State-of-the-Art of Resilience Using Bibliometric Analysis

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Abstract. The interest in the concept of Resilience in the scientific community has been growing consistently over the past few years to study the functionality and behavior of systems against natural and man-made hazards. This is reflected by the number of journal articles that can be accessed in the Web of Science database. In this paper, a bibliometric and visualization method is applied to explore the status of resilience research in civil engineering applications by analyzing the journal papers published from 1996 to 2020. The bibliometric analysis aims at consolidating the state of the art by identifying influential journals, most cited articles, the geographic distribution of resilience publications including the research institutions by country, the author keywords distribution, and the co-authorship status. The concept of resilience 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 last seven years. In terms of the geographical region of the studies, most of them have been carried out in the USA, the United Kingdom, China, and Italy. Finally, based on the author keywords analysis, it is possible to observe that recovery strategies, critical infrastructures, vulnerability, and community resilience have attracted prominent attention during the past decade.

Keywords: Resilience, Review, Bibliometric analysis, Bibliometric visualization, Civil Engineering

1 Introduction

The increased frequency of natural and man-made disasters worldwide has attracted deep attention to the concept of resilience in recent years. Resilience firstly emerged in academic literature in the 1970s from an ecological study on the functionality responses of the interacting population [1]. Over the last years, the topic of resilience has spread into several fields such as ecology, management, economics, social, and engineering. Hence, resilience itself is a multidisciplinary and broad concept and its definition is highly variable depending on the subject area.

In engineering, the concept of resilience is relatively new compared to other fields [2]. Resilience engineering is related to the capacity of a system to absorb environmental shocks and maintain its functionality and it is defined as the ability to "withstand stress, survive, adapt and bounce back from a crisis or disaster and rapidly move on" [3]. Bruneau et al. [4] 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". The resilience of a system depends on its performance level, which ranges between 0% (e.g., no service is available) and 100% (e.g., high level of the service). When a disaster occurs at time t_0 causing damages to the system, its functionality drops until it is restored to its initial state over the recovery period (t_1 - t_0).

Numerous applications and frameworks for evaluating resilience in the civil engineering field are available in the literature. Particularly, these studies address the resilience evaluation of systems subjected to natural hazards. Most of the studies focus on the resilience quantification aimed at planning for mitigation, recovery strategies of a physical system (e.g., lifelines). For instance, Liu et al. [5] developed a framework to combine dynamic modeling with resilience analysis. The framework has been applied to two interconnected critical infrastructures for a numerical evaluation of the resilience in terms of design, operation, and control parameter values for given failure scenarios. A conceptual model in which the concept of resilience is correlated to the concept of recovery is presented by [6]. In their work, the relationships between a community's business, lifeline networks, and neighborhood are related.

Most authors have been developing frameworks to quantify resilience at the community level. A quantitative framework for assessing resilience at the community level is the PEOPLES framework [7]. PEOPLES framework, which improves the resilience research at the Multidisciplinary Center of Earthquake Engineering Research (MCEER), consists of seven dimensions: Population, Environment, Organized government services, Physical infrastructures, Lifestyle, Economic, and Social capital [8, 9]. Recently, probabilistic, and fuzzy approaches have been introduced to estimate the recovery time and the resilience of buildings and infrastructures after a seismic event [10-13]. Moreover, the concept of resilience is also studied in the structural health monitoring research area [14-17]. Zhang et al. [18] described a strategy for enhancing structural resilience through the implementation of structural health monitoring (SHM) technologies into civil infrastructures.

The great variety of applications and methodologies that can be found in the literature shows the necessity of systematic analysis to indicate how resilience research has evolved over time and become an emerging topic in the scientific community. Several literature reviews have been conducted on resilience, recently. For instance, Annarelli and Nonino [19] reviewed studies on organizational resilience emphasizing strategic and operational management areas. A bibliographic review of papers on resilience related to industrial ecology was performed by Meerow et al. [20]. In their work, the design of resilient industrial ecosystems is discussed. A year later, a critical review of the qualitative and quantitative resilience frameworks from a built-environment engineering perspective was provided by Cerè et al. [21]. Furthermore, Fraccascia et al.

[22] reviewed the state of the art on the resilience of complex systems in different research areas through bibliometric tools.

The main purpose of this paper is to identify trends in resilience research in the context of civil engineering through a bibliometric and visualization analysis based on quantitative analysis of journal papers published on Web of Science (WoS). The remainder of this paper is structured as it 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 analysis among the paper reviewed. Finally, Section 4 summarizes the findings, identifies the gaps in literature and directions for future research.

2 Literature review methodology

The study is based on bibliometric research conducted in March 2021 to investigate the impact and importance of resilience in the field of civil engineering. The expected results of conducting the bibliometric analysis proposed in this work can be replicated by implementing the steps presented in **Figure 1**.

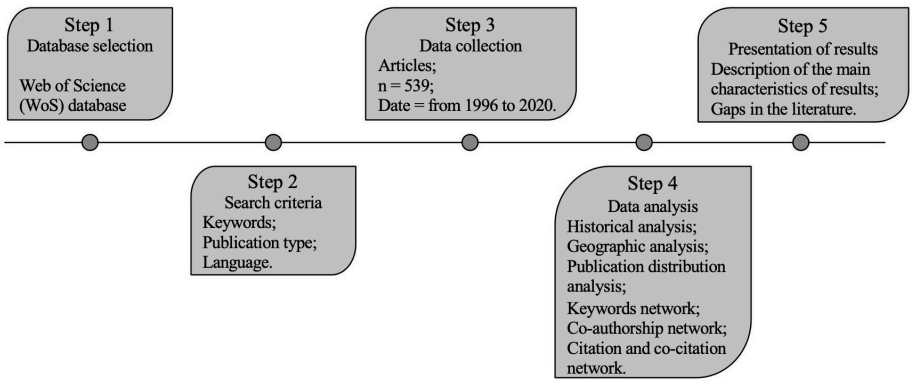

Figure 1. Steps of the bibliometric analysis for mapping the state of the art

Five steps are followed: (1) choosing the databases to cover relevant literature in the field of study; (2) defining inclusion and exclusion criteria and selecting the studies based on the criteria; (3); collecting and extracting the bibliometric data for the subsequent analyses, (4) performing quantitative data analysis through the construction of visualization bibliometric networks, and (5) presentation and discussion of the results. The data was retrieved from 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 [23]. Once the scientific platform to be used has been established, the search criteria of the publications need to be settled. 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 iden-

tify resilience in civil engineering applications, keyword searches within the titles, keywords, and abstracts of the different research outputs have been applied. No limit of the year was applied to the search criterion. However, the oldest article, according to the keywords, was from 1996. Thus, research articles were extracted from a period of 1996-2020. Only journal articles that have been cited and published in English were selected for further analysis. 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. First, postprocessing of the literature data was necessary to exclude papers that were insufficiently relevant (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 really 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.

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 (if any). The exported records were used for different analyses: (i) historical analysis was conducted for understanding 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 or universities taking into account the authors' affiliations as the criterion to locate the place of their origin; (iii) publication distribution analysis was investigated to highlight the most popular journal, the most cited records along with the corresponding authors in the realm of resilience research, and finally (iii) keywords analysis was performed for the author's keywords to understand the nature, linkages, 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 to create easily readable and comprehensive keywords in figures [24-26].

3 Results and discussion

3.1 Historical analysis

Results showed an increasing number of studies on the concept of resilience applied to civil engineering applications. The analyzed publications started in 1996 to study resilience in civil engineering applications. **Figure 2** shows the annual number of the most productive 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 which used the concept of resilience in civil engineering was pub-

lished by Fox and Suidan [27]. Most of the research on resilience within civil engineering was published during 2013-2018, i.e., 60%. This means a growing knowledge accumulation and research interest of the scientific community in resilience discourse.

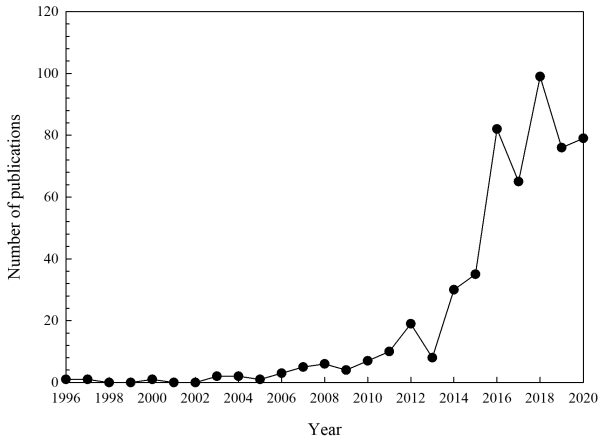

Figure 2. Most productive papers on resilience in civil engineering applications (1996-2020)

3.2 Number of publications by countries and institutes

The 539 papers analyzed were published in 52 different countries worldwide (**Figure 3**). A mapping approach is used to represent the country's performance in civil engineering resilience where the authors' affiliation in the records was used as the criterion to locate the place of their origin. The most productive country in this regard is the USA with 307 cited publications (i.e.,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 Western Africa. Therefore, the mapping approach indicates the dominance of western researchers. This can be justified by considering that researchers in these countries have resilience-related publications in non-English languages, which this study does not capture.

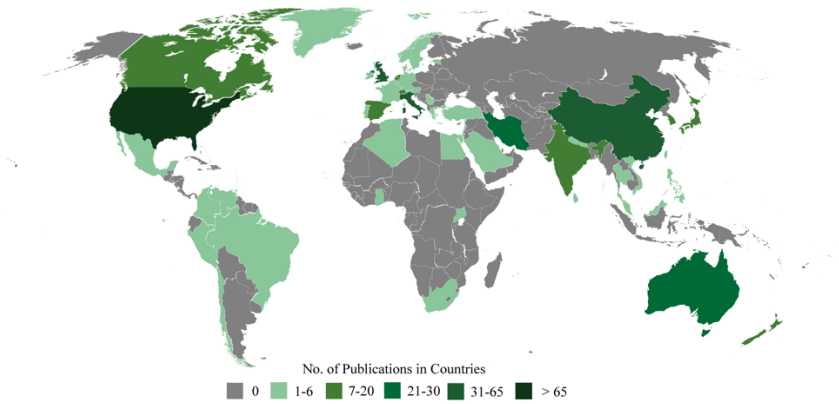

Figure 3. Distribution of publications by country

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 1** lists the top 5 journals in which the analyzed publications appear. 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 attracted was investigated. The top 5 journal articles with the most citations and their authors, publication year, and the title of the journals are presented in **Table 2**. The most prominent contributor in the area is Professor M. Bruneau who is the author in four of the top 5 cited journal papers. Similarly, Professors G.P. Cimellaro (Italy) and A. Reinhorn (USA) have also achieved excellent recognition with their names appearing as authors and co-authors in the top 5 paper list.

Table 1. Top 5 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

Table 2. Top 5 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

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 [28]. 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 two keywords.

Figure 4 shows the major keywords used in resilience studies in the civil engineering area. The figure represents a minimum of 5 times the co-occurrence of a keyword in extracted records. Only 61 out of a total of 1,453 authors' keywords met the threshold covering the studied interval, which equals to 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".

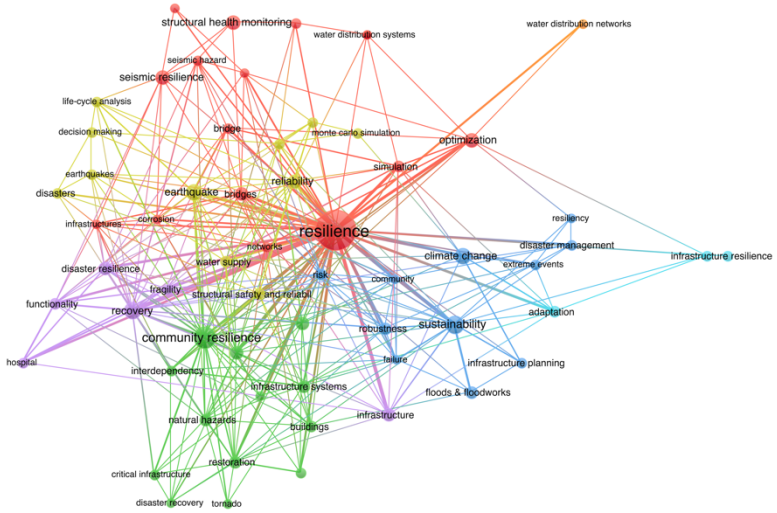

Figure 4. Map of Civil Engineering resilience of author's keywords (5 co-occurrence criteria with 61 keywords)

Table 3 lists the 5 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 of 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 link strengths of such node over all the other nodes and it can be used to indicate the relationships among two nodes [29]. For example, the node "resilience" presents thicker lines with "community resilience" (50), "recovery" (58), and "sustainability" (36). The relationship between "resilience" and "recovery" (link strength of 58) implies the close integration of recovery programs within the resilience estimation.

Table 3. Top 5 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

4 Conclusions

This paper proposes a bibliometric literature review of the 539 publications retrieved from WoS regarding resilience in civil engineering applications. The outcomes of the

study are investigated with a temporal analysis aiming at identifying intellectual communities, leading researchers, key knowledge of resilience in civil engineering applications. The following conclusions were drawn from this study:

1. Publications in resilience applied to civil engineering have significantly increased during the last 7 years, meaning that there is a huge number of journals, institutions, and countries involved in resilience research.
2. The research output is distributed worldwide. However, a clear disparity has been observed among developed and developing countries of the world. Industrialized countries such as the USA, China, UK, and Italy predominated in terms of article count and citation scores.
3. By analyzing the distribution of author keywords, it could be concluded that the research on community resilience, sustainability, recovery, and infrastructure attracted more attention, which are probably the most representative topics to the frontiers of resilience. Furthermore, many author keywords emerged after the year 2013, showing a growing interest in resilience research probably due to numerous natural and man-made hazards.

Compared to the more traditional literature reviews, the bibliometric method can be generalized and used as a tool to map discipline knowledge. A periodically bibliometric analysis should be conducted to further improve the resilience knowledge map provided in this study, as the field continues to evolve

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