current research gaps and critical aspects that could be addressed in future studies and policies. A periodic update of the bibliometric analysis should be conducted to further improve the resilience knowledge map provided in this study, as the field continues to rapidly evolve. Furthermore, collaboration among different research categories should be pursued to integrate knowledge coming from different expertise and domains.

CRediT authorship contribution statement

Melissa De Iuliis: Conceptualization, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Alessandro Cardoni:** Methodology, Visualization, Writing - original draft, Writing - review & editing. **Gian Paolo Cimellaro:** Methodology, Supervision, 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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