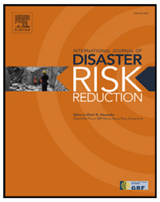
International Journal of Disaster Risk Reduction 97 (2023) 104063

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr



Review article

An exploratory bibliometric analysis of risk, resilience, and sustainability management of transport infrastructure systems

Monica Santamaria-Ariza [a,*], Hélder S. Sousa [a], José C. Matos [a], Michael H. Faber [b]

[a] *ISISE, ARISE, Dept. of Civil Engineering, University of Minho, Campus de Azurém, Av. da Universidade, Guimarães, 4800-058, Braga, Portugal*

[b] *Department of the Built Environment, Aalborg University, Thomas Manns Vej 23, Aalborg, 9220, Denmark*

ARTICLE INFO

Keywords:
Risk management
Transport infrastructure systems
Resilience
Sustainability
Robustness
Bridge networks
Flood risk
Climate change
Decision-making
Bibliometric analysis
Science mapping

ABSTRACT

Transport infrastructure systems (TIS) are key enablers of economic development and welfare. However, such infrastructures are exposed to natural and anthropogenic hazards that have caused structural failures, traffic disruptions, injuries and fatalities, and damages to the environment. These past events have underscored the need for more resilient transportation systems. However, reducing risks and achieving more resilient infrastructure systems may result in greater resource consumption and environmental impacts, demanding the consideration of sustainability requirements in the management of TIS. Therefore, this paper conducts an exploratory study to map the current knowledge in the domain of risk, resilience, and sustainability management of TIS. As a first step, the system identification of TIS in the context of their management is conducted for the purpose of providing the basis for searching for relevant information. This step sets the baseline for conducting a bibliometric analysis of 16,395 scientific works extracted from the Scopus database between 1990 and 2022. Two quantitative bibliometric techniques are used, namely term co-occurrence and bibliographic coupling. The former technique allows to distinguish the different disciplinary contributions and to identify research gaps. The latter technique facilitates the identification of the main contributors (authors and countries) and the relatedness of research communities. The bibliometric analysis performed provides the basis for future research and development to improve the management of TIS and highlights the potential for transferring knowledge from other research domains.

1. Introduction

Transport infrastructures have a wide range of beneficial impacts on economic welfare and equity, as well as on reducing prices and boosting levels of investment, trade, and productivity [1]. It is estimated that low and middle-income countries will need to invest in new transport infrastructure between 0.5% and 3.3% of their gross domestic product (GDP) annually (US$157 billion to US$1 trillion) by 2030, plus an additional 1.1% to 2.1% of GDP annually for maintenance of existing and new transport infrastructure [2]. Maintenance costs are even more relevant than new investment costs for countries with large transportation networks, such as European countries, with the aggravating fact that failing to perform routine maintenance will result in poor service and will cost 50% more overall because of additional rehabilitation needs [2].

Transportation networks have a wide geographical extension, exposing each infrastructure asset to stressors such as floods, earthquakes, tsunamis, landslides, hurricanes, wildfires, or extreme temperatures. This exposure, in combination with the inherent

---

[*] Corresponding author.
E-mail address: id8021@alunos.uminho.pt (M. Santamaria-Ariza).

https://doi.org/10.1016/j.ijdrr.2023.104063
Received 24 May 2023; Received in revised form 24 September 2023; Accepted 12 October 2023

vulnerability of transportation assets, have led in the past to huge economic losses. According to Koks et al. [3], Global Expected Annual Damages (EAD) due to direct damage from natural hazards to road and railway assets range from US$3.1 to US$22 billion, of which approximately 73% is caused by surface and river flooding. The estimated EAD can reach 0.5% to 1% of GDP annually in some countries, which corresponds almost to their national transport infrastructure budget. Natural hazards not only damage physical assets but also disrupt infrastructure services, with significant impacts on businesses and people. The World Bank estimated in $107 billion a year the impacts of transport infrastructure disruption on the capacity utilization rates of businesses from low- and middle-income countries [4]. The impacts included business losses and delayed supplies and deliveries. Other indirect impacts in the long-term were not covered, such as loss of international competitiveness, which highlights the substantial cost of unreliable infrastructure networks.

Challenges in the management of transport infrastructure systems are likely to be exacerbated due to the increase in frequency and magnitude of extreme weather events attributed to the warming of the climate system due to anthropogenic emissions of greenhouse gases [5]. In fact, the World Meteorological Organization (WMO) has shed light on the escalating impact of weather-related disasters over the past five decades (1970–2019). Drawing from EM-DAT records, the report highlights an increase of seven times in economic losses from the 1970s to the 2010s. Specifically, the losses documented during 2010–2019 averaged at US$ 383 million per day over the decade, a sevenfold increase compared to the amount reported from 1970–1979 (US$ 49 million) [6]. The large evidence of direct and indirect impacts that transport infrastructure networks face due to natural hazards at the global level has attracted the attention of the research community and the public authorities at local and global scales to allocate resources in terms of knowledge, time, and money, for improved risk and resilience management of existing and new transport infrastructure systems. The concept of risk as a measure to deal with and communicate the uncertainties associated with the outcomes of decisions has been used for decision support in engineered systems over many years [7,8], and has been incorporated into standards and regulations (e.g., [9,10]). However, conducting a risk assessment for transportation networks can be particularly challenging. Transport infrastructure systems have become increasingly complex due to the large number of interconnected physical assets and the different services that the system provides. In the case of an extreme natural event, physical damage may occur to one asset or to several assets simultaneously, in which each particular case would induce different direct and indirect impacts. Moreover, they are interconnected with other complex systems such as communication, power, and building infrastructure systems. Given the extent of the system and budget constraints, it is evident that strengthening all transport infrastructure assets to a very high safety level is not a cost-effective measure [3]. Thus, the system modeling should enable the identification of the more relevant scenarios contributing the most to the risks to prioritize the mitigation measures for the more critical assets, which could guarantee a minimum transportation functionality despite disrupted parts of the network. Several approaches have been developed to assess risks for transport infrastructure networks (e.g., [11–13]). Nevertheless, there is usually a lack of completeness in integrating all modeling aspects consistently in a spatial–temporal manner, i.e., hazard modeling, fragility assessment of system constituents, transportation network analysis, assessment of consequences to health, environment, and economy, and particularly in integrating the quantitative risk modeling results into decision-making processes for the definition of mitigation measures. Significant challenges for implementing these modeling frameworks arise from gathering all relevant data, computational costs associated with complex models (e.g., finite element structural models, agent-based traffic models), and major uncertainties involved in modeling and predicting the performance of TIS. In addition, consequences typically considered are too narrowly defined to the transportation sector and do not consider inequality of impacts across the population [14].

On the other hand, compared to risk assessment, resilience management of engineered systems is a more recent research field despite the concept being introduced some decades ago in the field of ecology [15]. Resilience is a more holistic system-level approach and can be understood as the ability of interlinked social-ecological-technical systems to sustain and recover from disturbances over time without support from the exterior [16]. Several methodologies for resilience assessment of TIS have been proposed in the literature, ranging from qualitative and semi-qualitative to fully quantitative methods, using a wide variety of resilience indicators and metrics which are typically selected depending on the perspective, objective and scale of the analysis (see, e.g., [17–21] for an overview). Generally, the resilience of TIS has been quantified using the system recovery curve, also known as the resilience curve, through different mathematical formulations. The first and most influential formulation introduced by Bruneau et al. [22] for seismic resilience of communities has been broadly used and adapted for resilience analysis of TIS. Following this approach, resilience is quantified as the integral over time of the system recovery curve after a disturbance event. Therefore, resilience is characterized by the drop in the service provision after a disruptive event which relates to the robustness of the system, and the particular shape of the recovery curve is related to systems characteristics such as preparedness and adaptive capacity, which determine the time to fully recover the service and the rapidity of recovery. Resilience loss is then assessed by the difference between the service provided if no disturbance event occurs and the service provided if a disturbance event occurs, often referred to as the resilience triangle. More recent approaches have proposed extensions to this formulation, e.g., systems recovering to higher/lower service provision than before the disruptive event (e.g., [23]), as well as more advanced mathematical formulations for resilience analysis and metrics (e.g., [24]). In addition, great attention has been given to the representation of the impacts of disturbance events on the service provision (e.g., [25,26]), and the characteristics of the recovery phase to define optimal strategies – in terms of resource coordination and sequence of repairs – following the event (e.g. [27–29]). However, as highlighted in [16,30], systems resilience models and assessments should also explicitly address the generation of system capacity, which is critical for successful and rapid reorganization, adaptation and restoration of service after disturbance events. This capacity develops over time through the service provided by the system. When a disturbance event occurs, some of this capacity is lost as it is needed to restore system functionality. At any given time, if any of the available system capacities, economic, social, and/or environmental, are no longer sufficient to restore system functionality, this can be defined as a resilience failure event. Therefore, systems resilience should

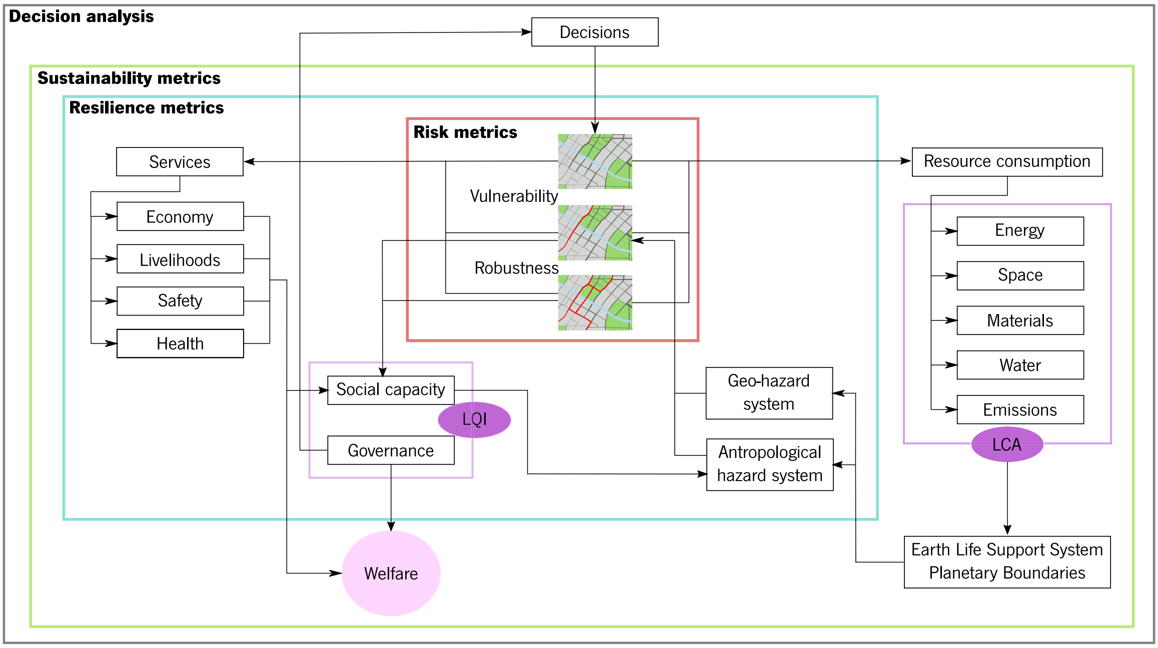


Fig. 1. Connections between risk, resilience, and sustainability with assessment metrics and techniques.
Source: Adapted from Faber [31].

be approached probabilistically and within a life cycle framework as the one proposed by Faber et al. [16], in which scenarios of benefit generation and losses are modeled and analyzed. In addition, the resilience of infrastructure systems is generally addressed at a small geographic scale, i.e., at the community or regional level, and at a short-term time scale. However, when the boundaries of resilience assessment are extended to the global scale and the long-term time scale, the capacities considered in the modeling of resilience failure must include the Earth system capacities, implying an evident coupling with sustainability. Therefore, by analogy with resilience failure, sustainability failure can be introduced as the event in which one or more of the Earth system's capacities to sustain human activities is exceeded. These formulations imply that sustainability and resilience failures are equivalent at the global Earth scale, and at the local level, resilience is conditional on sustainability [16]. Fig. 1 illustrates these interrelations between risk, resilience, and sustainability in the context of decision support for resilient and sustainable societal developments [31]. It can be observed that a resilient infrastructure system provides benefits to society in terms of economy, livelihoods, safety, and health, but, at the same time, imposes resource consumption and emissions to the environment. Thus, these trade-offs must be well understood when deciding how to optimize the resilience of infrastructure systems while guaranteeing long-term sustainability. These interrelations and conflicts between resilient and sustainable infrastructure systems have been recognized over the past years and have received increased attention (see e.g. [14,32–34]).

Based on the foregoing outlined challenges, the present study aims to establish a better understanding of the current state-of-the-art in the domain of risk, resilience, and sustainability management of TIS, with a focus on flood hazards. This focus is chosen given the challenges posed by climate change effects and the fact that floods generate the largest amount of economic damage for the transport sector among weather-related disasters. To the best of the authors' knowledge, previous state-of-the-art articles do not review risk, resilience, and sustainability concepts jointly, nor do they analyze the context of the TIS in terms of decision makers, stakeholders and their preferences, decision alternatives, and state of knowledge for managing the system. To that aim, this work outlines a generic and comprehensive system identification of TIS following the systems modeling framework of the JCSS [35]. This step sets the baseline for conducting a bibliometric analysis, which is a quantitative method for exploring and analyzing large volumes of scientific data, along with science mapping, that can facilitate deciphering and mapping a particular knowledge domain [36,37]. Two quantitative bibliometric techniques, namely term co-occurrence and bibliographic coupling networks, were employed to analyze the scientific literature from the emergence of the field in 1990 until 2022. The Scopus database was selected due to its extensive publication coverage within the research domain under study. The term co-occurrence technique is useful for identifying patterns and trends in the research field, studying how different sub-fields are interconnected, finding potential opportunities for bridging the gaps between sub-fields, and searching for approaches in other research domains which could be imported. The bibliographic coupling technique identifies the main contributors to the research domain (authors) and their geographic distribution (countries).

Section 2 describes the methodology proposed for performing the bibliometric analysis. Section 3 presents the results and interpretation of the bibliometric analysis. Section 4 discusses the main research findings and the potential for filling out the identified gaps, which provide the basis for future developments. Finally, Section 5 provides conclusions and an outlook for future research to improve the risk, resilience, and sustainability management of TIS.

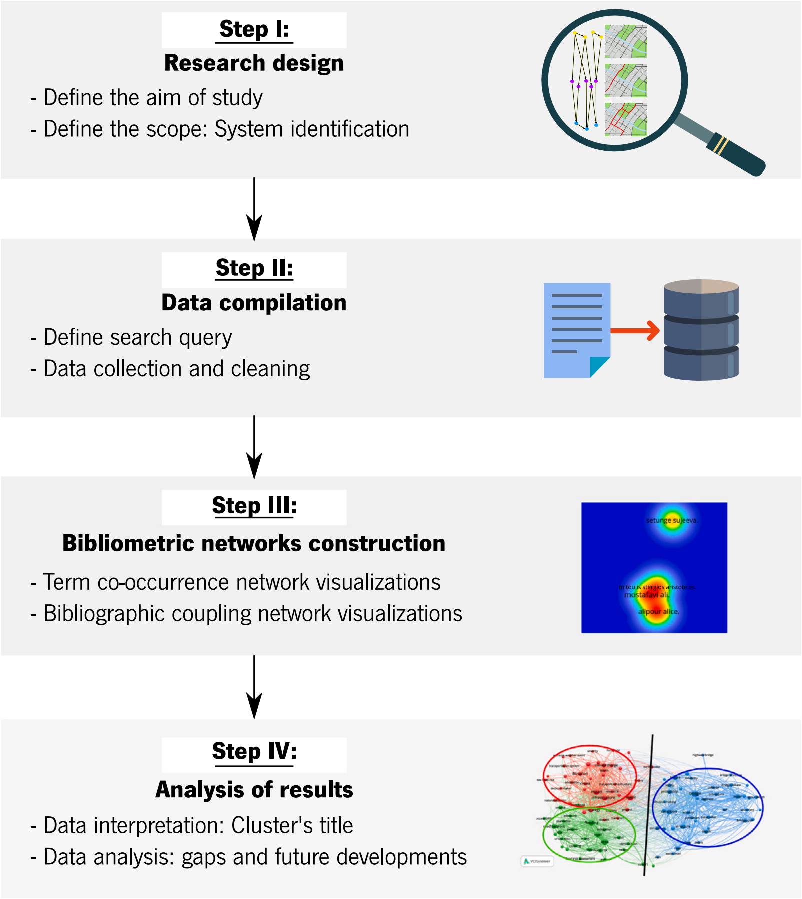


Fig. 2. Workflow of the methodology for conducting the bibliometric analysis.

2. Methodology for the bibliometric analysis

The methodology followed for conducting the bibliometric analysis consisted of four main steps, as depicted in Fig. 2. The first step is termed the research design and comprises the definition of the aim of the analysis and the system identification for the purpose of setting the scope of the analysis. The second step involves the definition of the search queries based on the research design and the data collection and cleaning. In the third step, the techniques for the bibliometric analysis are selected, and the networks to visualize the results are constructed. Finally, the fourth step consists of data interpretation and analysis. Further details concerning each of the steps are given in the following.

2.1. *Step I: Research design*

The first step in any bibliometric analysis is planning the research. This includes determining the main objective of the study and defining the research questions. In addition, the scope of the study should be defined, which requires an understanding of the system under study. Usually, the scope of a bibliometric study is defined by search terms selected by experts. In this work, the system identification is proposed as the basis for defining the scope of the bibliometric study. This approach allows for a thorough understanding of the system under study, i.e., transport infrastructure systems, and provides the logic for searching the relevant information in the context of their management.

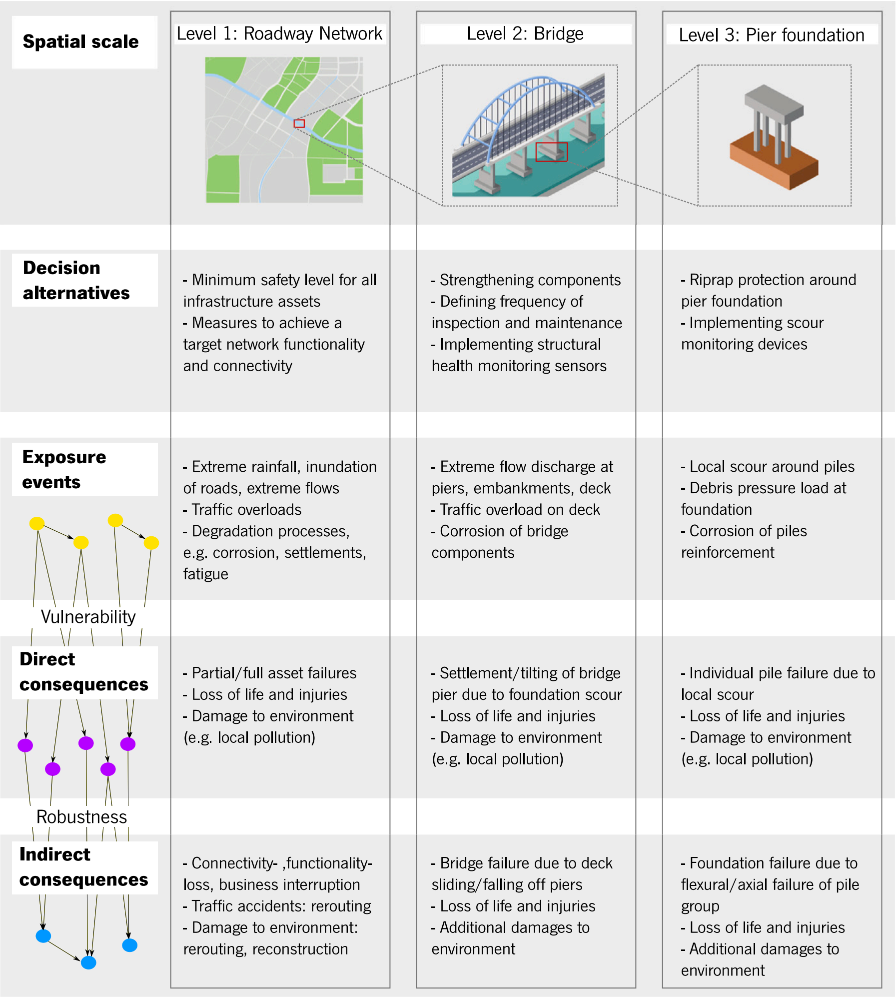
2.1.1. *Aim of the bibliometric study*

The main goal of the bibliometric analysis in this study is to understand the current state of the art in the domain of risk, resilience, and sustainability of TIS affected by flood events in the context of managing and governing the system. To gain this understanding, the following research questions are formulated: (i) How has the research domain grown over the past few decades? (ii) What are the main disciplines contributing to this research area? (iii) Are there potential gaps (research needs) in the existing knowledge? (iv) Are there approaches in other research areas outside the specific context of floods that could be imported (knowledge transfer)? (v) How is the distribution of the research among expert communities and countries? It should be noted that bibliometric studies allow us to identify where the major research streams have been concentrated, and the observations that can be derived are consistent with this big picture, where outliers are not the focus.

2.1.2. Scope of the study: System identification

The system identification comprises a description of the system's physical characteristics, temporal and spatial boundaries, main functionalities, exposure events and potential associated consequences, decision makers, stakeholders and their preferences, and plausible decision alternatives for managing the system and their effects on system performance [35,38]. When analyzing TIS, there may be different choices of scale to represent the system. For instance, Fig. 3 depicts an illustration of different choices of the spatial scale for the system representation. At the first scale (Level 1), the system can be a roadway network, and the constituents are different infrastructure assets, namely bridges, embankments, tunnels, retaining walls, and pavements, among others, which interact with each other to provide their intended service, i.e., transportation for people and goods. At the second scale (Level 2), each infrastructure asset is a system that provides connectivity at one specific location in the network. The asset system is comprised of several interacting constituents, namely structural components (e.g., bridge components might be deck, piers, abutments, foundation, bearing devices), non-structural components (e.g., pavements, guardrails), as well as monitoring and control systems installed at the assets (e.g., structural health monitoring devices). Each component can be considered a subsystem, constituting the third scale (Level 3). Each subsystem consists of interacting constituents, e.g., the foundation subsystem can comprise individual piles and a pile cap. Therefore, the system representation for decision analysis must be chosen in a way that facilitates the quantification of the expected values of benefits corresponding to the decision alternatives under consideration. The decision alternatives can thus be considered as the drivers for identifying the appropriate scale for the system model [39]. Fig. 3 presents some examples of relevant decision alternatives depending on the spatial scale of the system. At Level 1, decisions may relate to, e.g., the minimum safety level required for individual bridges, guaranteeing certain network functionality and connectivity for evacuation routes, among others. At level 2, decisions may pertain to strengthening bridge components to achieve safety, defining the optimal frequency of inspection and maintenance, installing sensors to monitor the condition of components, and others. Finally, at Level 3, decisions are more specific to the component under study, e.g., for a pier foundation subjected to scour, plausible alternatives may be to protect the foundation using riprap, installing sensors for monitoring the scour depth, among others. Moreover, the temporal scale of the system representation should also be consistent with the planning horizon of the decision problem. For instance, decisions made at the strategic level typically have a long-term perspective, which requires modeling the system in the long run. Conversely, at the operational level, decisions generally concern the management of the system from a more short-term perspective, focusing on day-to-day inspection, monitoring, maintenance, and repair activities. Lastly, at the tactical management level, which generally concerns loss reduction, it would be relevant to have a temporal system representation that supports decisions to react during the hazard event, e.g., evacuation and emergency response plans.

Depending on the spatial and temporal scale of the system representation, the definition of the exposure of the system and the consequences would also vary. In general, TIS exposure may comprise any threat that potentially results in the failure of physical infrastructure or disruptions to their functionality. Characterizing these exposures requires a joint probabilistic model considering all relevant impacts relative to time and space. Since the emphasis of the present study is given to flood hazards, the system representation of Fig. 3 provides examples of exposure events related to traffic overloading, floods, and degradation, at each spatial scale of the system. At Level 1, the exposure characterization requires consideration of the spatial correlation between hazard intensities at each asset location in the network. In addition, individual assets may be threatened by different degradation processes that should be characterized, such as corrosion, fatigue, erosion, among others. At Level 2, the characterization of exposure is asset specific and should take into account the correlation of hazard intensities acting on each component and the degradation processes applicable to each bridge component. Similarly, the Level 3 exposure characterization is component-specific and may address in more detail the modeling of each phenomenon, e.g., using a computational fluid dynamics model to determine the hydrodynamic forces acting on each pile of a pier foundation to derive the local scour depth. Given the exposure events defined, the systems modeling approach recommended by the Joint Committee for Structural Safety [35] can be utilized to divide the scenarios of events leading to consequences into direct and indirect consequences to health, environment, and economy. Direct consequences consist of all losses caused directly by the hazard event and/or caused by the failure (or damage) of the constituents of the system. Indirect consequences comprise all losses caused in the process of internal redistribution after the hazard event or any consequence associated with the loss of the system's functionalities. When the system under analysis is the pier foundation from Fig. 3 (Level 3), a direct consequence of local scour would be pile failure due to the loss of lateral support, which could trigger loss of lives and injuries, and damage to the environment, e.g., pollution due to collapsed pile debris, while indirect consequences would be foundation failure due to lack of robustness and redundancy in the pile group capacity, together with additional losses imposed to health and environment. On the other hand, if the bridge is the system under analysis (Level 2), a direct consequence of an extreme flow discharge acting on the structure would be physical damage to any of the elements, loss of lives and injuries, and damage to the environment caused by the failure of any bridge component (e.g., foundation failure), while indirect consequences would be additional losses due to complete bridge failure. Finally, when the roadway network is the system under analysis (Level 1), the direct consequences of a flooding event would be any loss associated with the failure of individual bridges, while the indirect consequences would be wider and include monetary, environmental, and social consequences due to loss of network connectivity, loss of functionality and business interruption. The distinction between direct and indirect consequences facilitates the modeling of two system characteristics, namely vulnerability and robustness. As depicted in Fig. 3, the relation between exposure or hazard events and the direct consequences is termed vulnerability, and the link between the direct consequences and the indirect consequences



Spatial scale	Level 1: Roadway Network	Level 2: Bridge	Level 3: Pier foundation
Decision alternatives	- Minimum safety level for all infrastructure assets - Measures to achieve a target network functionality and connectivity	- Strengthening components - Defining frequency of inspection and maintenance - Implementing structural health monitoring sensors	- Riprap protection around pier foundation - Implementing scour monitoring devices
Exposure events	- Extreme rainfall, inundation of roads, extreme flows - Traffic overloads - Degradation processes, e.g. corrosion, settlements, fatigue	- Extreme flow discharge at piers, embankments, deck - Traffic overload on deck - Corrosion of bridge components	- Local scour around piles - Debris pressure load at foundation - Corrosion of piles reinforcement
Direct consequences	- Partial/full asset failures - Loss of life and injuries - Damage to environment (e.g. local pollution)	- Settlement/tilting of bridge pier due to foundation scour - Loss of life and injuries - Damage to environment (e.g. local pollution)	- Individual pile failure due to local scour - Loss of life and injuries - Damage to environment (e.g. local pollution)
Indirect consequences	- Connectivity- ,functionality-loss, business interruption - Traffic accidents: rerouting - Damage to environment: rerouting, reconstruction	- Bridge failure due to deck sliding/falling off piers - Loss of life and injuries - Additional damages to environment	- Foundation failure due to flexural/axial failure of pile group - Loss of life and injuries - Additional damages to environment

Fig. 3. System representation of TIS at different spatial scales.

is related to the concept of robustness. Essentially, the vulnerability of a system indicates the degree to which exposures generate direct consequences, while robustness characterizes the degree to which a system is able to contain or limit indirect consequences associated with a hazard event [40]. If the indirect consequences of a scenario outweigh the direct consequences, then the system lacks robustness with respect to this scenario. The other two system characteristics which are crucial for the management of TIS are resilience and sustainability. When modeling these system characteristics, not only the losses but the capacity of the system (economic, social, and/or environmental) to sustain, adapt, and recover from adverse effects should be considered. The economic capacity is based on the benefits that TIS generates through the provision of services, i.e., mobility for people and goods through taxes or toll roads. In some cases, infrastructure assets such as bridges or viaducts may also provide a cultural and historical value that is transformed into an economical service related to tourism (refer to Turksezer et al. [41]). Moreover, transport infrastructure assets can assume other types of functionalities for economic benefits, such as carrying power and telecommunication lines, oil and gas pipelines, or water pipelines. The social capacity in the context of TIS encompasses the ability of the governance system (comprised of infrastructure owners/operators, local and national public authorities) to deal with hazard events in terms of reorganization, restructuring, and adaptive learning in and after an event [16]. Lastly, the environmental capacity may relate to, e.g., emissions of CO_2 or the availability of natural resources for the development and maintenance of TIS, such as raw materials, space, and water.

Another relevant issue when defining the appropriate system representation is that it should be consistent with available knowledge about the system, and it should facilitate that risks may be updated according to knowledge that may be available in the future. The knowledge about the system to be managed is a crucial factor for optimal decision-making. Basically, the “best” of our knowledge is used to formulate models of the real world, and these models are the basis for our decision-making. Generally, the best available knowledge about a system comprises phenomenological physical understanding and experience paired with information (commonly referred to as evidence) that has been gathered and processed over time [42]. Lack of knowledge or uncertainty, describes the typical condition in real-world decision-making. In the context of the management of TIS, there are large uncertainties involved since transport infrastructures such as bridges are designed for a long service life of 50 to 75 years, which sometimes is even extended beyond this period. Then, our knowledge about the future state of the system is incomplete in regard to, e.g., the structural condition, changing climate, socioeconomic developments, among others. Thus, it is crucial to appropriately represent and treat uncertainties consistently to allow for more rational decision-making. In addition, when modeling complex systems such as TIS, possible dependencies exist among random input variables and random events, which need to be properly accounted for when assessing risks. There are different types of dependencies that can be grouped into statistical dependence and functional dependence [35]. Statistical dependence exists when events or variables exhibit some correlation, e.g., spatial correlation or correlated information sources. For instance, if near bridges in a road network have been constructed around the same time, using concrete produced from a small concrete production plant near the construction site, as well as employing the same design standards, their structural capacity will have a statistical dependence which may be appropriately represented through correlation of the random variables used to model the capacities in the probabilistic modeling [35]. On the other hand, functional dependence exists when various constituent failures are dependent. This type of dependence may have different representations, such as common cause failures (CCF), cascading failures, or relief [43]. It is widely acknowledged that neglecting dependencies can lead to underestimating the risk associated with the functioning of complex infrastructure systems (see e.g. [44]). Therefore, to aggregate the risks for a portfolio of infrastructure systems correctly, it is necessary to account for all prevailing dependencies.

Lastly, the system identification should include the recognition of decision makers and stakeholders involved, along with understanding their organizational structure. Typically, decision makers and stakeholders of TIS are organized hierarchically at local, national, and global levels, and are connected by governance structures. At the local level (municipality or community level), decision makers are private or public asset infrastructure owners, managers, or operators in charge of operational decisions of maintenance and repair activities at the asset level in the short- to mid-term, as well as strategical decisions for the management of individual local projects at long-term. At the regional/state level, network managers are in charge of the entire transportation network or all infrastructure assets in a large geographical area. At the national to the global level, the governance system manages all previous levels based on its objectives, which include but are not limited to maximizing benefits, minimizing economic losses, satisfying population demands, maximizing the welfare of people, and minimizing environmental damage at local and global levels. The extent by which an objective is accomplished can be measured by attributes or criteria, e.g., safety, monetary cost, minimum level of service, life quality, emissions to the environment, among others. Through the use of utility theory, several attributes can be transformed (weighted) into a single metric — utility, which consistently reflects the preferences of decision makers and allows assessing the optimality of different decision alternatives [45,46]. Finally, the governance system ensures the achievement of its objectives by means of regulations. In other words, decision alternatives considered for the purpose of managing the system must comply with the boundary conditions and/or constraints imposed through codes, standards, and trans/national or global scale regulations. For instance, in the National Annexes of the European civil engineering technical standards (Eurocodes), individual nations specify their National Determined Parameters (NDPs) and decide on the level of safety for the design of new structures and assessment of existing ones.

2.2. Step II: Data compilation

2.2.1. Search query

The identification of search terms is one of the most critical steps in bibliometric analysis since it significantly influences the outcomes of the study. The system identification from Section 2.1.2 is used as a basis to formulate the different search queries. Five groups of search terms were first established and were organized into eleven search queries as illustrated in the workflow given in Fig. 4.

The first group provides the context to the technical system under study: Transport infrastructure systems. As described in Section 2.1.2, TIS can be modeled at different scales, i.e., from the component level to the asset level to the network level. Then, in an effort to reach research at any spatial scale and understand possible effects of the considered scale of the system, search terms in this group include component-level terms (e.g., bridge pier, bridge pile), asset-level terms (e.g., highway bridge, transportation asset), as well as network-level terms (e.g., road network, bridge network). It should be noted that terms used to refer to Transport Infrastructure Systems (as referred to in this study) are semantically different across many articles. For instance, some authors refer to them as highway networks (e.g., [47]), transportation networks (e.g., [48]), road networks (e.g., [12,49,50]), bridge networks — when the focus is given to bridges as the most vulnerable asset in the network (e.g. [27,51]), traffic networks (e.g., [52]), and so on. However, they refer to the same technical system under study, i.e., a system comprised of all infrastructures enabling terrestrial traveling of people and goods. Thus, an extensive literature screening was conducted to find semantically-related terms and complete the collection of keywords to refer to the same technical system (the complete list of terms belonging to each group is provided in Appendix). Moreover, wildcards are used to represent different combinations of characters in the construction of a query (e.g., "road* *structure" to represent road structure, roadway infrastructure). Lastly, the Boolean operator "OR" was employed to retrieve records containing any of the terms from Group 1 (n_0).

The second group corresponds to the system characteristics explained in Section 2.1.2: vulnerability, robustness, resilience, and sustainability. Risk is included in the search query together with vulnerability since the structural engineering community tends to employ the term risk more than vulnerability. Separate searches (n_1–n_4) are conducted to identify methods and indicators/metrics to characterize the different system characteristics. A combined search of all system characteristics with the "OR" operator (n_{OR}) was also performed for a subsequent search query combination with Group 4 and Group 5 terms (see Fig. 4).

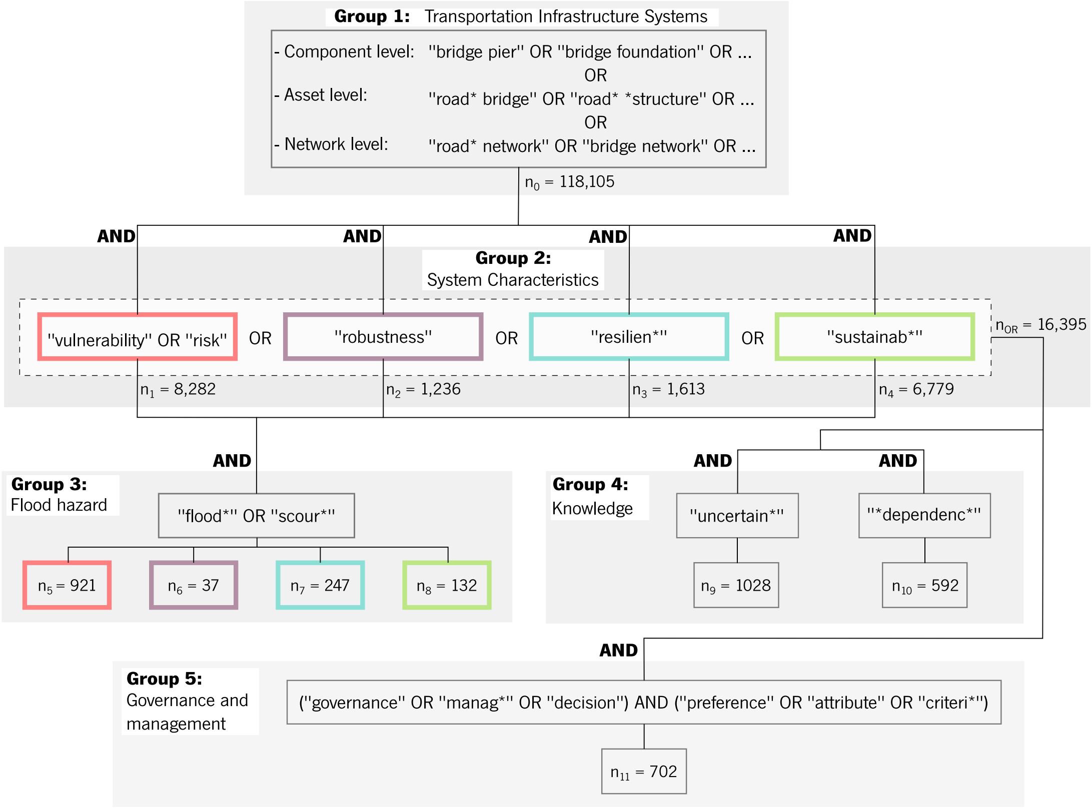


Fig. 4. Workflow of search queries for the bibliometric analysis.

The third group corresponds to the flood hazard to give the emphasis of the present study to understand particularly where the research state is in the domain of flood risks. The term scour is included herein since this erosional process is increased during flood events and has been regarded as one of the leading causes of bridge failures worldwide. As a result, a vast amount of research has been conducted on modeling this phenomenon and its influence on bridge safety. Then, each system characteristic from Group 2 is linked with Group 3 through the Boolean operator “AND” (n_5–n_8).

The fourth group corresponds to the state of knowledge with regard to the treatment of uncertainties and dependencies. The Boolean operator “AND” is used to link all system characteristics from Group 2 (n_{OR}) with each term from Group 4 (n_9 and $n_1 0$). Finally, the fifth group corresponds to the governance and management of the system, where the aim is to identify the preferences, attributes (or criteria), and objectives of decision makers. Similarly to Group 4, the Boolean operator “AND” is used to link all system characteristics from Group 2 (n_{OR}) with the search query from Group 5 (n_{11}). It should be mentioned that the term “objective“ is not included in the search query of Group 5 since this term is too general and retrieves many results along the lines of “the objective of this study”, “the objective of the paper”, and others. The complete search queries are provided in the appendix Table A.2.

2.2.2. Data collection and cleaning

The search queries defined are used to collect the records from the Scopus bibliographic database. The major advantage of choosing the Scopus database is its greater publication coverage for the research domain under study. Essentially, in addition to articles, the Scopus database contains other documents, such as conference proceedings and books. The queries were employed to search in the titles and abstracts field (TITLE-ABS) or author keywords field (AUTHKEY) of the Scopus database. As a general rule in the search queries, results from health sciences fields were excluded, as well as some specific life sciences such as Immunology and Microbiology, Pharmacology, among others (refer to appendix Table A.3 for the full list), as these subject areas were not deemed of relevance to the scope of this study. All papers in the historical series since 1990 have been considered until December 2022.

The Group 1 search (n_0) returned a total of 118,105 records. Then, when linked with the combined search of all system characteristics with the “OR” operator (n_{O_R}), the search returned a total of 16,870 records. These latter records were extracted and screened to remove duplicates and exclude documents from different context areas, e.g., space transportation systems, traffic signal control systems, and others (refer to appendix Table A.4 for the full list). A total of 16,395 unique records were finally used in this study. The number of records for each search query after data cleaning can be observed in Fig. 4. It can be seen that when the flood exposure is added (n_5–n_8), the number of records for all system characteristics drops significantly. In fact, the resulting dataset from search query n_6 is so small (37 records) that its use for a bibliometric analysis is not recommended since forcing the analysis in such a small sample would be an overkill [36]. Then, the bibliometric analysis for search query n_6 is not performed.

2.3. Step III: Bibliometric networks construction

Bibliometric networks are the way bibliometric research is visualized. A bibliometric network consists of nodes and edges, where nodes can be publications, journals, researchers, or keywords, and the edges represent the relations between pairs of nodes. Among the different types of available bibliometric networks, this study uses co-occurrence of terms extracted from titles, abstracts, and keywords, which allows exploring the relationships among topics in a research field and therefore supports the identification of potential research gaps, which is one of the main goals of the study. In addition, bibliographic coupling networks of authors and countries are also selected to analyze the relationships among expert communities and the distribution of research globally. VOSviewer [53] was used to construct both types of bibliometric networks. VOSviewer is a software tool for constructing and visualizing bibliometric networks, which provides distance-based visualizations, i.e., the distance between two nodes approximately indicates the relatedness of the nodes. Moreover, it provides three visualizations for a map: network visualization, overlay visualization, and density visualization. Further details regarding the construction of the bibliometric networks are provided in the following.

2.3.1. Term co-occurrence network visualizations

VOSviewer offers a text-mining functionality to construct and visualize co-occurrence networks of relevant terms extracted from textual data. The software tool performs part-of-speech tagging and utilizes a linguistic filter to identify noun phrases (terms) for which a relevance score is computed. A low relevance score shows that a word co-occurs with other terms randomly, while a high relevance score is assigned to noun phrases that co-occur with a limited group of other noun phrases [54]. Terms were derived from the titles and abstracts from publications collected in Step II. Terms with low relevance scores were excluded, as well as too general and non-context-specific terms (e.g., article, author, challenge, literature). Applying these filters shifts the focus to more specific and informative terms. The full list of excluded terms can be found in appendix Table A.5.

Network visualizations are chosen to display the co-occurrence of terms. The network visualizations are comprised of items (terms) and links. Terms are represented by their label and a circle, which size depends on the number of publications that contain the term in the title or abstract. There are two counting methods available, binary or full counting. In the binary option, only the presence or the absence of a term in a publication matters. Conversely, in the full counting option, all occurrences of a term in a publication are counted [54]. The binary option is chosen, so a term that occurs only once is treated the same way as one that occurs multiple times. The minimum number of occurrences of a term for its inclusion in the network is adjusted for each search aiming to obtain medium size network visualizations of 120 terms (refer to Appendix Table A.6). This helps to deal with the problem of very large networks being perceptually difficult to visualize and very small networks less informative due to few terms. On the other hand, links represent the connection or relationships that exist between two terms. Each link has a strength determined by the number of publications in which the two terms appear. The thicker the line in the visualization, the stronger the link. Terms that co-occur frequently are located closely, while terms with no or practically no co-occurrence are farther away. Additionally, terms are grouped together into clusters. A cluster represents a set of terms closely related, and each cluster has a distinctive color. Each term in a network belongs to one cluster only. The clustering technique employed by VOSviewer requires an algorithm for solving an optimization problem and is discussed in detail in [55,56]. Analyzing the clusters in the network visualizations makes it possible to identify the research area domains (fields and subfields) contributing to the knowledge.

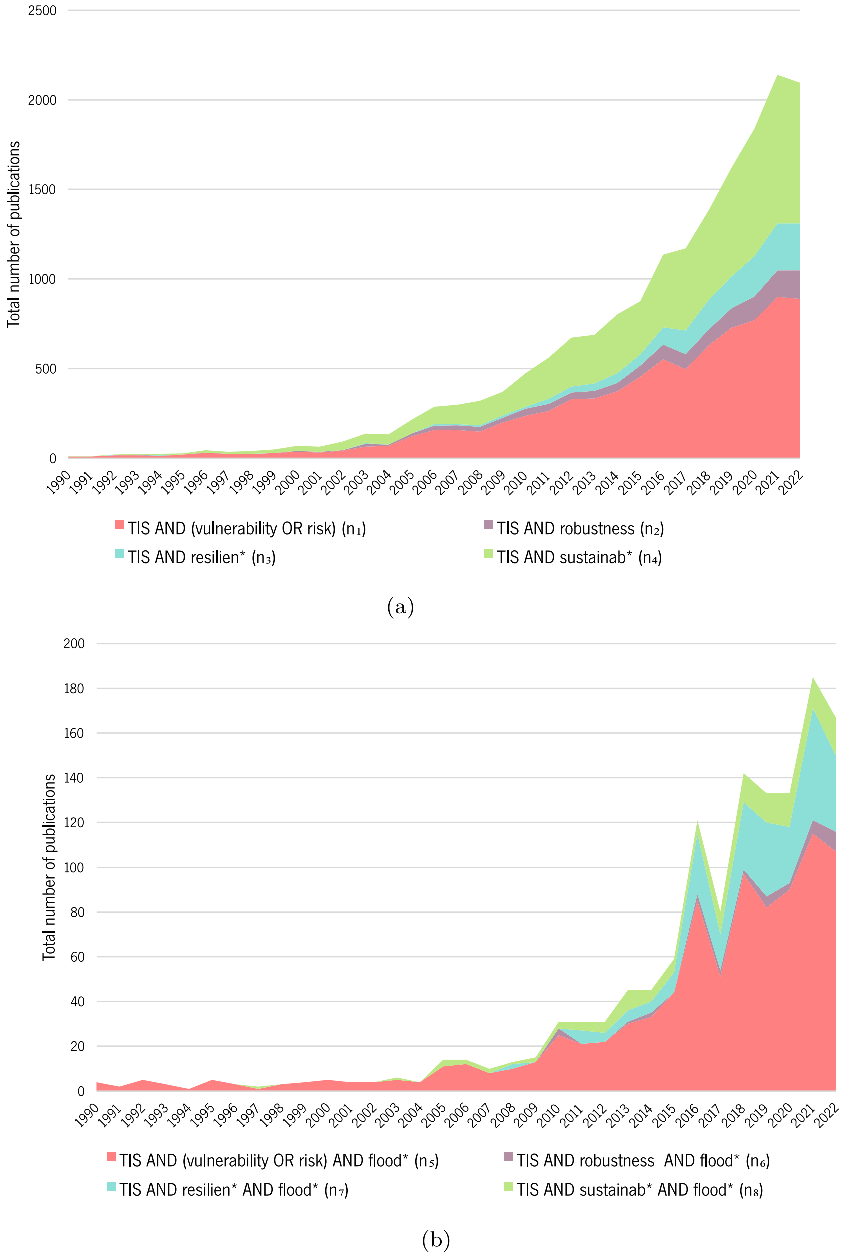
2.3.2. Bibliographic coupling network visualizations

Bibliographic coupling networks were also constructed using the VOSviewer software for two items: authors and countries. In this type of network, the relatedness of items is based on the number of references they share. In other words, the larger the number of references two publications have in common, the stronger the bibliographic coupling relation between them [54]. There are two counting methods available, full counting and fractional counting. In the full counting method, each bibliographic coupling has the same weight. Conversely, in the fractional counting method, the weight of a link is fractionalized to diminish the importance of highly cited publications or publications with a long reference list (e.g., review articles) [54]. As recommended by the authors, the fractional counting method is selected to include perspectives beyond citation numbers.

Density visualizations are chosen to display the bibliographic coupling of authors since they help to identify knowledge hubs and subject experts intuitively visually. In this type of format, authors are represented by their labels, and each point in the density visualization has a color that indicates the density of authors at that point. A rainbow color palette is used, which ranges from blue to green to red, to reflect the density of authors at each point. The 'hot' red zones of the map indicate a large number of authors in the neighborhood and high weights of the neighboring authors. Conversely, the 'cold' blue zones represent neighborhoods with a small number of authors and low weights of neighboring authors [53]. On the other hand, network visualizations have been used to display the bibliographic coupling for countries. Then, countries are represented by a label whose size indicates their relative importance, and the link between them indicates the relatedness of cited references. The bibliographic coupling networks were constructed from the publications collected in Step II. A minimum number of publications per author and per country for its inclusion in the networks were defined, aiming to obtain around 20–30 authors and 50–70 countries in each network (refer to appendix Table A.7).

2.4. Step IV: Analysis of results

The data interpretation, analysis, and recommendations are the focus of the following sections of the paper.



(a)

(b)

Fig. 5. Evolution of research in (a) system characteristics of TIS (n_1–n_4) (b) under flood exposure (n_5–n_8).

3. Results

3.1. Historical evolution and growth of research in system characteristics of TIS

Fig. 5 illustrates the historical evolution and volume of research in system characteristics of TIS. From Fig. 5(a), it can be observed that research in vulnerability and risk of TIS have the longest history and largest volume of publications, closely followed by sustainability research, while robustness has received less attention. All system characteristics show an upward trend, but risk and sustainability have increased at a higher rate in the last decade. When analyzing the system characteristics research in the specific context of flood exposure (Fig. 5(b)), vulnerability and risk are by far the dominant research field, robustness research is marginal, and resilience gains more importance over sustainability. Interestingly, there are two peaks of publications in the years 2016 and 2018, which may be motivated by the occurrence of flooding events with large consequences worldwide during that period.

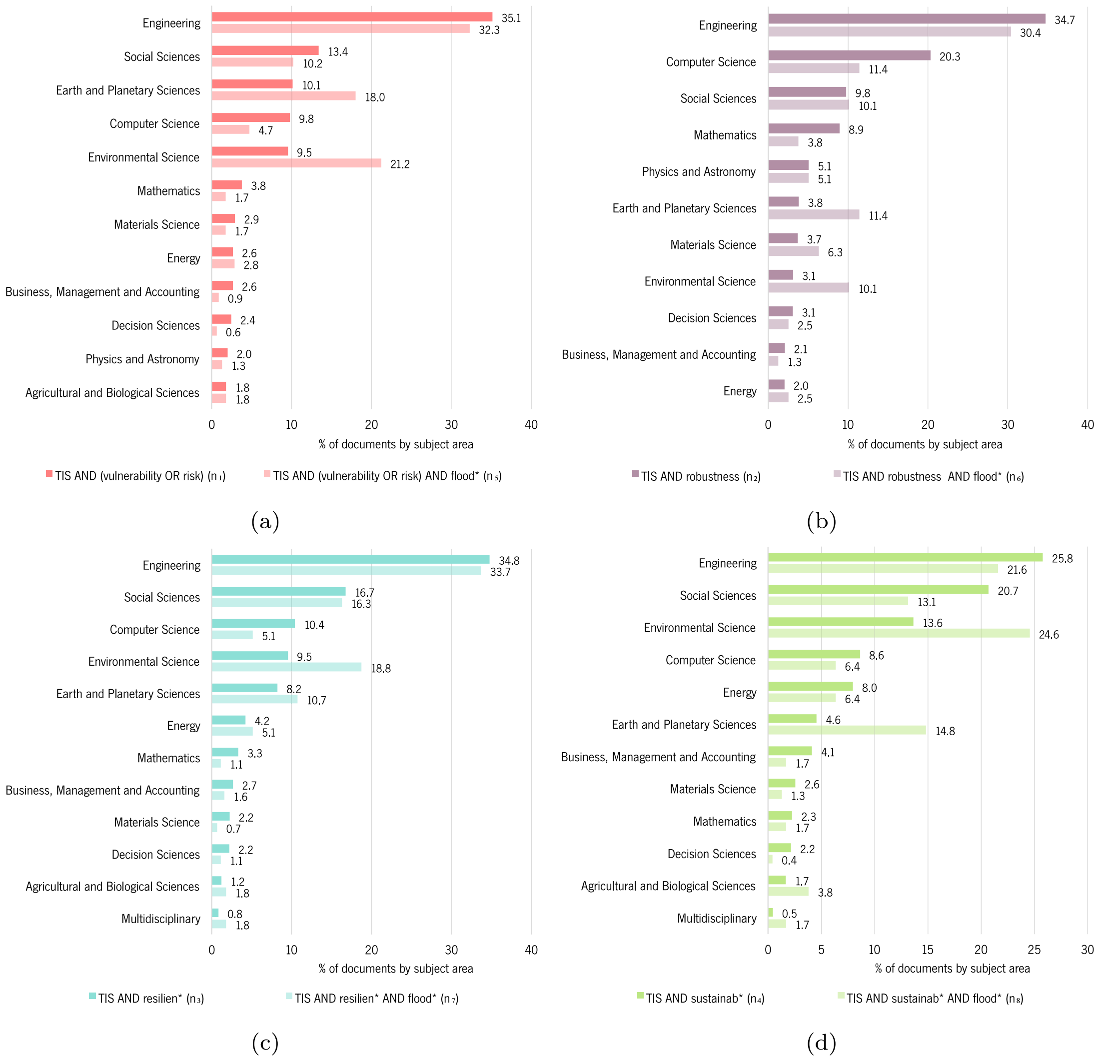


Fig. 6. Main subject areas in TIS research on (a) risk and vulnerability (b) robustness (c) resilience (d) sustainability.

3.2. Multi-disciplinary composition of research in system characteristics of TIS

The distribution of subject areas in the domain of system characteristics research of TIS is shown in Fig. 6. The top ten categories were selected for the non-hazard-specific queries (n_1–n_4) and the flood-specific queries (n_5–n_8). It can be observed that each bar chart contains around 11 to 12 subject areas, which means that the contribution of a discipline varies if the emphasis of the study is on flood exposure or not. Engineering is the predominant subject area for all system characteristics. However, when analyzing sustainability specifically under flood exposure, environmental science emerges as the leading subject area contributing to research. In general, the contribution from environmental science – and Earth planetary science – is significant in all search queries that include flood exposure. Another big contributing subject area is social sciences, which comes second in most system characteristics except for robustness research, where computer science becomes the second contributor. This is not a surprise since engineering disciplines heavily dominate research on robustness. Finally, decision sciences and business, management, and accounting contribute to research at a minor level. Therefore, it could be said that the top contributing subject areas for all search queries approximately represent the ecological, engineered, and social systems perspectives.

3.3. Term co-occurrence analysis results

This section presents the term co-occurrence maps created with VOSviewer. As explained in Section 2.3.1, the software uses a clustering technique to group related terms and assigns a specific color to each cluster. Then, the terms in each cluster are analyzed, and the research area that best represents the cluster is identified to name the cluster. It is acknowledged there is subjectivity involved in interpreting these maps. However, they are an efficient visualization tool to discover trends and patterns in large datasets and to identify potential research gaps based on the relationships between clusters. In addition, the networks will be explored in search of methods, techniques, tools, indicators, and metrics for modeling and managing TIS.

Fig. 7(a) shows the network map combining the domains of vulnerability and risk of TIS. In this non-hazard-specific search, there are four different clusters. The blue cluster corresponds to the civil/reliability engineering domain (probability, uncertainty, structure), which focuses on structural safety assessment. It can be observed that a large emphasis is given to seismic vulnerability, and the use of fragility curves comes up to characterize the performance of structures under different intensities of the hazard. In addition, considerations regarding the long-term performance of bridges are also found in this cluster (e.g., deterioration, (condition) state). The red cluster is the policy/governance (e.g., government, resource, stakeholder, planning), which is more concerned with management than assessment, and focuses on economic considerations (investment, economy). The green cluster is closely related to the red cluster and represents the transportation engineering community (e.g., traffic, route, vehicle, city), with considerations regarding road safety and the environment. Lastly, the yellow cluster is the natural hazards domain (flooding, landslide, climate), which focuses on weather-related hazards affected by climate change.

Fig. 7(b) presents the network map combining the domains of vulnerability and risk of TIS exposed to flood events. The network shows two closely related clusters (green and red) located far from a third cluster (blue). The green cluster represents the transportation engineering domain (e.g., service, access, person, urban area), where the main considerations are service provision and accessibility for the population during disasters. Also, GIS tools appear to be commonly used in this cluster for mapping the extent of the inundation area. The red cluster is closely related and corresponds to the natural hazards and climate change domain (sea level rise, extreme weather event, storm). Even though the policy and governance cluster from Fig. 7(a) disappears when the flood exposure is included, some governance goes to the red cluster (e.g., decision maker, strategy, adaptation). The blue cluster, which represents the civil/reliability engineering (e.g., uncertainty, probability, safety), sits rather far from the other two clusters. In this cluster, there is a large contribution from the research community focused on bridge scour. Some considerations regarding long-term performance also take place, probably focusing on formulations for scour depth prediction (e.g., erosion, state, prediction). However, it can be seen that the term “fragility curves” disappears, meaning their use is not as frequent as in the case of seismic hazards. The distance of the blue cluster with the other clusters means that there might be a lack of integration of this community, more focused on the asset/bridge level analysis, with respect to transportation and natural hazards domains which focus on regional and country level scales.

Fig. 8 shows the network map in the domain of robustness of TIS. The blue cluster corresponds to classical structural engineering (e.g., load, response, sensitivity analysis, numerical simulation), where structural assessment, damage identification, and structural health monitoring considerations are found. The green cluster is related to transportation engineering (e.g., vehicle, algorithm, technology, and intelligent transportation systems). This research domain has focused on developing new technologies for transportation/traffic systems, e.g., sensors and image detection. Considerations in this domain are accuracy, stability, and effectiveness of new solutions. However, these are classical terms and do not refer to systemic robustness as defined in Section 2.1.2, which also holds for the blue cluster. Conversely, the red cluster represents the systemic risk and resilience engineering perspective (e.g., redundancy, recovery, consequences, resilience, risk, vulnerability). This cluster includes important considerations such as network robustness, connectivity, travel time, and traffic congestion, which are relevant to quantify indirect losses due to network disruptions. It is worth noting that the flood-specific search for robustness research (n_6) returned insufficient records to perform a bibliometric analysis. Yet, this allows concluding that more research in this domain is still missing.

Fig. 9(a) presents the network map in the domain of resilience of TIS. The red cluster is the densest and represents the policy/governance research (policy, planning, stakeholder, government). Besides economic aspects, this cluster has considerations with regard to the population, such as mobility, access(ibility), and quality of transportation service. Also, it is concerned with sustainability, adaptation to climate change, and some interdependency among different infrastructure systems, namely energy, water, transport, and other critical infrastructures. The blue cluster is the civil/reliability engineering (probability, uncertainty, response), which is focused on research at the component/bridge scale (e.g., damage, loss, structure, component), so the resilience metrics found are related to the level of structural damage after the occurrence of hazards, particularly from seismic hazard events. Lastly, the green cluster represents transportation engineering research (traffic, congestion, flow, travel time). In this cluster, metrics to characterize the network resilience are identified, such as travel time, connectivity, and traffic flow, as well as resilience indicators like robustness and redundancy. This map shows that transportation engineering can play an important role in bridging the gap between policy and civil engineering research. On the right side, the nodes recovery and functionality from the transportation cluster are closely associated with the nodes component, response, and damage from the civil engineering cluster. This is expected since the time for recovering the complete functionality of the transportation network depends on the number of damaged components, their damage level, and the repair sequence. On the left side, nodes like traffic and connectivity from the transportation cluster are strongly linked with the service node in the governance cluster, which is a dominating node in this cluster.

Fig. 9(b) presents the network map in the domain of resilience of TIS under flood events. The same three clusters from the non-hazard-specific search are maintained. However, their composition is slightly different. For instance, the explicit modeling of the hazard/disruptive event does not appear to be relevant in the transportation engineering cluster from Fig. 9(a). Conversely, the transportation cluster from Fig. 9(b) integrates natural hazards research of hydrological nature, such as coastal flooding, sea level rise, hurricanes, and their impacts on the road network service (inundation, access, mobility), particularly for emergency response. As a result, the prevailing metric to characterize resilience is connectivity. On the other hand, the civil/reliability engineering cluster (blue) gains more importance in this map. Besides research about the restoration of assets/bridges as a function of their damage severity and the recovery of functionality, this cluster includes resilience indicators like robustness and redundancy in close

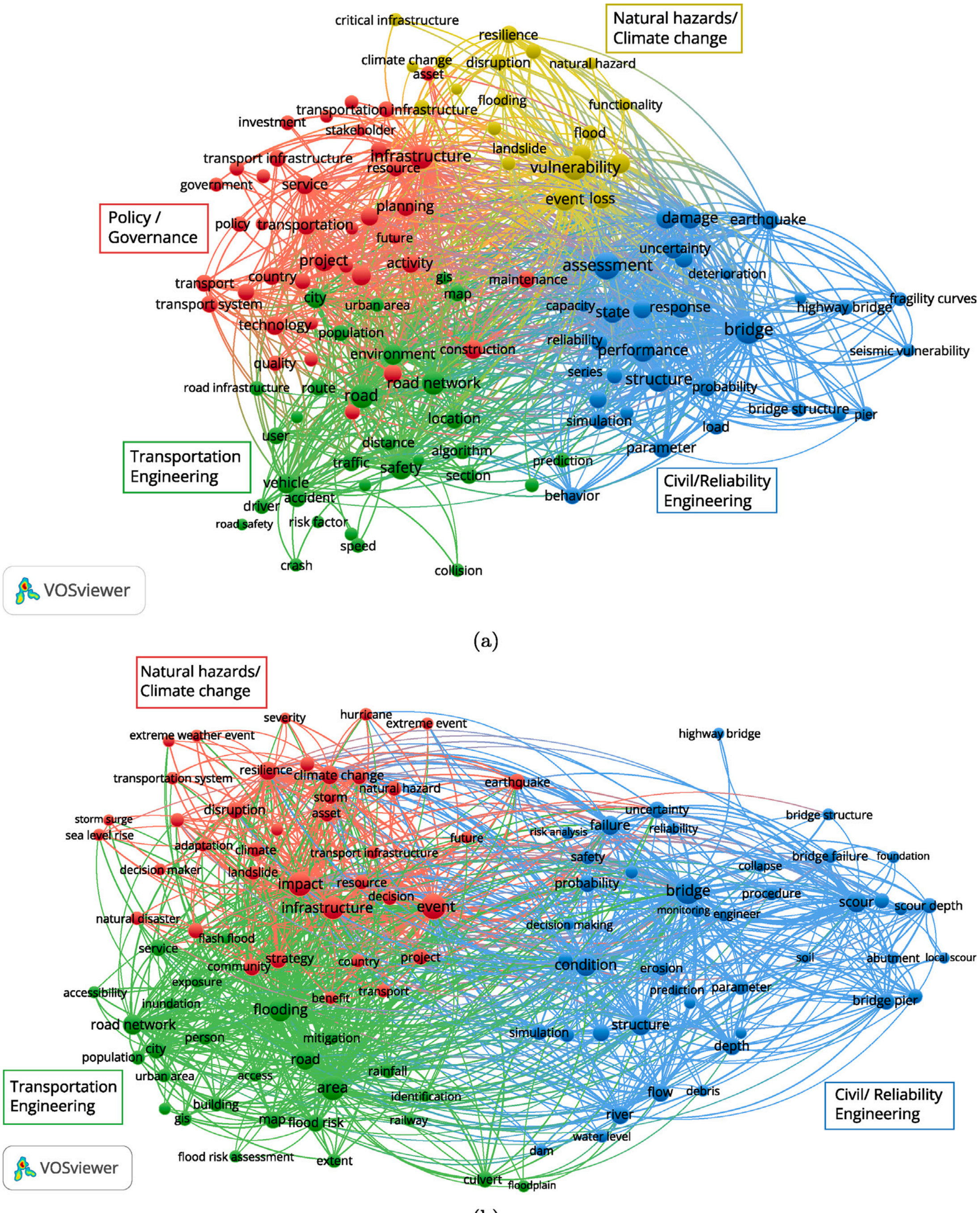


Fig. 7. (a) Network map of research in the domain of risk and vulnerability of TIS (n_1) (b) under flood events (n_5).

relationship with the green cluster. In fact, these two indicators were in the transportation cluster in Fig. 9(a), which indicates the relevance of these indicators to link both research communities. Finally, the policy/governance cluster (red) is similar to the non-hazard-specific map. Yet, it is less dense, and some relevant considerations with regard to the quality of the transportation service to the population and sustainability are missing.

Fig. 10(a) presents a network map in the sustainability domain of TIS. This is a dense network with three clusters. The blue cluster is the civil engineering domain (e.g., construction, project, maintenance, infrastructure), where sustainability and environmental impacts are considered for managing the built environment, as well as risk and safety. The long-term performance of bridges

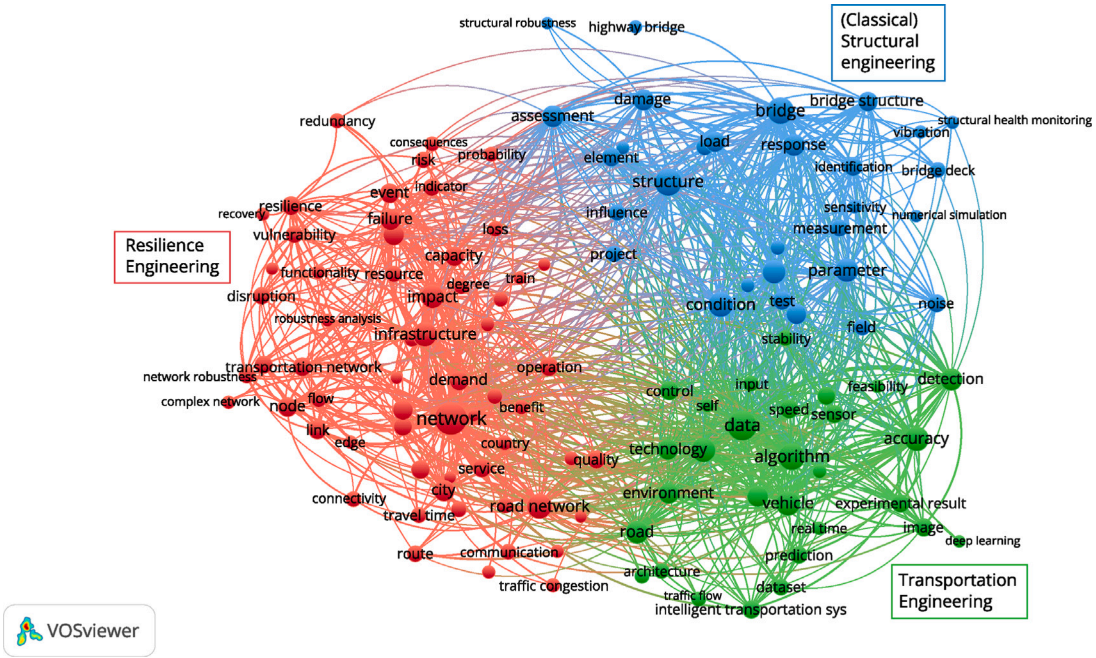


Fig. 8. Network map of research in the domain of robustness of TIS (n_2).

appears to be considered (e.g., state, performance, year) to define maintenance strategies that ensure sustainability. The green cluster is the transportation engineering community, focused on sustainable mobility, e.g., reduction of traffic congestion, and energy consumption, as a means to reducing air pollution and emissions. Lastly, the red cluster is the policy/governance research (country, government, investment), which underlines the need for sustainable development, growth, and land use planning.

Fig. 10(b) displays the network map in the sustainability domain of TIS under flood events. There are three interacting clusters, yet with some loosely connected nodes, which may be explained by the small dataset for this search (132 publications). In fact, this network map contains only 100 terms (rather than 120), since the minimum number of occurrences of a term was set in 5 instances to avoid the influence from one particular research group (see details in Appendix Table A.6). The green cluster is the densest and can be associated with hydrology environmental science research (river, floodplain, erosion, water supply). This knowledge hub integrates research on river/catchments modeling and how the built environment interacts with it. Its slight dominance in the network map is congruent with the finding in Fig. 6(d), where environmental science is the leading contributor to research for the sustainability search under flood events, followed by engineering. The red cluster is the urban land-use planning (urban area, land use, space, urbanization), which contains some governance aspects (investment, mitigation, long term). Lastly, the blue cluster is the civil/reliability engineering cluster (e.g., bridge failure, uncertainty, structure), where the main considerations are related to bridge damage, loss, consequences, and adaptation to climate change impacts.

Finally, the last three network maps correspond to the search queries related to knowledge, and governance and management. Fig. 11(a) shows the network map in the domain of uncertainties in the system characteristics of TIS. The predominant cluster is the civil/reliability engineering in blue, with a major focus on bridges. The use of probabilistic approaches dominates the treatment of uncertainty in this cluster, and seismic fragility curves appear as a strong application that accounts for uncertainties in the assessment of structural vulnerability. On the other hand, the green cluster representing the transportation engineering community is comprised of loosely connected nodes. The approach for treating uncertainties in this cluster is not evident from the network map. Yet, this research community seems to acknowledge uncertainties in vehicle route choice, travel time, and traffic assignment solution algorithms. The red cluster corresponds to the policy/governance research. This is a more dense cluster with stronger links between nodes, yet it does not provide many insights either regarding the treatment of uncertainties. Lastly, the yellow cluster, which is the resilience engineering community (resilience, robustness, functionality), is a loosely connected cluster that appears to be making efforts to link the civil engineering community at the bridge level (blue cluster) with the infrastructure system level, through the assessment of the system functionality and characteristics like robustness and resilience. However, there is still a significant gap between the treatment of uncertainties at the asset level to the network level.

Fig. 11(b) presents the network map of research in the domain of dependencies in the assessment of system characteristics of TIS. The network shows two closely related clusters (green and red) located far from a third cluster (blue). The blue cluster represents the systemic risk and resilience engineering perspective (vulnerability, risk assessment, robustness, functionality, resilience). The treatment of uncertainties is governed by the use of probabilities, and cascading effects are among the dependencies of random events underlined in this cluster. Also, there is great consideration of interdependency and cascading failures with other infrastructure

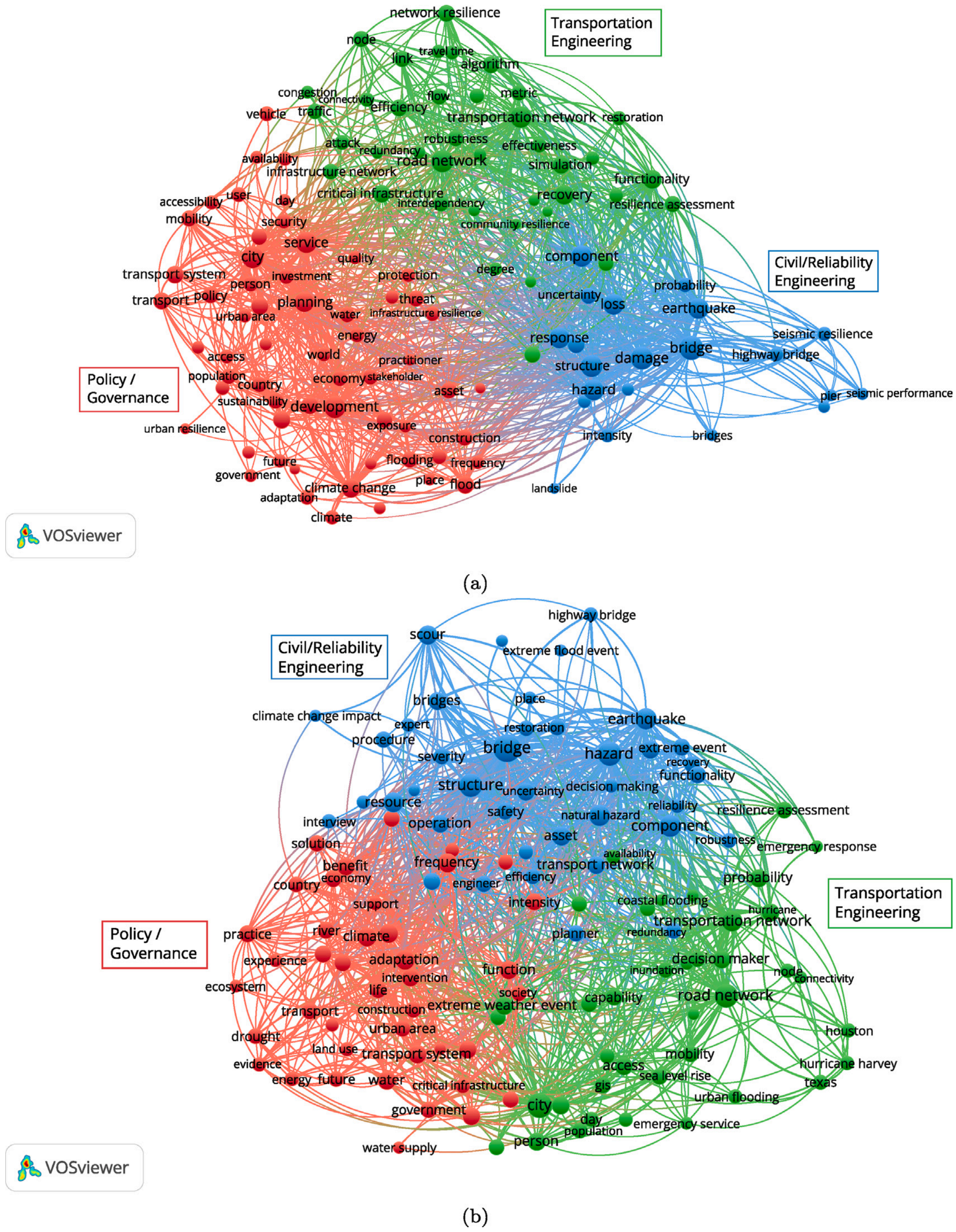


Fig. 9. (a) Network map of research in the domain of resilience of TIS (n_3) (b) under flood events (n_7).

systems: electricity/power, water, and telecommunication systems, as well as interdependencies with supply chains. The two other clusters located apart from the blue, are the green cluster which corresponds to transportation engineering (mobility, vehicle, traffic), and the red cluster, which represents the policy/governance (government, policy, country) from a societal infrastructure planning perspective. However, dependencies considered in these two clusters do not refer to the type of dependence related to knowledge as described in Section 2.1.2.

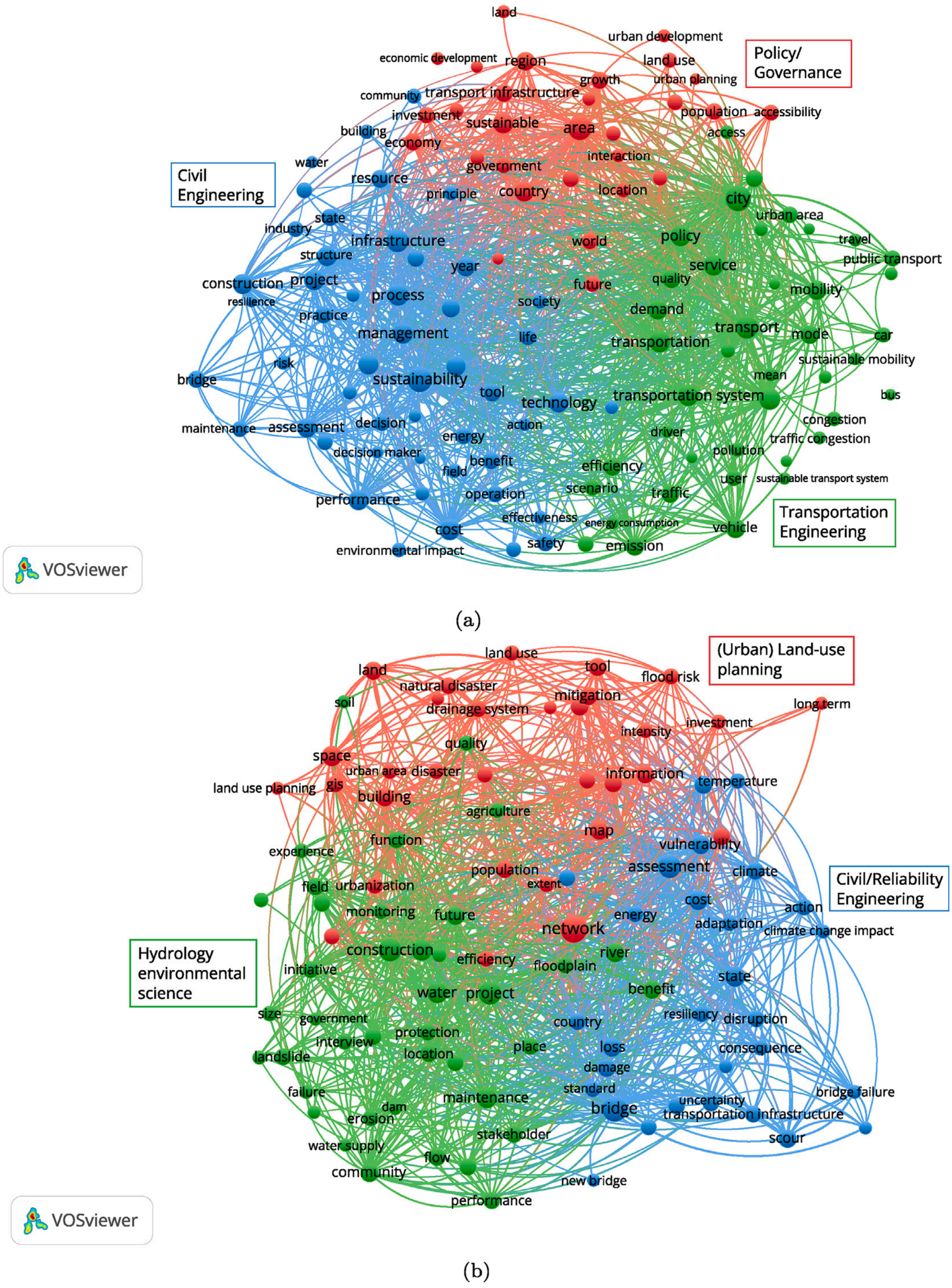
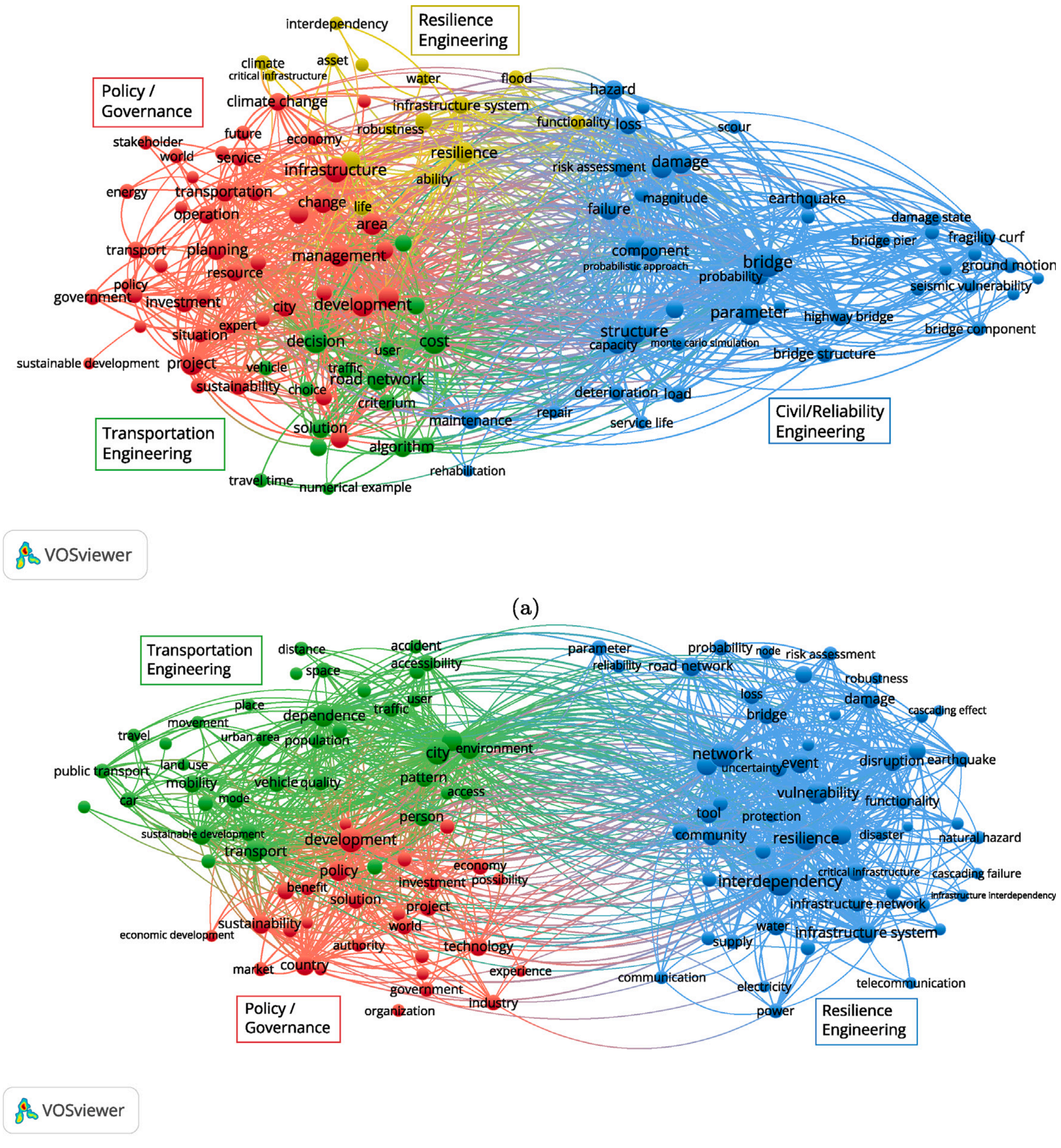


Fig. 10. (a) Network map of research in the domain of sustainability of TIS (n_4) (b) under flood events (n_8).

Lastly, in Fig. 12, a network map in the domain of decision-making of TIS under a normative context is given. There are three distinct clusters. The dominant cluster is the red one and represents the governance perspective (stakeholders, policy, country, investment). There is a lot of decision analysis in this cluster. Some preferences that arise are economy, sustainability with criteria like emissions, and some societal criteria related to mobility, such as availability, accessibility, and travel time. The green cluster belongs to the urban transportation planning (urban area, land use, route, road safety). In this cluster, decision-making methods appear like analytical hierarchical process (AHP) and multi-criteria decision analysis, with preferences like road safety and criteria



(a)

(b)

Fig. 11. Network map of research in the domain of (a) uncertainties in the system characteristics of TIS (n_9) and (b) dependencies (n_{10}).

like accidents. Lastly, the blue cluster represents the civil/reliability engineering perspective (risk, uncertainty, vulnerability), using risk-informed decision-making. The concept of utility comes up in this cluster, very closely related to reliability and society which might be attributes accounted for and transformed into utility to assess the optimality of decision alternatives. Most certainly, decision-making in this cluster is performed from an individual project perspective (bridge, structure, building), including long-term considerations for decision-making (e.g., age, condition state, maintenance). The network analysis is thus more addressed by the green and red clusters.

3.4. Bibliographic coupling analysis results

In this section, the last results from the bibliometric analysis are presented, corresponding to the bibliographic coupling analysis. The bibliographic coupling networks are used to show the distribution of knowledge by authors and countries in the system characteristics of TIS (search queries $n_1 - n_8$). The use of bibliographic coupling of authors facilitates the identification of the

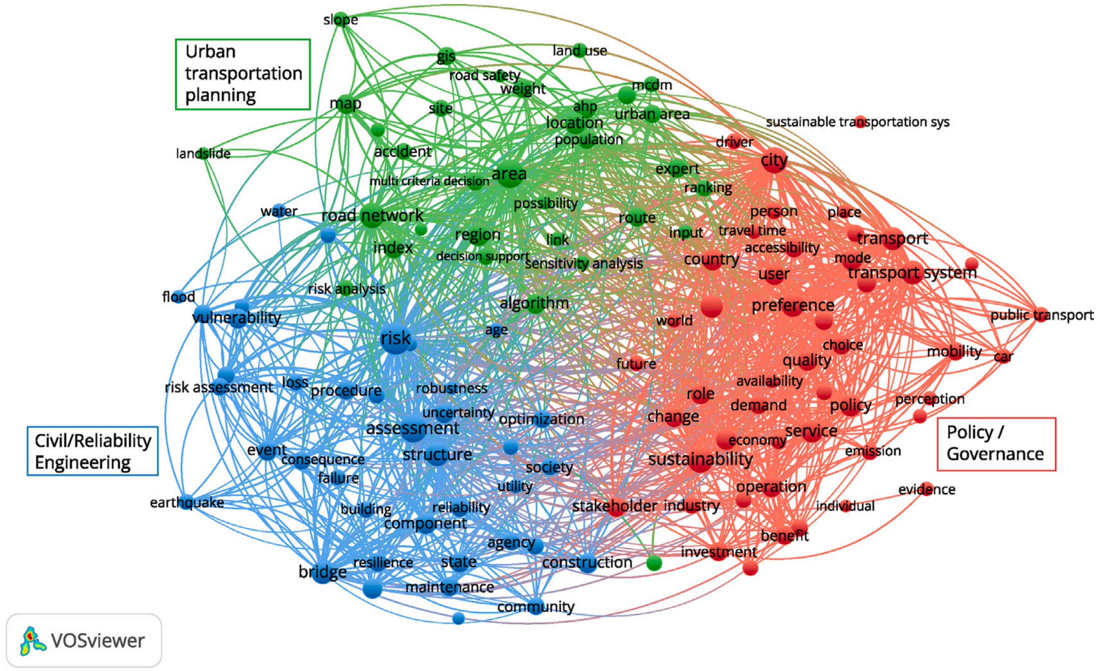


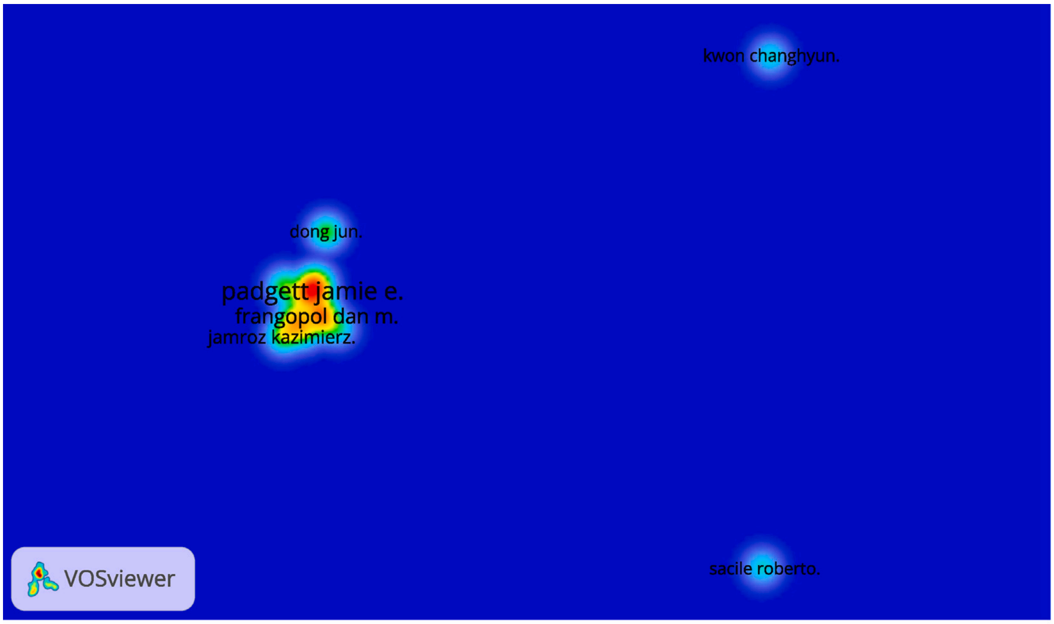
Fig. 12. Network map of research in the domain of decision-making preferences for TIS management (n_{11}).

relatedness of expert communities, or the fragmentation of research. Similarly, the bibliographic coupling of countries allows the observation of the major producers of research globally and collaborations among countries.

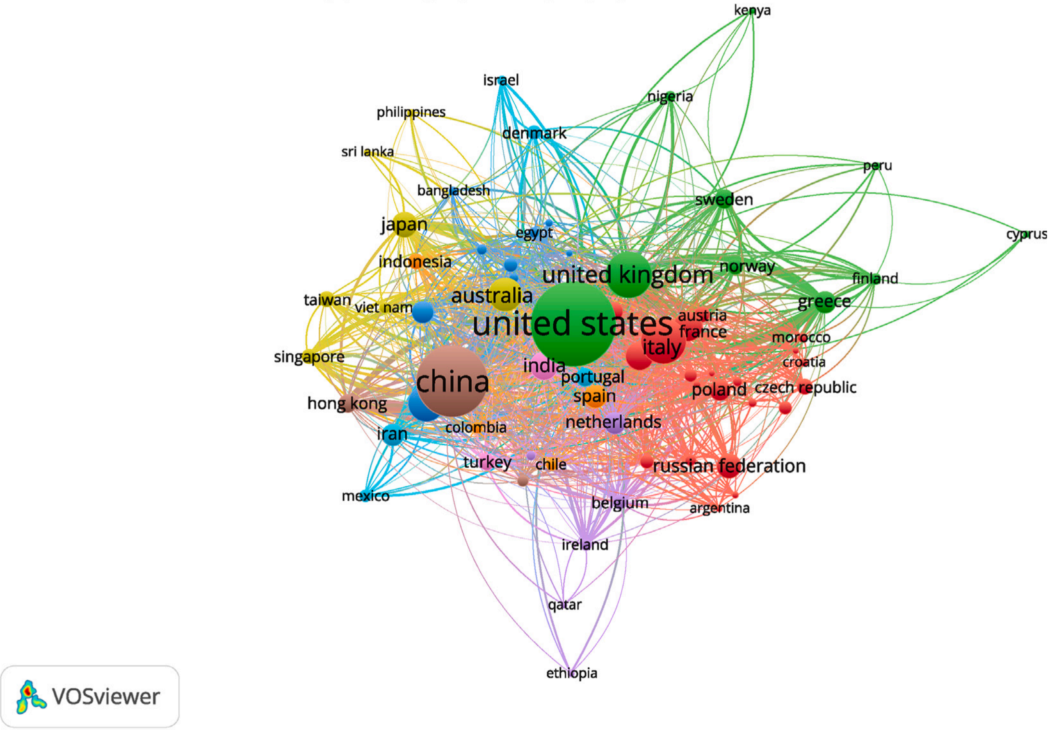
In Fig. 13(a), the bibliographic coupling by authors in research on vulnerability and risk of TIS is shown. There is a very interlinked group at the left and two distant authors at the right. These two authors are experts in risk management of hazardous materials transport on road networks. This division is interpreted as a result of the common practice of classifying hazards based on their source of origin, where hazardous material transport is not accounted for together with natural hazards, which is the main focus of the group from the left. Fig. 13(b) presents the bibliographic coupling by countries for this search. The two dominant producers of research are the United States (USA) and China, although the exchange between them is not very strong. Conversely, there is a strong relationship between the former and the United Kingdom (UK). They both belong to the green cluster, together with some Scandinavian European countries. Australia also has proximity to the USA, although it belongs to the yellow cluster together with some southeast Asian countries. Canada (hidden beneath China) has a strong relationship with China and belongs to the same cluster as South Korea and some Middle East countries. In the red cluster, several European countries are located, with Italy and Germany (hidden beneath Italy) having the lead and being strongly related. Russia is also a significant contributor to this cluster. The rest of the clusters have a smaller number of countries.

Fig. 14(a) displays the bibliographic coupling by authors in research on vulnerability and risk of TIS under flood exposure. Similarly to Fig. 13(a), there is a very interconnected group at the left and two distant authors at the right. One of the author's expertise is in bridge hydraulics and scour research, while the other author's expertise is in urban planning and disaster management. This separation is partially explained by the different spatial scales used by the authors for the assessment of risks — from bridge level to network/regional level. Fig. 14(b) presents the bibliographic coupling by countries for this search. Compared to the one from Fig. 13(b), which was not specific to flood hazard, the USA in the blue cluster is also a predominant producer of research, but the UK in the green cluster becomes the second more relevant, having a greater contribution than China. This finding can be explained by the fact that the UK has been severely affected by floods in the past years, which has motivated growing research in this area. Likewise, other countries greatly affected by floods are also relevant in this network including Italy, France, Australia, and Germany.

In Fig. 15(a), the bibliographic coupling by authors in research on the robustness of TIS is displayed. There are five different author groups, which are somehow related to those identified in Fig. 8. Essentially, the largest group of authors on the left belongs to the classical structural engineering community, as well as the two small groups closer to this group. On the other hand, the medium size group of authors on the right, along with the last single author, belong to the transportation engineering community. The separation of these two research communities in the co-occurrence of terms network is therefore reflected in the bibliographic coupling of authors. Fig. 15(b) shows the bibliographic coupling by countries for this search. In this map, China takes the lead in the production of research, closely followed by the USA, although weakly related among them.



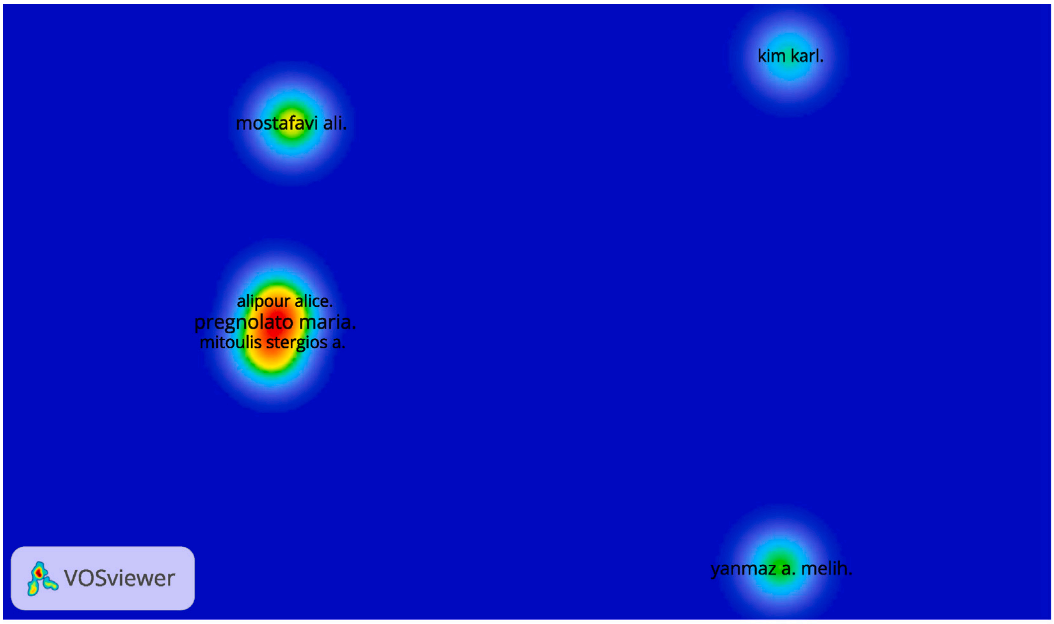
(a) Bibliographic coupling by author



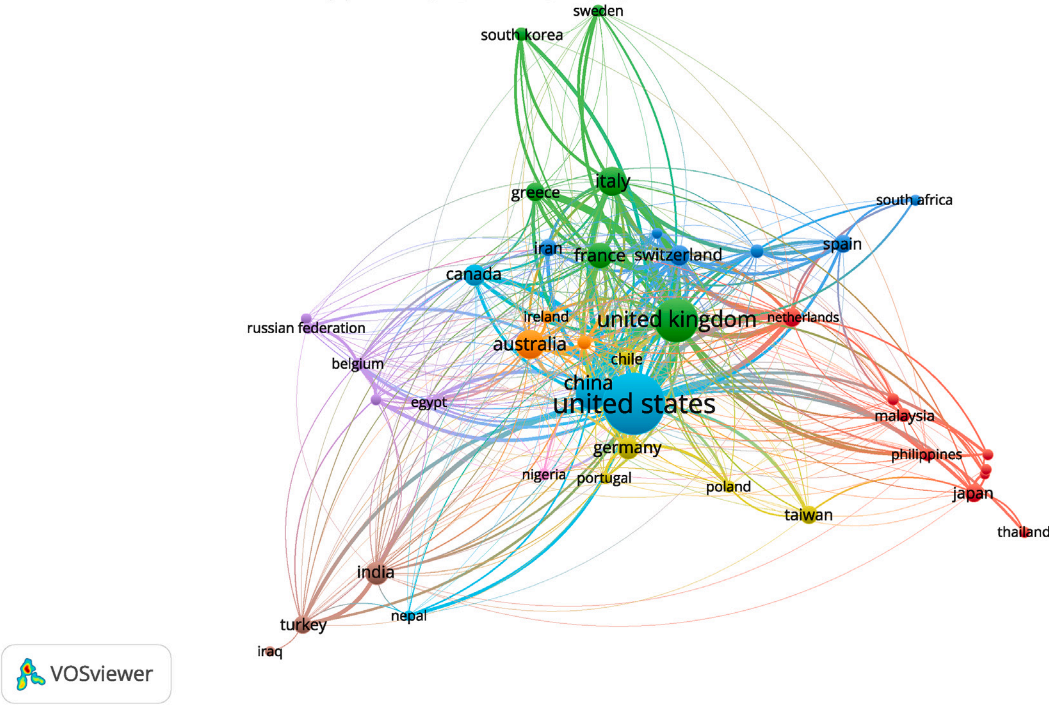
(b) Bibliographic coupling by country

Fig. 13. Bibliographic coupling of vulnerability and risk of TIS.

In Fig. 16(a), the bibliographic coupling by authors in research on the resilience of TIS is shown. There are three groups of authors on the map. The author at the top of the figure is focused on transport infrastructure resilience from a policy/governance perspective. This might explain the distance with the largest group of authors from the left, more related to transportation and civil/reliability engineering. The last group of authors located at the right is focused on railway infrastructure resilience. Despite belonging to civil/reliability engineering research, the distance from the large group of authors may be explained by the distinct structural behavior and characteristics of railway components and assets, which makes their bibliographic references dissimilar. The



(a) Bibliographic coupling by author

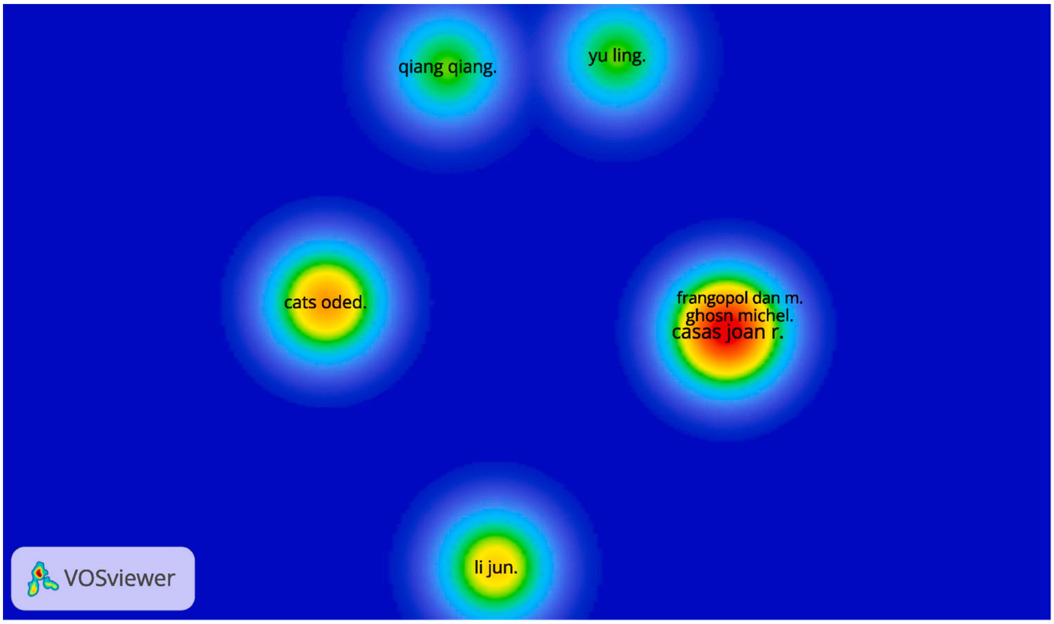


(b) Bibliographic coupling by country

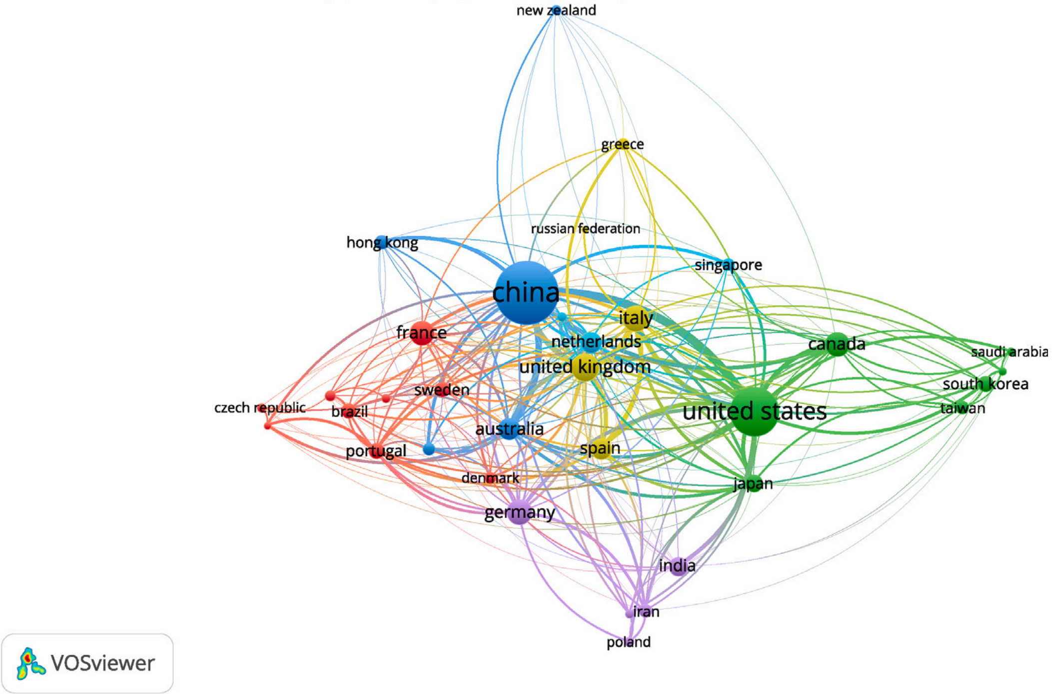
Fig. 14. Bibliographic coupling of vulnerability and risk of TIS under flood events.

bibliographic coupling by country for this search is displayed in Fig. 16(b). The two dominant producers of research are the USA and China, followed by Italy and the UK.

In Fig. 17(a) presenting the bibliographic coupling by authors in research on the resilience of TIS under flood exposure, a similar trend to that from Fig. 16(a) is exhibited. Essentially, there is one large group of connected authors on the left, along with a small group relatively close and connected to it, and three disconnected groups of authors on the right. Some of these authors are focused on adaptation planning from a policy/governance perspective, which explains their disconnection from the large group belonging to the engineering clusters. In addition, the other group is focused on pavements and underground infrastructures, which particular



(a) Bibliographic coupling by author

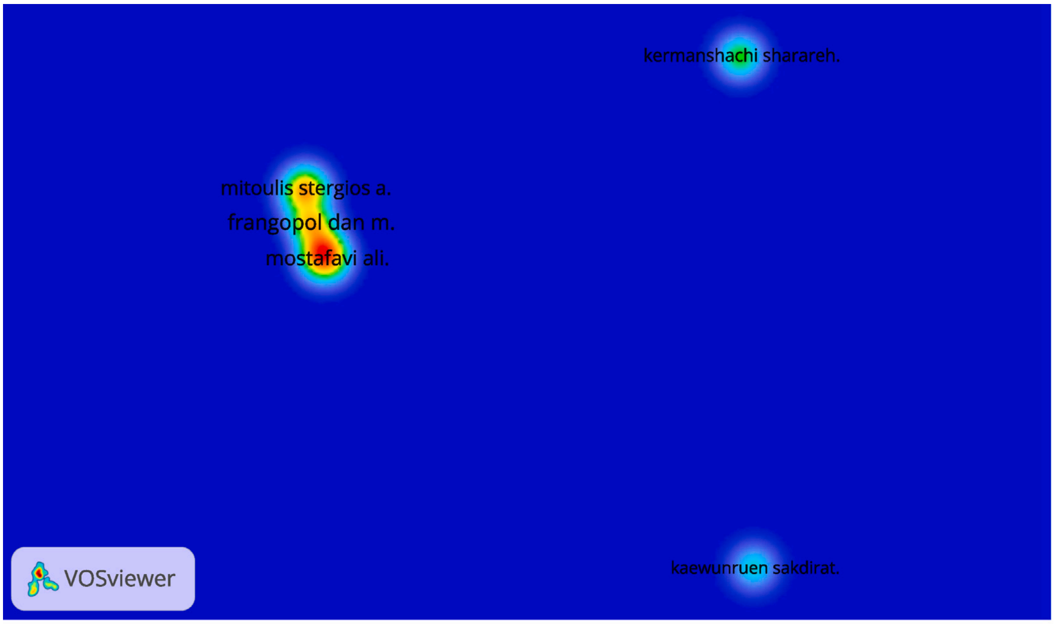


(b) Bibliographic coupling by country

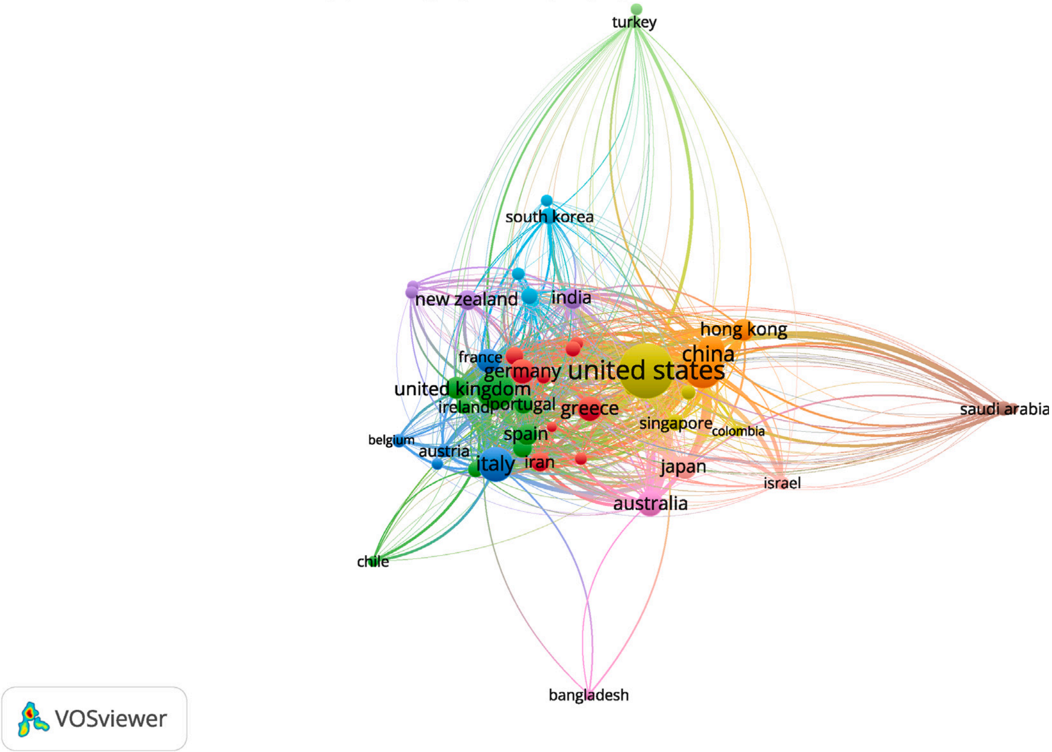
Fig. 15. Bibliographic coupling of robustness of TIS.

characteristics appear to have created some distance from research on bridges. The bibliographic coupling by country for this search is shown in Fig. 17(b). This map is dominated by what could be called the Anglo-Saxon group: USA, UK, Australia, and Canada, and to a lesser extent China.

Fig. 18(a) shows the bibliographic coupling by authors in research on the sustainability of TIS. In this map, there are many groups with no connection among them. This evidences different perspectives, approaches, and diversity in research around the sustainability of TIS. This effect is also appreciated in the bibliographic coupling by country for this search in Fig. 18(b). Despite a larger contribution of research from the USA, China, and the UK, the distribution of research is quite spread around the world.



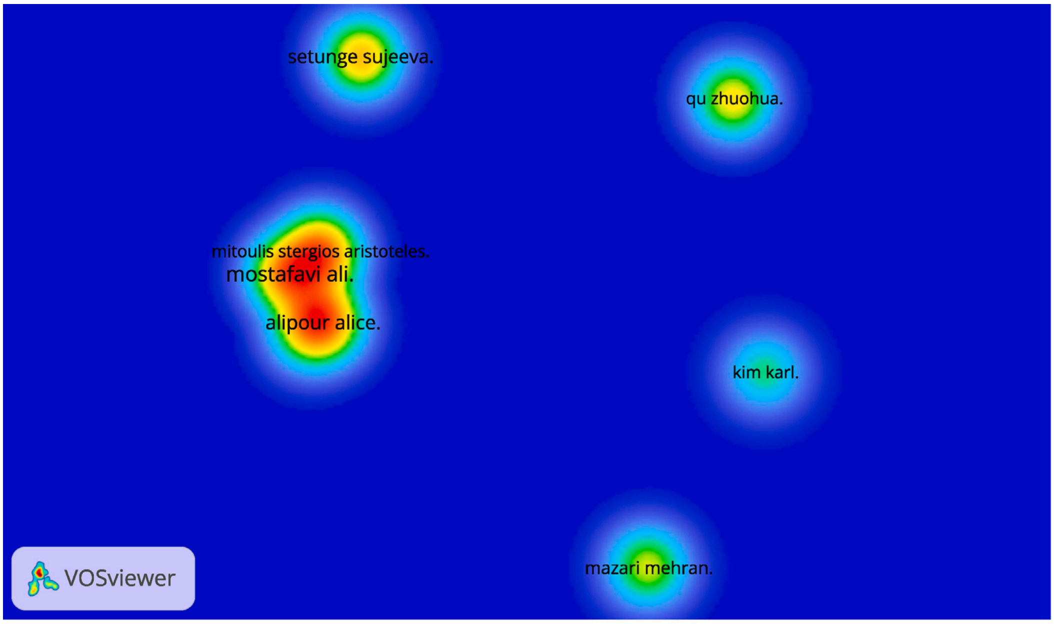
(a) Bibliographic coupling by author



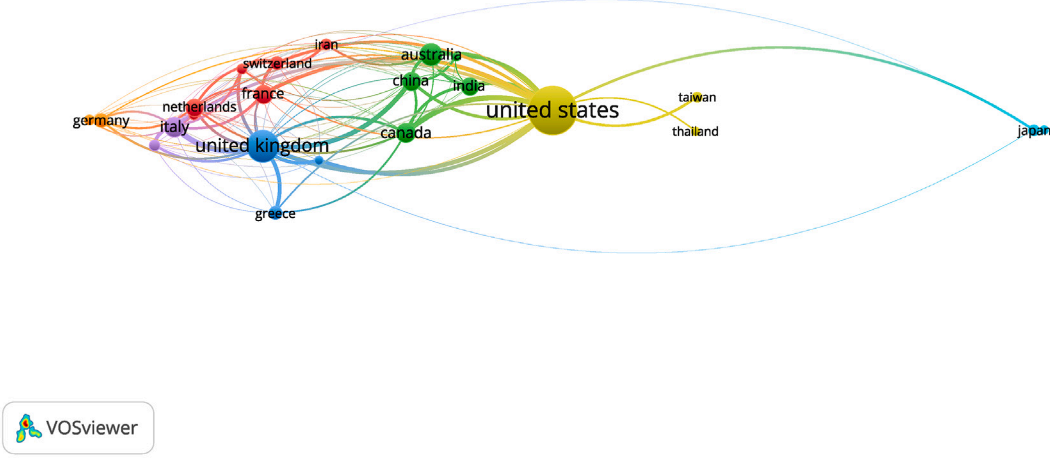
(b) Bibliographic coupling by country

Fig. 16. Bibliographic coupling of resilience of TIS.

Finally, in Fig. 19(a) the bibliographic coupling by authors in research on the sustainability of TIS under flood exposure is presented. However, only six authors have more than two publications in this search. Thus, the map does not represent all the expert communities but indicates that research on this topic is quite fragmented and comes from diverse research hubs. This is also evidenced in the bibliographic coupling by country (Fig. 19(b)), where many countries are disconnected.



(a) Bibliographic coupling by author



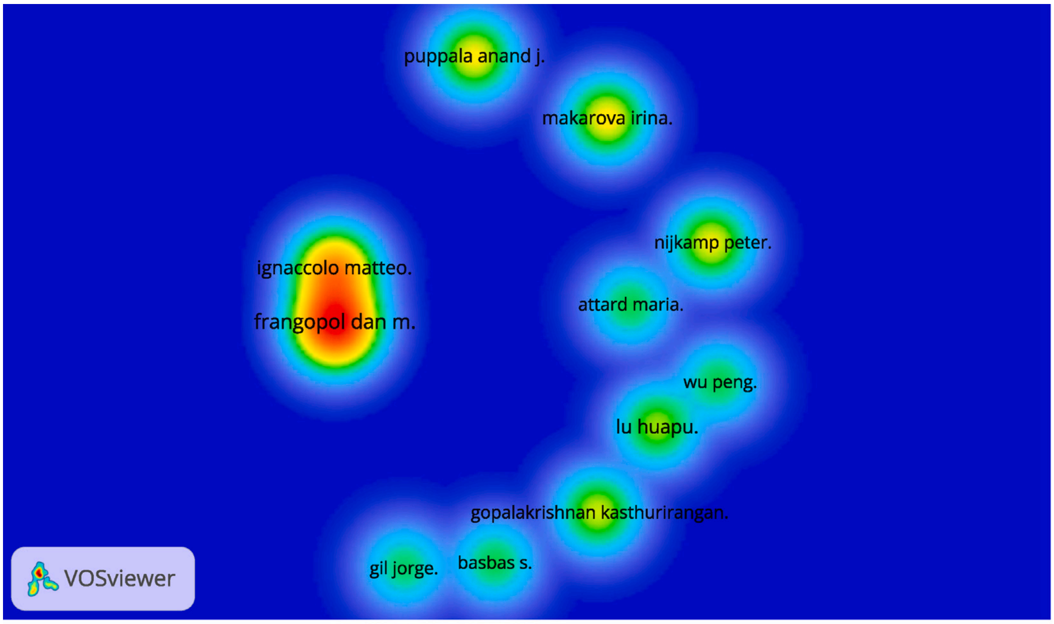
(b) Bibliographic coupling by country

Fig. 17. Bibliographic coupling of resilience of TIS under flood events.

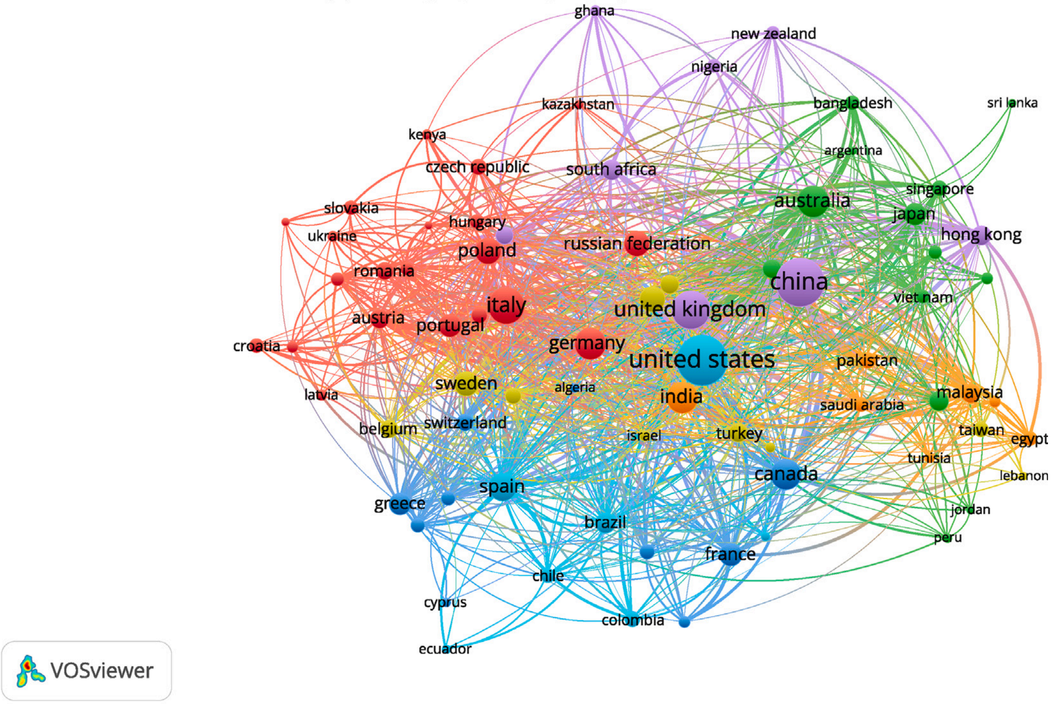
4. Discussion

Through 24 bibliometric network maps, Section 3 illustrates the different disciplines, important authors, and geographic distribution in the production of research in risk, resilience, and sustainability management of TIS. Overall, the top three research domains contributing to knowledge in risk, resilience, and sustainability management of TIS are civil/reliability engineering, transportation engineering, and policy/governance. In addition, the analysis of geographic distribution shows that the USA and China are the two major contributors to research in most of the search queries. This observation is predictable considering the larger number of researchers in these countries due to their large populations and large extents. However, countries that are more affected by floods contribute significantly to research in flood-specific search queries. This can be attributed to increased interest and government funding for research and development (R&D) aimed at understanding the risks and better preparing for these events.

One of the key problems identified in the bibliometric networks relates to the effect of the scale of the system representation. Basically, there is a substantial distance between clusters focused on research at the asset/bridge level to those focused on research at the network level, as shown in Fig. 7–Fig. 9. This distance suggests that there is a weak relatedness among asset- and network-level research. This effect is even more pronounced in Fig. 7(b), which evidences a potential gap in integrating flood risk and vulnerability research at the component and bridge level stemming from the civil/reliability engineering community, with research at



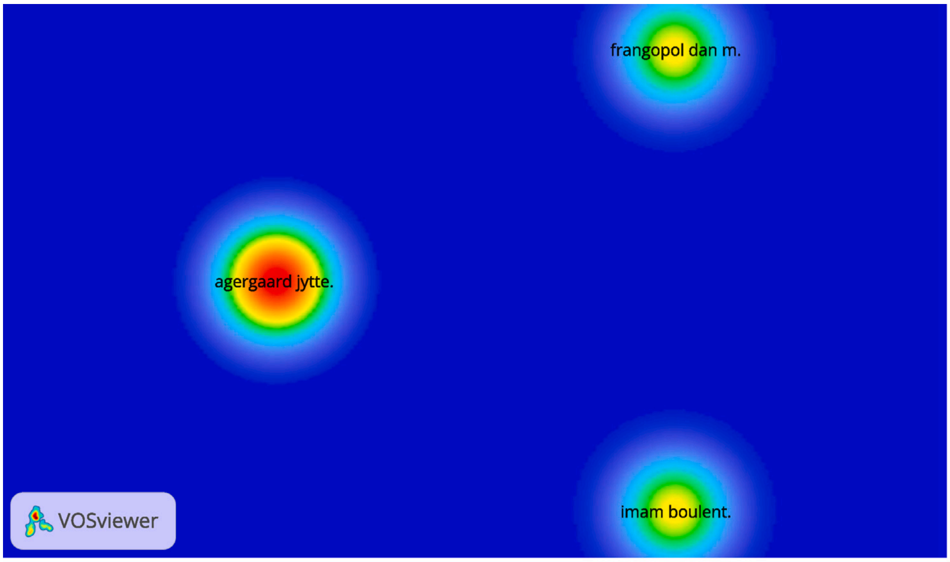
(a) Bibliographic coupling by author



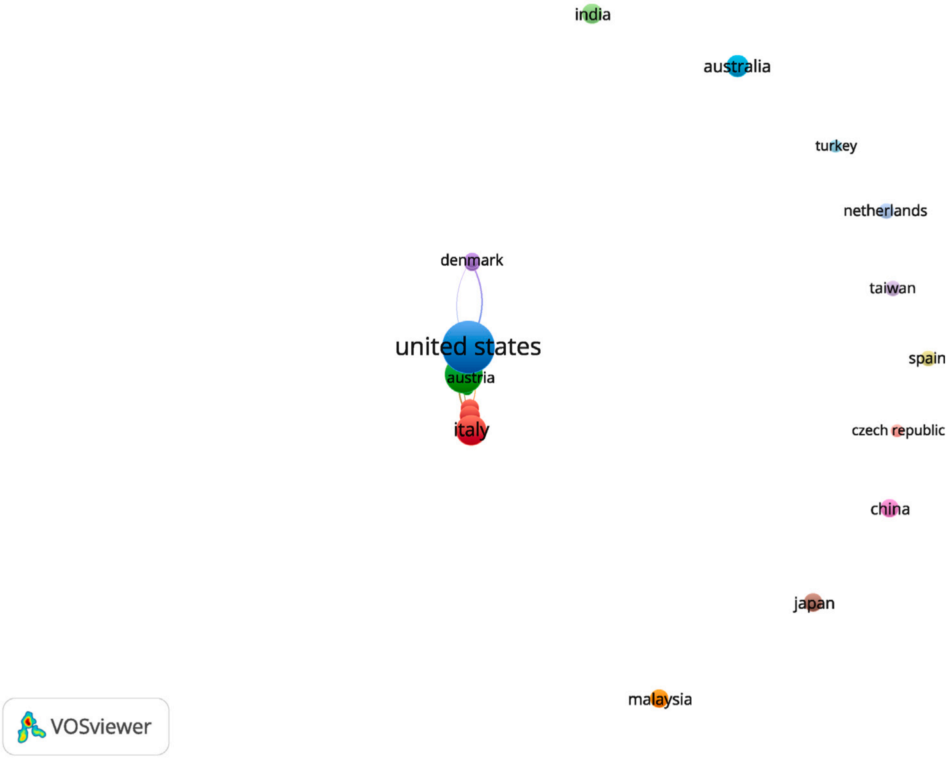
(b) Bibliographic coupling by country

Fig. 18. Bibliographic coupling of sustainability of TIS.

the network/regional level coming from the transportation engineering community and the natural hazards domain. Future research developments should focus on bridging this gap related to the spatial scale of the systems modeling and how it affects optimal decision-making across scales. Likewise, it would be relevant to examine how the temporal scale defined for the decision context influences the choices. For example, in the vulnerability and risk network maps (Fig. 7), it can be seen that the civil/reliability engineering cluster includes considerations of the long-term performance of bridges (e.g., deterioration, erosion). In contrast, the resilience network maps (Fig. 9) show a short-term view of the time scale, as the focus is on tactical management, i.e., ensuring



(a) Bibliographic coupling by author



(b) Bibliographic coupling by country

Fig. 19. Bibliographic coupling of sustainability of TIS under flood events.

optimal recovery and restoration in the aftermath of disaster events, without considering a long-term perspective. Conversely, the sustainability network map again shows some consideration of the long-term performance of bridges (Fig. 10(a)), which is to be expected since sustainability in civil engineering has been assessed through a life-cycle perspective. These differences between the spatial and temporal boundaries of the system for addressing each concept may contribute to the apparent lack of integration of risk, resilience, and sustainability considerations for managing TIS. One observation that reflects this fragmentation is the substantial drop in the number of records in sustainability research when flood exposure is added (Fig. 5(b)). This is interpreted as a lack of consideration of infrastructure safety – with respect to disruptive events such as natural hazards and the associated risks – in decisions concerning the sustainable development of TIS. This separation is also evidenced in Fig. 7, where sustainability is an absent term in the network maps of research on risk and vulnerability of TIS. This lack of integration of risk, resilience, and sustainability from the engineering knowledge domain is also reflected in other disciplines taking the lead in the production of research. For instance, environmental science has been the greatest contributor to sustainability research of TIS under flood exposure (see Fig. 6(d)). Moreover, it can be observed that the policy/governance research domain is the one attempting to integrate sustainability objectives in resilience research (Fig. 9(a)), by including considerations of resource consumption of energy and water. However, the development and maintenance of TIS also have relevant impositions on the Earth system with regard to *material* consumption for construction and *emissions* of toxic substances to the environment (e.g., CO_2). None of these terms are found in the network map, which suggests that decisions about how to improve resilience are not comprehensively addressing their (positive or negative) impact on sustainability. Furthermore, the impositions to the environment generate a back-coupling between the exposures and the decisions to manage the infrastructure systems. In other words, since the management of TIS is associated with GHG emissions triggering climate change, the exposure to extreme weather events will change depending on the scenario of GHG emissions in accordance with our decisions to develop and maintain our infrastructures. Therefore, future research developments should explore further these interrelations, which enable making decisions that are safe, resilient, and sustainable.

Another issue that is observed in the bibliometric networks is the existence of multiple competing concept definitions. This is the case with the concept of robustness as observed in Fig. 8. Essentially, the red cluster represents the systemic perspective where robustness is defined as the link between direct and indirect consequences (see Section 2.1.2), and the system is perfectly robust if consequences stop at direct consequences. On the other hand, in the blue cluster corresponding to classical structural engineering, robustness is the ability of a structure to withstand extreme events without being damaged to an extent disproportionate to the original cause [57]. This definition does not provide a specific measure of robustness and does not relate to other system characteristics, such as vulnerability and risk. Likewise, in the green cluster representing transportation engineering, robustness is defined from a design optimization perspective, where a robust solution is the one that has the best performance/accuracy. It is evident that this inhomogeneity in concept definitions hinders communication among scientific experts from different research clusters. It also may explain why robustness research is so marginal compared to the other system characteristics individually, as shown in Fig. 5. To address this issue, future research could focus on harmonizing concept definitions, thereby potentially promoting collaboration between experts from various disciplines. Similarly, this inhomogeneity issue is exhibited in the network maps of research in the domain of resilience of TIS, where multiple competing indicators and functionality metrics to measure resilience are found in each cluster. Essentially, the transportation engineering cluster in Fig. 9(a) employs various metrics related to the functionality or service provided by the transportation network for the quantification of resilience. Some of the metrics found, such as connectivity, are usually measured through graph theory and represent topological features of a transportation network, while other functionality metrics found, such as travel time, traffic flow, and congestion index, are traffic-related and measure properties related to traffic flow and system capacity in addition to topological aspects. On the other hand, the policy/governance cluster employs resilience metrics more targeted to capture socioeconomic impacts from transportation service disruptions affecting the population, e.g., loss of mobility, accessibility, availability, security, and economy. Given that both perspectives are essential for quantifying resilience, future research is needed to harmonize resilience metrics across disciplines. Likewise, they should be harmonized for all types of hazards, as it can be observed in Fig. 9(b) that resilience metrics under flood exposure are less exhaustive and vary from those in Fig. 9(a).

Finally, some relevant aspects were lacking in the network maps concerning the treatment of uncertainties (Fig. 11(a)), which only has a role in the civil/reliability engineering cluster. Likewise, dependence related to Knowledge, as described in Section 2.1.2, only has a role in the resilience engineering cluster. This can be interpreted as a knowledge transfer need since the engineering community has the available knowledge which can be extended to other research communities. Similarly, available knowledge that has been identified within the earthquake engineering community regarding the concept of fragility curves for vulnerability and risk assessment of TIS (observed in Fig. 7(a)) can be transferred to characterize the performance of transport infrastructures under flooding events.

5. Conclusions

Research on risk, resilience, and sustainability of transportation infrastructure systems has gained attention in recent decades as the demand for efficient and reliable TIS to promote economic growth, social welfare, and environmental sustainability has increased. However, this goal is associated with many challenges that are addressed by different disciplines as the scope of TIS has broadened from a purely technical system perspective to a social–technical system perspective. In this sense, understanding what the research field encompasses and what potential gaps exist is critical to identifying research and knowledge transfer needs.

To this end, an exploratory study using bibliometric networks has been used to understand the current state of the art in the management of TIS, with a focus on flood hazards. For the purpose of providing the basis for searching for relevant information, a generic and comprehensive system identification of TIS was outlined. This set the baseline for conducting the bibliometric analysis of 16,395 scientific works covering more than 30 years of research. The analysis showed that research in all system characteristics of TIS had seen a consistent upward trend, with research in vulnerability and risk having the longest history and largest volume of publications, followed by sustainability, resilience, and lastly, robustness, which has received little attention. In the context of flood exposure, the trend is similar, except that resilience gains importance over sustainability. Based on the assessment of the term co-occurrence network maps, it has been identified that the top three main disciplines contributing to the research domain are civil/reliability engineering, transportation engineering, and policy/governance. In addition, the examination of the bibliographic coupling networks of countries revealed that the USA and China are the two major contributors to the research domain. Nonetheless, the UK, Italy, France, Australia, and Germany, become significant contributors within the context of flood exposure, which can be attributed to the fact that they have been greatly affected by floods in the past years, which has motivated growing research in this area.

Furthermore, the study identified potential research gaps through the interpretation of the bibliometric networks. One of them relates to the spatial scale of the system modeling, which has created a separation between asset- and network-level research. This effect is evidenced both in the term co-occurrence networks as well as in the bibliographic coupling of authors, where the distances among clusters represent a weak relatedness and lack of collaboration among them. Therefore, future research developments should aim at bridging this gap to ensure optimal decision-making of TIS across scales. Nonetheless, a prerequisite to promoting collaboration among these research clusters is to have a common understanding of the different concept definitions. However, it was found in several bibliometric networks that there exists inhomogeneity in concepts, as well as a large variety of indicators and metrics used by each discipline. Therefore, harmonization of concept definitions across various disciplines is also needed to enhance collaboration among them, together with an agreement on a set of indicators and metrics that could be adequate regardless of the scale of the system and the hazard under analysis. Another research gap that should receive more attention concerns the fragmentation of risk, resilience, and sustainability research for the management of TIS. Based on the analysis of the network maps, this lack of integration could be attributed to differences in how the spatial and temporal boundaries of the system are typically defined to address each concept individually. However, the three concepts are strongly linked, and there are relevant trade-offs that should be considered when managing TIS. For instance, considering the impacts of different decision alternatives with regard to sustainability facilitates that decisions with less environmental impacts, e.g., improving the preparedness of the governance system and the capacity to recover, are preferred over alternatives imposing material consumption and emissions to the environment. Therefore, it is necessary that future research developments focus attention on the trade-offs between acceptable risks, target levels of resilience, and sustainable developments, as well as the back-coupling effects between our decisions to manage the infrastructure systems and their effect on the exposures. Finally, a need for knowledge transfer has been identified from the reliability engineering knowledge domain to other disciplines with respect to the treatment of uncertainties. Essentially, resilience and sustainability of infrastructure systems can only be meaningfully approached and modeled probabilistically, like risk and robustness, given the lack of knowledge and inherent natural variability. However, there appears to be insufficient consideration of uncertainty treatment in some research domains — especially in those analyzing the system at a large spatial scale. Thus, reliability engineering knowledge could be introduced to these navigation domains for appropriately representing and treating all uncertainties consistently across spatial and temporal scales. Likewise, insights from earthquake engineering concerning the development of fragility curves for vulnerability and risk assessment of TIS can be applied to assess transport infrastructure performance during floods.

It should be noted that the methodology implemented in this study to map the current state of the art in the management of TIS was based on a bibliometric analysis that enables identifying where the main research streams are. This does not exclude that there may be scientific literature looking at some of the specific gaps identified in this analysis. Yet, the main goal was to provide a big picture of where the majority of research activities are concentrated. The study presents some limitations due to the selection of search terms, which were the result of the system identification followed by several trials to ensure that the obtained datasets contained relevant studies for the intended analysis. In the process, some context areas were excluded to avoid unrelated articles, but this may have led to the exclusion of actually related ones. Moreover, the inclusion of additional databases may improve the coverage of scientific literature. Still, it was herein deemed unnecessary since the database with the greater publication coverage for the research domain under study was chosen. Future work could include other types of infrastructure systems in the bibliometric analysis, such as water distribution systems and/or electricity/power systems, as a way to further investigate the potential for introducing approaches from different research navigation domains and the interdependencies among infrastructure systems.

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.

Acknowledgments

This work was partly financed by FCT/MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/04029/2020, and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under reference LA/P/0112/2020. This work is financed by national funds through FCT — Foundation for Science and Technology, under grant agreement SFRH/BD/144749/2019 attributed to the first author.

Appendix

See Tables A.1–A.7.

Table A.1
Full search query of Group 1: Transport Infrastructure Systems (TIS).

Component level	“bridge pier“ OR “bridge pile” OR “bridge foundation“ OR “bridge abutment” OR “bridge deck“ OR “bridge component” OR...
Asset level	“bridge *structur*“ OR road* W/1 bridge OR “rail* bridge”OR“highway bridge”OR“coastal bridge“OR“river* bridge”OR“waterway bridge“ OR “river crossing bridge” OR “culvert” OR “transport* asset“ OR “transport* *structure” OR “road* *structure“ OR “road* segment” OR...
Network level	“road* network“ OR “bridge network” OR “highway network" OR...
	“transport* network“ AND (“road*” OR “rail*” OR “bridge“ OR “urban” OR “highway“ OR “infrastructure”)[a] OR...
	“transport* system“ AND (“road*” OR “rail*” OR “bridge“ OR “urban” OR “highway“ OR “infrastructure”)[a] OR...
	“traffic network“ AND (“road*” OR “rail*” OR “bridge“ OR “urban” OR “highway")[a] OR...
	“traffic system“ AND (“road*” OR “rail*” OR “bridge“ OR “urban” OR “highway")[b] OR. . .
	“infrastructure system“ AND (“road*” OR “rail*” OR “bridge“ OR “highway” OR “transport*“ OR “traffic”)[b] OR. . .
	“infrastructure network“ AND (“road*” OR “rail*” OR “bridge“ OR “highway” OR “transport*“ OR “traffic”)[b]

[a] Search query after AND gives context to transportation systems and infrastructure that enables the traveling of people and goods (transport/traffic systems and traffic networks are sometimes used in different context areas).

[b] Search query after AND gives context to transportation.

Table A.2
Search query combinations.

Search query		Results
n_0	TIS	118,105
n_1	TIS AND (“vulnerability“ OR “risk”)	8,282
n_2	TIS AND “robustness"	1,236
n_3	TIS AND “resilien*"	1,613
n_4	TIS AND “sustainab*"	6,779
n_{OR}	TIS AND (“vulnerability“ OR “risk” OR “robustness“ OR “resilien*” OR “sustainab*")	16,395
n_5	TIS AND (“vulnerability“ OR “risk”) AND (“flood*“ OR “scour*”)	921
n_6	TIS AND “robustness“ AND (“flood*” OR “scour*")	37
n_7	TIS AND “resilien*“ AND (“flood*” OR “scour*")	247
n_8	TIS AND ‘sustainab*“ AND (“flood*” OR “scour*")	132
n_9	TIS AND (“vulnerability“ OR “risk” OR “robustness“ OR “resilien*” OR “sustainab*“) AND “uncertain*”	1028
n_{10}	TIS AND (“vulnerability“ OR “risk” OR “robustness“ OR “resilien*” OR “sustainab*“) AND “*dependenc*”	592
n_{11}	TIS AND n_{OR} AND (“governance“ OR “manag*” OR “decision“) AND (“preference” OR “attribute” OR “criteri*")	702

Table A.3
Scopus subject areas excluded from the search.

Health sciences	Life sciences
Medicine(MEDI)	Biochemistry, Genetics and Molecular Biology (BIOC)
Nursing (NURS)	Immunology and Microbiology (IMMU)
Veterinary (VETE)	Neuroscience (NEUR)
Dentistry (DENT)	Pharmacology, Toxicology and Pharmaceutics (PHAR)
Health Professions (HEAL)	Chemistry (CHEM) (Physical Sciences)

Table A.4
Context areas excluded from the search.

Research context	Keywords to exclude in search query
Computer networking and communication	vehic* ad hoc networks (vanets) broadcast transmission flood*
Traffic signal systems	signal control* traffic control* traffic signal
Connected, automated and electric vehicles	autonomous W/2 vehicle autonomous W/2 buses “platoon*” “recharg*” or “charg*” or “batter*”
Location Privacy and Security	“mobile users” “map matching”
Space transportation systems	“moon” or “mars” or “lunar”

Table A.5
Non-context-specific terms excluded from visualizations.

knowledge
account
improvement
perspective
addition
face
example
chapter
characteristic
need
investigation
literature
kind
methodology
wide range
question
advantage
requirement
problem
basis
focus
order
lack
point
research(er)
overview
need
study area
characterization
implementation
comparison
article
view
difference
consideration
form
estimation
application
end
review
recent year
hand
context
understanding
attention
author
case study
presence
effort
gap
(important) role
type
limitation
feature
regard
set
variety
factor
cause
challenge
concept
concern
goal
good
insight
issue
new method
principal
set
use
variation
way

Table A.6
VOSviewer specifications for term co-occurrence analysis networks.

Search query	n_1	n_2	n_3	n_4	n_5	n_7	n_8	n_9	n_{10}	n_{11}
Total number of records	8282	1236	1613	6779	921	247	132	1028	592	702
Binary count	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Min. no. of occurrences of a term[a]	170	23	37	150	25	8	5	23	15	18
No. of terms	170	174	171	169	175	170	148	170	177	168
% of relevant terms[b]	71%	69%	70%	71%	69%	71%	68%	71%	68%	71%
Final no. of terms selected	120	120	120	120	120	120	100	120	120	120
No. of clusters	4	3	3	3	3	3	4	4	3	3
No. of links	7064	6256	6506	7135	5232	4316	2788	6136	5973	6164
Total link strength	309949	49606	48598	413514	45836	8958	4862	42480	29648	29909

[a] The minimum number of occurrences of a term is adjusted aiming to obtain medium size network visualizations of 120 terms.

[b] Percentage of terms to be selected based on their relevance score (set to exclude around 30% of terms with low relevance score).

Table A.7
VOSviewer specifications for bibliographic coupling analysis networks.

Search query	n_1	n_2	n_3	n_4	n_5	n_7	n_8
Total no. of records	8282	1236	1613	6779	921	247	132
Fractional counting	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Min. no. documents per author	10	5	6	8	5	3	2
No. of authors	32	11	31	24	18	29	8
Min. no. documents per country	10	5	5	10	5	3	3
No. of countries	69	34	47	76	44	23	22

References

[1] M. Roberts, T. Bougna, M. Melecky, Y. Xu, Transport corridors and their wider economic benefits: A critical review of the literature, World Bank Policy Res. Work. Pap. 1 (8302) (2018).

[2] J. Rozenberg, M. Fay, Beyond the Gap: How Countries Can Afford the Infrastructure They Need While Protecting the Planet, World Bank Publications, 2019.

[3] E.E. Koks, J. Rozenberg, C. Zorn, M. Tariverdi, M. Vousdoukas, S. Fraser, J. Hall, S. Hallegatte, A global multi-hazard risk analysis of road and railway infrastructure assets, Nat. Commun. 10 (1) (2019) 1–11.

[4] S. Hallegatte, J. Rentschler, J. Rozenberg, Lifelines: The Resilient Infrastructure Opportunity, World Bank Publications, 2019.

[5] S. Seneviratne, X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A.D. Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S. Vicente-Serrano, M. Wehner, B. Zhou, Weather and climate extreme events in a changing climate, in: V. Masson-Delmotte, P. Zhai, A. Pirani, et al. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2021, pp. 1513 – 1766.

[6] World Meteorological Association, et al., WMO Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970–2019), Technical Report, 2021.

[7] M. Stewart, R.E. Melchers, Probabilistic Risk Assessment of Engineering Systems, Springer, 1997.

[8] M.H. Faber, M.G. Stewart, Risk assessment for civil engineering facilities: Critical overview and discussion, Reliab. Eng. Syst. Saf. 80 (2) (2003) 173–184.

[9] ISO, ISO 31010:2009; risk management — Risk assessment techniques, 2009.

[10] ISO, ISO 13824:2009; bases for design of structures — General principles on risk assessment of systems involving structures, 2009.

[11] I. Kilanitis, A. Sextos, Integrated seismic risk and resilience assessment of roadway networks in earthquake prone areas, Bull. Earthq. Eng. 17 (1) (2019) 181–210.

[12] J. Hackl, J.C. Lam, M. Heitzler, B.T. Adey, L. Hurni, Estimating network related risks: A methodology and an application in the transport sector, Nat. Hazards Earth Syst. Sci. 18 (8) (2018) 2273–2293.

[13] M.M. Messore, L. Capacci, F. Biondini, Life-cycle cost-based risk assessment of aging bridge networks, Struct. Infrastruct. Eng. 17 (4) (2020) 515–533.

[14] P. Gardoni, C. Murphy, Society-based design: promoting societal well-being by designing sustainable and resilient infrastructure, Sustain. Resil. Infrastruct. 5 (1–2) (2020) 4–19, http://dx.doi.org/10.1080/23789689.2018.1448667.
[15] C.S. Holling, Resilience and stability of ecological systems, Annu. Rev. Ecol. Syst. 4 (1) (1973) 1–23.
[16] M.H. Faber, S. Miraglia, J. Qin, M.G. Stewart, Bridging resilience and sustainability-decision analysis for design and management of infrastructure systems, Sustain. Resil. Infrastruct. 5 (1–2) (2020) 102–124.
[17] W. Sun, P. Bocchini, B.D. Davison, Resilience metrics and measurement methods for transportation infrastructure: The state of the art, Sustain. Resil. Infrastruct. 5 (3) (2020) 168–199, http://dx.doi.org/10.1080/23789689.2018.1448663.
[18] L. Capacci, F. Biondini, D.M. Frangopol, Resilience of aging structures and infrastructure systems with emphasis on seismic resilience of bridges and road networks, Resil. Cities Struct. 1 (2) (2022) 23–41.
[19] S.A. Argyroudis, Resilience metrics for transport networks: A review and practical examples for bridges, in: Proceedings of the Institution of Civil Engineers-Bridge Engineering, Thomas Telford Ltd, 2022, pp. 1–14.
[20] S. Pan, H. Yan, J. He, Z. He, Vulnerability and resilience of transportation systems: A recent literature review, Physica A 581 (2021) 126235.
[21] M. Nogal, A. O'Connor, Resilience assessment of transportation networks, in: Routledge Handbook of Sustainable and Resilient Infrastructure, Routledge, 2018, pp. 199–215.
[22] M. Bruneau, S.E. Chang, R.T. Eguchi, G.C. Lee, T.D. O'Rourke, A.M. Reinhorn, M. Shinozuka, K. Tierney, W.A. Wallace, D. Von Winterfeldt, A framework to quantitatively assess and enhance the seismic resilience of communities, Earthq. Spectra 19 (4) (2003) 733–752.
[23] B.M. Ayyub, Systems resilience for multihazard environments: Definition, metrics, and valuation for decision making, Risk Anal. 34 (2) (2014) 340–355.
[24] N. Sharma, A. Tabandeh, P. Gardoni, Resilience analysis: A mathematical formulation to model resilience of engineering systems, Sustain. Resil. Infrastruct. 3 (2) (2018) 49–67.
[25] A. Alipour, B. Shafei, Seismic resilience of transportation networks with deteriorating components, J. Struct. Eng. 142 (8) (2016) C4015015.
[26] I. Kilanitis, A. Sextos, Impact of earthquake-induced bridge damage and time evolving traffic demand on the road network resilience, J. Traffic Transp. Eng. (English Edition) 6 (1) (2019) 35–48.
[27] P. Bocchini, D.M. Frangopol, Restoration of bridge networks after an earthquake: Multicriteria intervention optimization, Earthq. Spectra 28 (2) (2012) 427–455.
[28] E.D. Vugrin, M.A. Turnquist, N.J. Brown, Optimal recovery sequencing for enhanced resilience and service restoration in transportation networks, Int. J. Crit. Infrastruct. 10 (3–4) (2014) 218–246.
[29] Y. Liu, S. McNeil, J. Hackl, B.T. Adey, Prioritizing transportation network recovery using a resilience measure, Sustain. Resil. Infrastruct. 7 (1) (2022) 70–81.
[30] M.H. Faber, J. Qin, S. Miraglia, S. Thöns, On the probabilistic characterization of robustness and resilience, Procedia Eng. 198 (2017) 1070–1083.
[31] M.H. Faber, On Sustainability and Resilience of Engineered Systems, Routledge Abingdon, 2018.
[32] W. Saunders, J. Becker, A discussion of resilience and sustainability: Land use planning recovery from the canterbury earthquake sequence, New Zealand, Int. J. Disaster Risk Reduct. 14 (2015) 73–81.
[33] Z. Lounis, T.P. McAllister, Risk-based decision making for sustainable and resilient infrastructure systems, J. Struct. Eng. 142 (9) (2016) F4016005.
[34] P. Gardoni, Routledge Handbook of Sustainable and Resilient Infrastructure, Routledge, 2018.
[35] JCSS, Risk assessment in engineering—Principles, system representation & risk criteria, Joint Committee Struct. Saf. (2008).
[36] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, W.M. Lim, How to conduct a bibliometric analysis: An overview and guidelines, J. Bus. Res. 133 (2021) 285–296.
[37] L. Nielsen, M.H. Faber, Impacts of sustainability and resilience research on risk governance, management and education, Sustain. Resil. Infrastruct. 6 (6) (2021) 339–384, http://dx.doi.org/10.1080/23789689.2019.1611056.
[38] M.H. Faber, M.A. Maes, J.W. Baker, T. Vrouwenvelder, T. Takada, Principles of risk assessment of engineered systems, in: 10th International Conference on Application of Statistic and Probability in Civil Engineering, ICASP10, 2007, pp. 1–8.
[39] M.H. Faber, Risk informed structural systems integrity management: A decision analytical perspective, in: International Conference on Offshore Mechanics and Arctic Engineering, vol. 57779, American Society of Mechanical Engineers, 2017, V009T12A040.
[40] M. Faber, Codified risk informed decision making for structures, in: Symposium on Reliability of Engineering System, SRES2015, Hangzou, China, 2015, pp. 15–17.
[41] Z.I. Turksezer, M.P. Limongelli, M.H. Faber, On a generic framework for systems resilience modelling of bridges - Accounting for historic and cultural values, Sustain. Resil. Infrastruct. 7 (5) (2022) 366–379, http://dx.doi.org/10.1080/23789689.2020.1859272.
[42] L. Nielsen, S.T. Glavind, J. Qin, M.H. Faber, Faith and fakes – dealing with critical information in decision analysis, Civ. Eng. Environ. Syst. 36 (1) (2019) 32–54, http://dx.doi.org/10.1080/10286608.2019.1615476.
[43] D. Straub, Lecture notes in engineering risk analysis, 2018.
[44] Y.Y. Bayraktarli, M.H. Faber, Bayesian probabilistic network approach for managing earthquake risks of cities, Georisk 5 (1) (2011) 2–24.
[45] O. Morgenstern, J. Von Neumann, Theory of Games and Economic Behavior, Princeton University Press, 1953.
[46] R. Schlaifer, H. Raiffa, Applied Statistical Decision Theory, MIT Press, 1961.
[47] N. Zhang, A. Alipour, Multi-scale robustness model for highway networks under flood events, Transp Res. Part D: Transp. Environ. 83 (2020) 102281.
[48] N. Zhang, A. Alipour, A multi-step assessment framework for optimization of flood mitigation strategies in transportation networks, Int. J. Disaster Risk Reduct. 63 (2021) 102439.
[49] W.H. Lam, H. Shao, A. Sumalee, Modeling impacts of adverse weather conditions on a road network with uncertainties in demand and supply, Transp. Res. Part B: Methodol. 42 (10) (2008) 890–910.
[50] S. Argyroudis, J. Selva, P. Gehl, K. Pitilakis, Systemic seismic risk assessment of road networks considering interactions with the built environment, Comput.-Aided Civ. Infrastruct. Eng. 30 (7) (2015) 524–540.
[51] P. Gehl, D. D'ayala, System loss assessment of bridge networks accounting for multi-hazard interactions, Struct. Infrastruct. Eng. 14 (10) (2018) 1355–1371.
[52] M. Nogal, A. O'Connor, B. Caulfield, B. Martinez-Pastor, Resilience of traffic networks: From perturbation to recovery via a dynamic restricted equilibrium model, Reliab. Eng. Syst. Saf. 156 (2016) 84–96.
[53] N.J. van Eck, L. Waltman, Vosviewer manual version 1.6.17, 2021.
[54] N.J.V. Eck, L. Waltman, Visualizing bibliometric networks, in: Measuring Scholarly Impact, Springer, 2014, pp. 285–320.
[55] L. Waltman, N.J. Van Eck, E.C. Noyons, A unified approach to mapping and clustering of bibliometric networks, J. Informetrics 4 (4) (2010) 629–635.
[56] L. Waltman, N.J. Van Eck, A smart local moving algorithm for large-scale modularity-based community detection, Eur. Phys. J. B 86 (11) (2013) 1–14.
[57] CEN, Eurocode 1: Actions on structures; part 1-7: General action - accidental action, 2003, European Committee for Standardization.