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Review

Indicator-based resilience assessment for critical infrastructures – A review

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ABSTRACT

A Safety Science focus on research in the science and technology of human and industrial safety. Critical Infrastructures (CIs), as a crucial part of urban technological systems, are highly correlated with urban safety management in terms of their resilience when cities are facing a crisis or disaster. According to many studies, indicator-based resilience assessment has been used frequently to manage CIs in recent decades. Defining and characterising indicators can be useful for managers of human and industrial safety, as it could help monitor and improve the capacities and performance of CIs.

In recent years, critical infrastructures (CIs) have been damaged with increasing frequency (and will be so in the future) following natural or technological disasters. CIs, such as buildings, transportation networks and power systems, play an indispensable role in our society due to their importance for maintaining critical societal functions, economic organisation and national defence. Therefore, the popularity of "critical infrastructure resilience" has exploded in both academic and policy discourses. Indicator-based assessment is a convenient and common tool to help understand, analyse and improve CI resilience in the scientific field. This paper produces a state-of-the-art review of the existing indicator-based assessment of CI resilience. After a terminology presentation, which helps clarify the objective of this study, this paper will show: 1) two methods for selecting the current scientific papers applying indicators to assess CI resilience; and 2) analysis of the indicators in these papers based on the study objective. The results show that there are many indicators and they do not have a uniform standard system, which means an indicator system for CI resilience assessment must be established.

1. Introduction

On 28 February 2022, the Intergovernmental Panel on Climate Change (IPCC) of the United Nations published a new report, Climate Change 2022: Impacts, Adaptation and Vulnerability Pörtner et al. 2022, aiming to assess the impacts of climate change, by looking at ecosystems, biodiversity, and human communities at global and regional levels. This report sets forth that most global territories are facing increasing adverse impacts of climate change on infrastructures and suggests integrated action for climate resilience to avoid natural disasters, including planning and investment in urban infrastructure. Meanwhile, the planet is also confronted with a growing number and magnitude of technological and technical disasters worldwide. For example, on 4 August 2020, an explosion in the main port in Beirut because of poor management of stored products, resulted in damage to many local infrastructures. In particular, three of Beirut's hospitals were wrecked by the blast Dyer, 2020, and two others were damaged, which added to the performance disruption of hospital infrastructures already facing the COVID-19 crisis. Infrastructures, especially critical infrastructures (CIs), including buildings, roads, schools, and hospitals, play a central role in modern city management when facing both technological and natural disasters. Therefore, in recent years, the popularity of "CI resilience" has exploded in both academic and policy discourses. The implemented actions for improving CIs based on

Abbreviations: CI(s), Critical Infrastructure(s); PrES, pre-event stage; DES, during event stage; PoES, post-event stage; NEPS, next event preparation stage.

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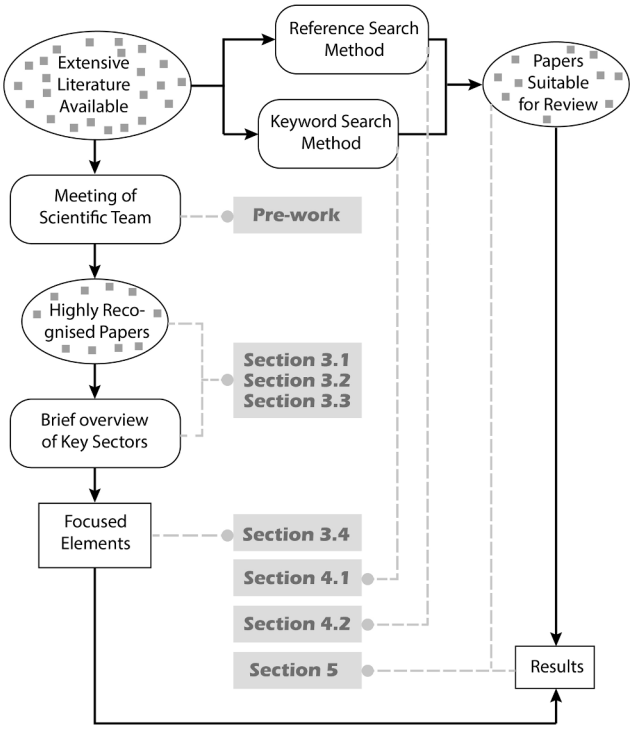


Fig. 1. Structure of this study.

resilience assessment help reduce cities' vulnerability.

Resilience can be defined as the ability to absorb and adapt to a changing environment ISO, 2021. However, as the term "resilience" is broadly used in different contexts, it relates to various aspects, such as the capacity to manage with connected systems, to gracefully degrade and to improve the ability to cope with future risks Woods, 2019; Wied et al., 2020; Yang et al., (2022-a).. The United Nations United Nations, 2016; United Nations, 2020) increasingly recognises the importance of city resilience in facing a crisis or disaster.

Recently, resilience assessment has become a key component of disaster management since it is a wildly accepted process that is used to understand the functionality and performance of a complex system exposed to disasters CORDIS-IMPROVER Project, 2016. "Resilience" is an abstract concept, and resilience assessment is a process for knowing its value or level by applying appropriate steps Tang, 2019. The approaches built for CI resilience assessment are frequently based on indicators (Hosseini, 2016; CORDIS-Smart Resilience Indicators for Smart Critical Infrastructures, 2018; Yang et al., (2022-a.). Indicator, being a less abstract concept than resilience, can be used to show positive or negative changes in resilience. Therefore, the indicator-based resilience assessment could help stakeholders to analyse CIs on a practical and situational basis and to make efficient decisions. The identification of indicators is considered key before assessing resilience. Indicators are based on basic data or accounts that are produced under strict quality assurance Eurostat, 2014. One other challenge of resilience assessment is therefore to transform data into actionable knowledge by the means of indicators Vogel and Canada, (1997); CORDIS-Smart Resilience Indicators for Smart Critical Infrastructures, 2018.

Until recently, there were not enough studies to review numerous existing scientific papers that focus on indicator-based assessment for CI resilience, and to analyse them based on indicators. The aim of this article is therefore: to select as much as possible the current scientific papers relevant to the CI resilience indicator; and to analyse the indicator-based resilience assessment in these papers.

2. Methodology and structure

The method used to develop this review consists of two principle steps that build two sections (sections 3 and 4) of this article, with which the reader could find the specific methods concern. In considering the aims of this study, these two steps are used respectively to define the significant elements to be investigated of this study, and to identify suitable scientific papers to be analysed (see Fig. 1). Both two steps are based on current extensive literature available relating to indicators-based assessment for CIs resilience.

As indicators-based resilience assessment is a broadly used method in science and practice, a large number of factors or elements in the current papers are worth noting. To define the valuable elements that this study should investigate in each reviewed paper, the step in section 3 is to give a brief overview of the key sectors involved in reference to highly recognised scientific papers. The selection of these highly recognised papers was based on the knowledge and interview of a dozen authors of this work, all from the relevant sectors. Section 4 shows the process of paper searches. Two methods are presented for identifying useful scientific papers: (1) the common search method through keywords on electronic scientific websites; and (2) the reference search method based on some high-level review papers, thereby addressing some of the weaknesses of Method (1). Section 5 presents the results in tables and graphs. In section 6, the study further analyses the results based on a discussion of the elements identified in section 3.

3. Key sectors and focused elements

The study of CIs resilience has developed rapidly in the last decades and indicator-based assessment has become an important part of it. The scientific team for this study considers the work to involve three sectors: "Critical Infrastructures", "Resilience", and "indicator-based assessment". Moreover, the group has identified numerous highly recognised scientific papers in these three sectors after several exchanges. This section, taking into account these highly recognised papers, gives brief overviews of the common or significant aspects of these three sectors. As a result, based on this information, eight elements were elected to be investigated.

3.1. *Critical infrastructures*

There is no universally accepted standard for the classification of CIs. One of the reasons for this is that internationally there is no commonly accepted definition of CIs. Nevertheless, all definitions emphasise the contributing role of infrastructure to society or the potentially debilitating effect in the case of disruption CIPedia, 2020. For Brown et al. (2006), infrastructures that represent a significant public investment and where even minor disruptions can degrade the performance of systems and cause significant societal damage can be called critical infrastructures. Barroca et al. (2012) consider an infrastructure (i.e., a set of facilities providing services necessary for a city to function), as critical if its malfunctioning threatens the security, economy, lifestyle or public health of a city, region or even a state. For U.S Department of Homeland and Security U.S Department of Homeland and Security (2022), the infrastructure system, "whose incapacity or destruction would have a debilitation impact on the defence and economic security", could be considered critical. The European Commission identifies CIs as those physical and information technology facilities, networks, services and assets that, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of citizens or the effective functioning of governments in European Union countries EUR-Lex, 2010. The disruption of infrastructure would have a serious impact on the well-being, health, and safety of citizens and weaken the whole defence and economic organisation Rinaldi et al. 2001; Serre and Heinzlef, 2018).

According to a review article by Moteff et al. (2003), it is difficult to

Table 1
Sectors of CIs.

N°	Sectors of CIs
1	Agriculture and Food
2	Airport
3	Banking
4	Chemical
5	Commercial Facilities
6	Communications
7	Critical Manufacturing
8	Dams, Emergency Services
9	Defence
10	Drinking Water and Water Treatment
11	Energy
12	Government Facilities
13	Industrial Base
14	Information Technology
15	Materials and Waste
16	National Monuments and Icons
17	Nuclear Reactors
18	Postal and Shipping
19	Public Health and Healthcare
20	Seaport/Harbour
21	Transportation Systems

Source: Proag (2014)

define what types of infrastructure are critical. The sectors of CIs, decided by each country, government or organisation, depends on their contexts and priorities. The Cybersecurity & Infrastructure security Agency of USA Cybersecurity & Infrastructure security Agency of USA (2020) updated 16 sectors of CIs, Chemical, Commercial facilities, Communications, Critical manufacturing, Dams, Defence industrial base, Emergency, Energy, Financial service, Food and agriculture, Government facilities, Healthcare and public health, Information technology, Nuclear reactors, Materials and waste, Transportation systems and Water and wastewater systems. CIs in Canada, called essential infrastructures (infrastructures essentielles), include Energy and Utilities, Information and Communication Technologies, Finance - Health, Food - Water, Transport - Security, Government and ManufacturingSecurité public Canada, (2022) European Commission (2005) divides CIs into 11 sectors: Energy, Information, Communication technologies, Water, Food, Health, Financial, Public & Legal Order and Safety, Civil administration, Transport, Chemical and nuclear industry, Space and research. This study suggests using 21 sectors defined by Proag (2014). Because, according to his study, resilience is considered important in these CI sectors (see Table 1).

3.2. Resilience and CIs resilience

Similarly, the term "resilience" is multidisciplinary and difficult to define because of its very broad use. Etymologically, resilience comes from the Latin, resilio, resilire, which means a return and the ability to resume. Many resilience studies argue that Holling (1973) first introduced the concept for studying ecological science and defined "resilience" as a persistent ability to absorb change and disturbance and still maintain the same state variables. Over time, a series of interpretations of resilience has been presented. As the definition of the term resilience is not the focus of this article, some relevant review studies Manyena, 2006; Meerow et al., 2016; Hosseini et al., 2016; Martin-Breen and Anderies, 2011; Curt et al., 2018; Heinzlef et al. 2022 are suggested here without further discussion. Overall, resilience has little orthodoxy in its conceptualization and application and becomes problematic when trying to measure it Cutter, 2016.

In the field of CIs, resilience has no broadly accepted definition either, but is highly related to engineering or socio-technical science Cutter et al., 2010; Smith and Stirling, 2010; Mottahedi et al., 2021). For infrastructures exposed to disasters and interdependent in modern society, the definition of resilience is extended with multiple aspects and perspectives. Among the various interpretations of resilience, this study favours the one that accords with the highly accepted perspective in the scientific community, focusing on engineering resilience and socio-technical dimension.

3.2.1. Properties and capabilities of CIs

The value or level of CI resilience can be described through the properties (like safety, sustainability, etc.) or capabilities of CIs from the narrower interpretation. Capabilities of a system could be capacities, characteristics, abilities, resources and knowledge Makadok, 2001; Renn, 2008; Hills, 2005; Eriksson and Juhl, 2012; Lindbom et al., 2015). Both property and capability are indeed used frequently for CI resilience. Leveson et al. (2017) focus on the safety of the socio-technical system for resilience assessment. Bruneau et al., (2003) emphasise the importance of five properties (capacity, robustness, redundancy, resourcefulness and rapidity) in engineered systems. Hollnagel (2014) mentions responding, monitoring, learning, anticipating ability,

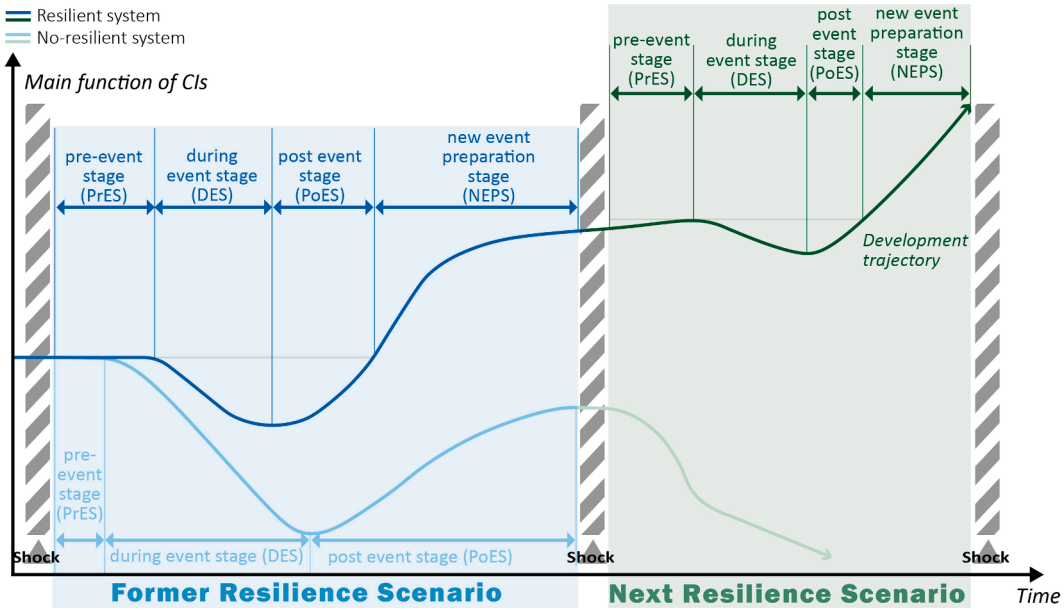


Fig. 2. Stages of resilience scenario, source: Ouyang et al., 2012-a.; Francis and Bekera, 2014; Tendall et al., 2015; Yang et al., 2022-a.; CEREMA, 2020.

sustainability and safety properties, and required knowledge for the resilience of the built environment, including infrastructures. Barroca and Serre Barroca and Serre, (2013)believe that cognitive competence (i.e. having enough knowledge of CI and potential hazards) is one of the most essential aspects for infrastructure resilience. Vulnerability and fragility, highly related to resilience, are two characteristics of CIs that describe the damaging effects of a hazard Proag, 2014; Argyroudis et al., (2019). Furthermore, from an organisational point of view, for CIs exposed to natural hazards, resilience contains characteristics related to mitigation, planning and prior disaster experience Cutter et al., 2010. Ouyang et al. Ouyang et al., (2012-a.)highlight three capacities for urban infrastructures: resistant, absorptive and restorative. Concerning recovery ability, the availability of resources in the CIS system has been usually mentioned (Turniquist and Vugrin, 2013; Ouyang and Wang, 2015).

3.2.2. Temporal stages of resilience scenario

Resilience could also be described through the change in performance or function over time. Therefore the resilience scenario presents with different temporal stages. Based on the existing theories of CI resilience (Ouyang et al., 2012-a. Ouyang et al., 2012-a.; Francis and Bekera, 2014; Tendall et al., 2015; CEREMA, 2020; Yang et al., 2022-a., this study divides the resilience scenario into four stages (see Fig. 2):

- pre-event stage (PrES): from the occurrence of a hazard to the beginning degradation of the function of CIs,
- during event stage (DES): from the beginning of the degradation to the maximum degradation of the function of CIs,
- post-event stage (PoES): from the maximum degradation of the function of CIs to the function returning to the level of the pre-event stage or recovering to an ideal state, structure or property (but still lower than the original state), and
- next event preparation stage (NEPS): from the function returning to the level of the pre-event stage to the occurrence of the next shock on CIs. This stage emphasises the ability of learning and improving from experience.

The NEPS in the former scenario is highly related to the PrES in the next scenario. In addition, it is necessary to emphasise that the ability of improvement may affect different following stages and scenarios. In each scenario, performance should improve at least in one stage compared to previous scenarios, thanks to the ability to learn and improve from experience.

3.2.3. Effects of implemented actions

As Barroca and Serre (2013) argue, a resilient CI should have different aspects of capabilities and involve actions to improve its capabilities. Potential action analysis helps identify decisions that should be taken to reconcile objectives and constraints in the best possible manner Alderson et al. (2015). Many researchers emphasise the benefit of implemented actions in a single scenario. Zhang et al. (2015), Zhang and Wang (2016), Ruas et al. (2018) recognise, for engineering-based systems, the effects of preparedness action at PrES and adaptive response actions at DES to recover efficiently and effectively. Zhang et al. (2015), Sharifi and Yamagata (2016) mention the cost-benefit of actions in discussing action efficiency. Madni and Jackson (2009) consider resilience actions as immediate or short-term actions while adaptation implies long-term learning. The latter highlights that the benefit of implemented action beyond a single scenario corresponds exactly to the improved capacity described above. Meanwhile, due to the interaction of CIs and cities' components, the actions of one CI potentially bring unexpected side effects on itself Leveson et al., 2017; Costella et al., 2009; Hollnagel and Woods; 2017), even on the connected urban components Robert and Hémond, 2012; Serre and Heinzlef, 2018). From the point of view of organisational management, the positive or negative impact of an action is related to issues of efficiency and safety, which determine the degree of satisfaction of the action Atkinson et al., 2006; Tillement et al., 2009; Costella et al., 2009). Therefore, the effects of implementing actions should also be a key aspect during CI resilience assessment.

3.2.4. Interdependence

Recently, more and more CI resilience studies discuss the connections and interdependencies, which are primarily between CIs Rinaldi et al., 2001; Reed et al., 2009; Ouyang and Wang, 2015; Serre, 2016), sometime between CIs and non-technical components in human-environment Bambara et al., 2015; Yang et al., (2022-b).. Human-environment include physical, atmospheric, biological, social, economic and politic components, conditions, and factors which impact the state, condition, and quality of living conditions, employment, and health Academies and of Sciences, Engineering, and Medicine. , (1992) . Nan and Sansavini (2017) assess resilience by taking into account infrastructure interdependence, which can correspond to one infrastructure (internal interdependency) or more infrastructures (external interdependency). Going beyond CI sectors, Markolf et al., 2018 rethink the resilience of the interactions between infrastructures and socio-ecological components. Similarly, Yang et al. (2022-a) believe that a resilient infrastructure should have the ability to manage multiple equilibriums with other urban systems. In modern society, due to the interdependencies of all built environments, the damage of one single CI, like physical disruption or dysfunction, frequently affects other urban components. The resilience of interdependence between infrastructures requires each system to guarantee its functionality when faced with the failure of other systems Serre and Heinzlef, 2018. This trend of CI resilience comes from the awareness of the cascading effects due to interconnected urban components. Increasing hazards require the urban system to cope with potential cascading effects after negative consequences on CIs. Furthermore, from a consequence-based approach, the negative effects caused by used resources should also be taken into account in the analysis of interdependencies Robert and Hémond, 2012. This opinion is equally related to the side effects of implementing the aforementioned actions.

Overall, CI resilience could be described through different properties, capabilities, stages and potential effects (positive, negative, side or cascading) in considering implementing actions and interdependency. The potential that occur after a disaster affects an infrastructure may occur in the same infrastructure or its connected urban components. The scope of urban components is broad, and could be categorised into socio-economic systems, government organisation, nature and energy flow systems, and technical-infrastructural systems Yang et al., 2022-b.. According to some historical events, the origin of catastrophic impacts of CIs (disruption, construction, action, etc.) have already occurred on socio-economic systems Chang, 2016; Tatano and Tsuchiya, 2008; Rose and Wei, 2013), government organisation Marples, 2006; Rania et al., 2019; Duffaut, 2013), nature and energy flow systems Gyau-Boakye, 2001; Buesseler et al. 2017; Aldeberky, 2007).

3.3. Indicator-Based assessment

Resilience assessment is a popular and common method in resilience studies due to its effort to evaluate and characterise the characteristics of a complex system Tang, 2019. Assessment is a process by which information (could be data or an indicator) is obtained relative to some known objective or goal Kizlik, 2012. The framework built for resilience assessment, whether it is quantitative, qualitative or semi-quantitative, is frequently based on indicators Hosseini et al., 2016; Cantelmi et al., 2021. Quantitative approaches offer domain-agnostic measures to quantify value across applications and structural-based modelling approaches that model domain-specific representations. Semi-quantitative approaches provide a general numerical description of the classification, without detailed formulae or models. Qualitative approaches are related to approaches without a numerical descriptor and based on people's



Fig. 3. Factors and phases of "Indicator-based Resilience Assessment".

Table 2
Target elements to be identified in each selected paper.

N°	Elements to be investigated	Description
I	Capabilities or properties	Capabilities or properties in each reviewed paper, which could be characteristics, capacities, abilities, resources or knowledge described in relation to CI resilience. As capabilities are numerous and difficult to be listed, they were clarified during the lecture of selected papers.
II	Temporal stages	Temporal stages addressed in each paper, including pre-event stage (PrES), during-event stage (DES), post-event stage (PoES) and next event preparation stage (NEPS):
III	Aspect of positive and negative effects of implemented action	Whether these aspects are within its consideration during resilience
IV	Aspect of cascading effects due to interdependence	assessment in the paper
V	Indicators	Indicators described, used and applied for indicator-based assessment in each paper
VI	Suitable CI sectors of indicators	Suitable CI sectors of identified indicators
VII	Resilience assessment method	Assessment approach in each paper,
VIII	Indicator assessment method	which could be quantitative, qualitative or semi-quantitative

Table 3
Three review articles of reference search.

Review article	Article
Hosseini et al. (2016)	A review of definitions and measures of system resilience.
Meerow et al. (2016)	Defining urban resilience: A review. Landscape and urban planning
Curt and Tacnet (2018)	Resilience of critical infrastructures: Review and analysis of current approaches

Table 4
Synonyms or related vocabularies of keywords in three categories.

Category	Keyword	Synonyms or related vocabularies
1	Critical Infrastructure	all types of infrastructural systems or networks, technical systems, systems, engineered systems, engineering and industry (industrial)
2	Resilience	resilient, all capabilities and properties concerning CI resilience mentioned in section 3.
3	Indicator (for Assessment)	Index, criterion, criteria, metric, indices and some terms considered as general indicator (such as loss, damage, time, etc.) Assess (assessing, assessed), Estimation (estimating, estimate, estimated), measurement (measure, measuring, measured), evaluation (evaluating, evaluated, evaluate), determining, simulation (simulating), quantification (quantifying, quantified, qualified), modelling

judgments and analysis, like surveyed experts or operators Hosseini et al., 2016; Cantelmi et al., 2021. Furthermore, qualitative approach includes also graphics or illustrations, which present the value or change of indicator and data without numerical calculations.

Resilience assessment is frequently based on indicators Cutter, 2016. To produce knowledge, which can be used to make decisions, and set policies, requires information systems to transform data into information Peris-Mora et al., 2005; Bourgeois, 2014). Moreover, according to Eurostat Eurostat, 2014, indicator-based assessment consists of setting the expected evolution for the indicator by reference. Indicator-based resilience assessment could be therefore defined as an approach to knowing resilience value or level by observing indicators with a set reference. In the context of CIs resilience assessment, an indicator provides information to measure or assess the level of properties, functionality, or capabilities.

An indicator is measurable, associated with a criterion, intended to observe its evolution at defined intervals Yang et al., 2022-a. . A criterion is a character or a sign, which is used to distinguish a thing, a concept or to make a judgment of appreciation. An indicator is objective information, whose assessment, like resilience assessment, could be quantitative, semi-quantitative or qualitative. For example, temperature could be an indicator assessed through objective quantitative methods, such as thermometer readings. Meanwhile, indicator assessment can be based on many subjective judgments, which we call qualitative assessment. For example, for an indicator, "the number of satisfied customers served", the "number" is objective information, but the method of getting this information is based on the subjective judgements of customers. Semi-quantitative indicator assessment, for example, quantifies the number of satisfied customers, which is categorised by level as below 50 per cent and above 50 per cent; Temperatures are classified as below 20 degrees, between 20 and 40 degrees and above 40 degrees.

Moreover, the indicator measure needs reliable data Vogel and Canada, 1997; Cutter, 2016; CORDIS-Smart Resilience Indicators for Smart Critical Infrastructures, 2018). Data is a discrete fact, a raw element or the result of an observation, an acquisition, or a measurement, carried out by a natural or artificial instrument. Data are objective and don't have to function to evaluate or assess an object. For collective work to be done based on data, it is necessary to ensure a unit of format and a standard of measurement. The process that transforms numerous data into actionable indicators is called indicator assessment.

In conclusion, indicator-based resilience assessment for CIs refers to an approach including three factors, CI resilience, Usable indicator, Required data and two phases (see Fig. 3):

- resilience assessment: a process in which resilience values are obtained by usable indicators
- Indicator assessment: a process in which indicator values are obtained by reliable data

3.4. Focused elements

Each existing resilience assessment is based on appropriate steps designed by the creators or users themselves. In designing the steps, many elements of the assessment process need to be specified, such as criteria, indicators, assessment methods, data, indicator weights, etc. According to the current state presented above, this review work will focus on eight elements (see Table 2) of the assessment process in each of the selected papers. Since the assessment approach for CI resilience and indicator has been studied in several current research papers Hosseini et al., 2016; Cantelmi et al., 2021; Gasser et al, 2021; Sun et al. 2020), it is simply categorised into quantitative, qualitative and semi-quantitative.

4. Suitable papers and indicator identification

The online bibliographical databases are becoming an increasingly popular tool to screen scientific literature with key words Macedo-Rouet et al., 2012. The first paper search method is therefore based on an online database, Web of Science. Based on the aims of this study, "Critical infrastructure", "Resilience" and "Indicator" are selected as key words. However, the limit of these keywords would miss some articles in the search scope, for example, a paper describing hospital building as

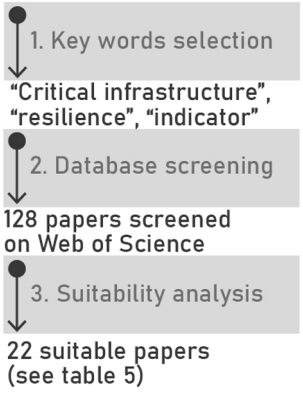


Fig. 4. Keyword search method.

"hospital facility" Grimaz et al., 2021. This paper would not be selected through keyword search with "infrastructure". On the other hand, if "hospital facility" were also considered as a key word, the research result would include many articles not related to infrastructures. It illustrates how expanding the search to nearby terms can catch many irrelevant articles. This opinion has been mentioned in the study of Yang et al. (2022-a) in terms of the keyword "indicator". Therefore, a second approach, a reference search based on three recently popular review papers in resilience study Hosseini et al., 2016; Meerow et al., 2016; Curt and Tacnet, 2018), is used for the paper search work. Indeed, some existing tools for reference review, like PRISMA[1] or CORTEX,[2] are able to screen automatically by keywords. But again, for this study, keywords cannot be clearly defined, while the extension of the search to nearby terms would lead to select many unsuitable articles. Consequently, a reference search through manual selection is necessary and inevitable.

Paper searches in this study involve several manual steps, including selecting based on the title and abstract. During the operational process, three people perform these steps, but the whole research team decides the selection criteria. Each result has been discussed several times and approved by the research team. The keywords of suitable article selection are based on the identification of indicators because the indicator is the priority target of this article. Papers that do not contain indicators were excluded from our study.

4.1. Keyword Search Method

The Keyword Search Method in this study deploys and adjusts the methodology used in the review paper of Yang et al. (2022-a), which includes three main steps: Key words selection, Database screening and Suitability analysis. An electronic search with keywords "Critical infrastructure", "resilience" and "indicator" was applied on Web of Science on 25 January 2022. The search strings "critical infrastructure", "resilience" and "indicator" were set as "Topic" items, with the conjunction "and" and 128 papers were screened. The suitability analysis, based on the paper abstract, was applied to exclude the papers that match the keywords, but not the research interests. For example, Jeong and An (2016) discuss the usefulness and applicability of risk assessment from the point of view of the weight of key performance indicators (KPI), without description of concrete KPIs. Another example is from Wang et al. (2019) to assess energy infrastructure models from the resilience perspective, not the resilience of energy infrastructures. After excluding articles for which resources could not be found, 22 papers, which are considered to contain resilience indicators for CIs, were selected (see Fig. 4).

[1] https://www.prisma-statement.org/Default.aspx.
[2] https://scirev.org/journal/cortex/.

4.2. Reference Search Method

The reference search used in this study is based on three manual steps, 1) Review Articles Selection, 2) Selection through Title and 3) Suitability Analysis.

4.2.1. Review articles selection

The first consideration is that, due to the widespread use of the term resilience, there are already several review articles studying system resilience or CI resilience. These studies may not have the same purpose as this review study, but they make it possible to collect many references about resilience assessment. Three review articles are useful for this study (see table 3). Many articles were documented and discussed in these three review studies, so their references are browsed in detail and those that do not meet study interest are filtered out. Filtering consists of two steps: Selection through Title and Suitability Analysis.

4.2.2. Selection through Title

This step aims to observe whether the title of the reference contains the three keywords abovementioned for the Keyword Search Method and their synonyms or related vocabularies. All terms and vocabularies are divided in three categories (see table 4) corresponding to the three key sectors mentioned in section 3. The criterion is that the title must contain at least one element from each category. For example, if an article is entitled "Travel time of safety road networks", it is considered to correspond to criteria with its elements: "road networks" as category 1; "safety" as category 2; and "travel time" as category 3. We should point out, that the terms in this table are limitless. All types of "critical infrastructure", all capabilities or properties concerning "resilience" and all terms nearby "indicator" are recognised as relevant. Which terms can be considered relevant relies on the subjective judgement of the screener. Because of this, many words cannot be predicted before the reference search. Automatic searches are unreliable and manual searches are necessary.

4.2.3. Suitability analysis

Similar as the suitability analysis in the Keyword Search Method, this step aims to exclude the papers that don't match the research interests. The suitability analysis in the second method is more complex than the keyword search. In the keyword search, three applicable keywords guarantee every screened paper concerns "indicator", "resilience" and "critical infrastructure". The main task of suitable paper selection in the keyword search is checking whether the indicator mentioned is to assess CI resilience. However, for the second method, with a larger scope (see table 3), more information needs to be checked in reading papers' abstracts:

1) Whether a paper assesses the resilience, or relating capabilities and properties.

This task can be completed based on the definitions and examples listed in section 3.1. The goal is to observe whether papers assess CI capabilities or properties relating to resilience.

- 2) Whether the assessed system is critical infrastructure.

As we only have CI sectors (see table 1), not specific CI types, it is recommended to use the criteria in Moteff et al., (2003) to identify whether the target system is CI or not. Moteff et al., (2003) did not specify which infrastructures should be considered critical but argue "… *for an infrastructure to be judged critical it must be vital to one or more broad national functions. That set of functions has expanded over time, beginning with national defence and economic security, to include public health and safety, and then national morale*". As long as the system assessed in the paper meets this criterion, we can consider the system to be critical.

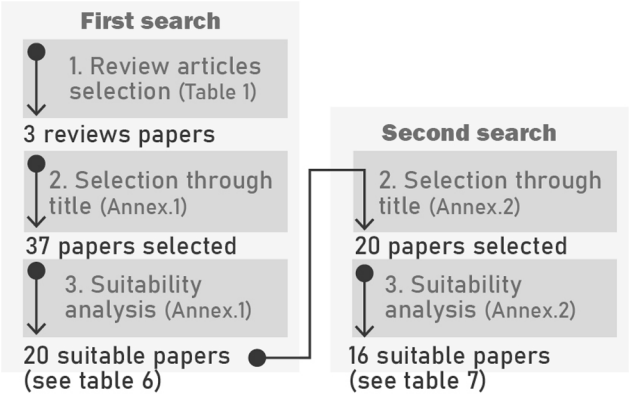


Fig. 5. Reference search method.

- 3) Whether a paper applies the "indicator" function to other terms or terminologies, and whether they are used to assess CI resilience.

According to the study by Yang et al. (2022-a), some studies use other terms, which fit the definition of "indicator", for assessment, such as indices, parameter and metrics. Like a second task, which terms or vocabularies should be considered as "indicator" could not be specified. This study focuses on the term or terminology fitting the definition of indicator (i.e., "a chosen piece of information, intended to observe its evolution of something").

With the three mentioned pieces of information, we could finally identify the papers concerning indicator-based resilience assessment for CIs. Consequently, 20 papers were selected after the reference search based on the three review articles (see Fig. 5). Furthermore, in order to analyse more papers, this study applies a second time reference search method based on the 20 selected papers in the first reference search. 16 papers were selected after the second reference search (see Fig. 5. The details of suitability analysis are presented in Appendix 1 and 2 (see A.1 and A.2): "X" means that the article is suitable and selected for this study; "repeat" signifies the articles found through the second reference research were also found during the first reference research.

5. Results

All target elements in each paper relevant to this study are identified and listed in Fig. 6 and in three tables:

- Table 5. Results summary for the 22 papers selected through keyword search
- Table 6. Results summary for the 20 papers selected through first reference search
- Table 7. Results summary for the 16 papers selected through second reference search

From left to right, three tables illustrate paper numbers, references, capabilities or properties, temporal stages, relevance of interdependence, relevance of implementing action, identified indicators, suitable CI sectors of identified indicators, resilience assessment approach and indicator assessment approach. The same indicators used by several different documents appear in one column. Due to space limitations, the indicators in the original article have been simplified in this paper. This study only discusses the identified and exportable contents. Elements not discussed in papers are marked as Not Available ("NA"). For example, in the case of the first article in Table 5 from Kołowrocki and Soszyńska-Budny (2019), which does not clarify the resilience stages involved, this study prefers to note "NA" to avoid misinterpreting the author's intentions.

"A" means that indicators are suitable for all CI sectors. We highlight that suitable CI analysis of each indicator focuses on the indicator itself, not the CIs mentioned in papers. For example, LaLone et al. (2017) applies the indicator "human noise" on the power grid system, but this indicator is suitable for all types of CIs and noted as "A" meaning all sectors of CIs. In some cases, the suitable CI sectors of an identified indicator could be in several sectors, for example, "the days of CI disruption" Murdock et al., 2018 fitting all sectors and "number of passengers" Adjetey-Bahun et al., 2014 suitable for Transportation Systems, Seaport/Harbour and Airport. Moreover, this paper considers that the assessment of resilience is based on a whole indicators system that includes numerous indicators. Therefore, when an indicator is part of an indicator system, the identification of adapted CI sectors depends on the indicator system established by authors.

6. Results analysis

Before discussing the results, it is necessary to highlight that since resilience and CI are terms that don't have standard definitions, this review study is based on the aspects presented in section 3 and the research method designed by our research team. The discussion focusses on the popularity level in the field, rather than on the concrete quantity of each category in Fig. 6, as this study do not cover all of the existing papers, but is based on the 58 articles identified.

6.1. Capabilities or properties (I)

According to an analysis of the number of recurrences, among 125 "capabilities or properties" in total, the four most common words are performance (22 times), safety (11 times), vulnerability (8 times), recovery (8 times), accounting for more than 39 percent of all recurrences. The phenomenon that performance recurs most frequently can be explained by the fact that many articles have described resilience in terms of changes in performance over time. However, resilience is a multi-scale and complex concept Wang et al., 2019, which requires assessment relating to various perspectives and all temporal stages. An assessment aiming only at a part of capacities or stages could not assess CI resilience completely. The majority of investigated papers do not meet this requirement.

6.2. Temporal stages (II)

Fig. 6 shows that, except for the articles not concerning temporal stages, the majority of indicators aim at the During Event Stage (38 papers) and Post Event Stage (39 papers) of the resilience scenario. Only six articles focus on all stages of resilience scenarios. This proves that the analysis of preparedness and improvement stages of the resilience scenario is not enough. In particular, NEPS is not discussed in many reviewed papers. This study considers this stage highly relevant to the effectiveness of implementation actions. The lack of discussion of NEPS might be related to the insufficient focus on implementation actions.

6.3. Interdependence and implementing action (III and IV)

Moreover, positive or negative effects concerning "interdependencies" and "implemented actions" are not discussed enough in selected papers. Section 3 highlights that damage and implemented actions of one CI could cause effects over time. Positive effects refer to the Effectiveness of actions, which could be reflected in various ways, such as the increase of functionality, the change of functional reduction in speed and degree, and the speed of functional recovery. Negative effects signify: 1) the damage caused by implemented actions to target CI and its connected components in human-environment; and 2) the cascading damage to target CI and connected urban components due to interdependencies. Both positive and negative effects are likely to occur over the long term. Resilience indicators should go beyond the boundaries of one shock event or one CI and help create an ongoing resilience

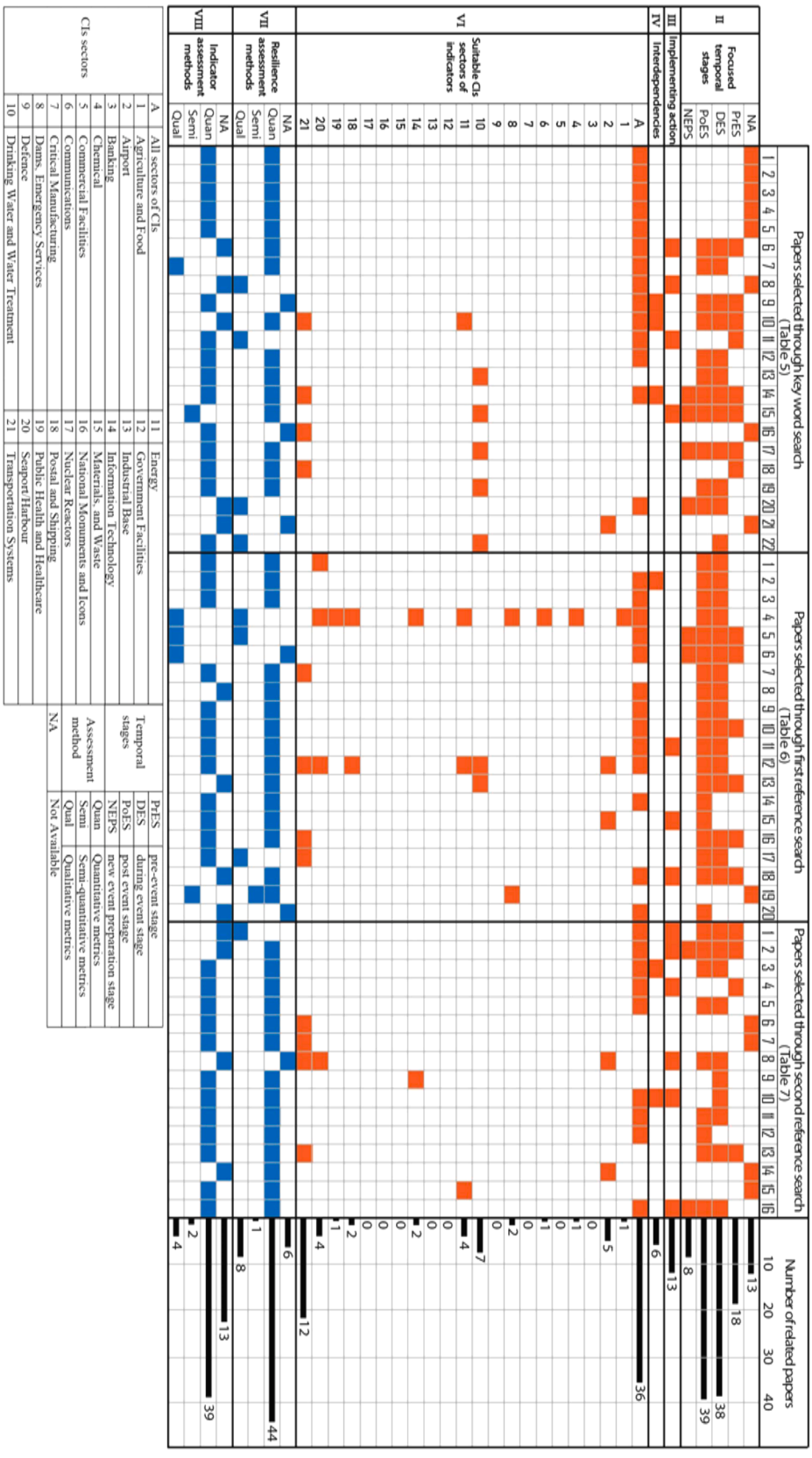


Fig 6. Results summary for all selected papers.

Table 5
Results summary for the papers selected through keyword search.

N°	References	I Capabilities or properties	II Temporal stages	III Implementing action	IV Interdependence	V Indicators	VI CI Sectors	VII Assessment methods	VIII
								Resilience	Indicator
1	Kołowrocki and Soszyńska-budny, (2019)	Safety	NA	No	No	safety function; risk function; fragility curve; critical infrastructure	A	Quantitative	Quantitative
2	Kolowrocki, 2020	Safety	NA	No	No	unconditional lifetime up	A	Quantitative	Quantitative
3	Kołowrocki et al., 2019-a	Safety	NA	No	No	to exceeding critical safety state; the standard deviation of the critical infrastructure lifetime in the safety state not worse than the critical state; the moment of exceeding the acceptable value of the critical infrastructure risk function level; the intensities of degradation of the critical infrastructure; the intensities of critical infrastructure departure from the safety state subset; the limit values of transient probabilities of the operation process at the particular operation states; intensities of ageing at the operation states	A	Quantitative	Quantitative
4	Kołowrocki et al. (2018)	Safety	NA	No	No	the unconditional safety function; risk function;	A	Quantitative	Quantitative
5	Kołowrocki et al., 2019-b	Safety	NA	No	No	fragility curve; unconditional CI lifetime in the subset of safety state, times of the CI staying at particular states of safety; CI lifetime standard deviation of the CI staying in the subset of safety states, the moment of exceeding the acceptable value of the critical infrastructure risk function level; the coefficients of the climate-weather change influence on CI ageing intensities; process influence on CI; the limit value of the process influence on CI; the mean value of the process influence on CI; intensities of ageing at the operation states	A	Quantitative	Quantitative
6	Hromada and Lukas, (2012)	Vulnerability, Coefficients (of the relationships and interdependencies of risks) Countermeasures (ability to recover): Detection, Delay, Response, quality	PrES DES PoES	Yes	No	activity coefficient; passivity coefficient (sub-indicator: total number of risks, possibility of risk, risk importance correlation, risk coefficients) the time needed to verify alarm information and probability of successful communication; breaking resistance; the time needed for the guards to transfer from A to B; sum of positive answers	A	Quantitative	NA
7	LaLone et al. (2017)	Recovery efforts	DES PoES	No	No	human noise	A	Quantitative	Qualitative
8	Bialas (2016)	Effectiveness, Efficiency	NA	Yes	No	A large number in four aspects: security, safety, reliability, resilience,	A	Qualitative	NA

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Table 5 (*continued*)

N°	References	I Capabilities or properties	II Temporal stages	III Implementing action	IV Interdependence	V Indicators	VI CI Sectors	VII Assessment methods	VIII
								Resilience	Indicator
						technical and management issues; CI specific phenomena; cost and benefit parameters dealing with the entire CI protection system; Incident statistics (for details see the list in the reference)			
9	Liu et al. (2021)	Mitigation, Recovery, Performance	PrES DES PoES	No	Yes	resilience by mitigation and recovery (sub-indictor: performance function, time, complement of insufficiency function)	A	NA	Quantitative
		Sensitivity				failure magnitudes and recovery rates			
10	Kamissoko et al. (2020)	Functionality	PrES DES PoES	No	Yes	the number of trucks in circulation (sub-indictor: the performance, the safety and the number of circulating trucks)	21	Quantitative	NA
						the electricity used, the quantity of required electricity	A		
						the number of good functioning periods; the number of bad functioning periods when the value is greater than the normal maximum; the number of bad functioning periods when the value is lower than the normal minimum; the duration of all bad functioning periods;			
						the quantity of electricity produced, the number of incoming trucks	11		
11	Roe and Schulman (2012)	Performance reliability, Resource-benefit	PrES	Yes	No	variables include daily or hourly load forecast errors, hardware malfunctions, grid congestion and software glitches; the impact imposed by the input conditions of unscheduled generator outages on the grid; line mitigations	A	Qualitative	Quantitative
12	Murdock et al. (2018)	Redundancy, Flexibility, Robustness	DES PoES	No	No	disruption days (sub-indictor: the number of people affected by the disruption in CI services and the days of disruption)	A	Quantitative	Quantitative
13	Zhan et al. (2020)	Reliability, Performance	DES PoES	No	No	failure duration; failure magnitude; severity; the global surplus hydraulic power above the minimum required nodal water head; Capital costs; Operational cost	10	Quantitative	Quantitative
14	Ghosn et al. (2016)	Redundancy, Safety	PrES DES PoES NEPS	No	Yes	capacity; damage level; probability of structural collapse; liability; direct risk associated with the cost of local failure due to exposure to a hazard, indirect risk associated with the cost of collapse given local damage;	A	Quantitative	Quantitative
		Fragility, Vulnerability, Robustness, Functionality							

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Table 5 (*continued*)

N°	References	I Capabilities or properties	II Temporal stages	III Implementing action	IV Interdependence	V Indicators	VI CI Sectors	VII Assessment methods	VIII
								Resilience	Indicator
						connectivity loss; efficiency; time; statistical independence; Service flow reduction network; topology			
		Performance				Interruption duration; average customer interruption duration; average system interruption frequency all nodes are connected to the source nodes total number of highway sections open; total length of highway open; total weighted "connected" length of highway open; travel time; travel distance; user cost	21		
15	Upadhyaya et al. (2018)	Functionality	PrES DES PoES NEPS	Yes	No	dry weather/wet weather flow; monitoring of the demographic pattern; Change in impervious area; etc. (for details see the list in references)	10	Quantitative	Semi-quantitative
		Resiliency				assessment of potential damage; assessment of reconstruction need; Recovery plan; etc. (for details see the list in references)			
		Sustainability				Energy used to provide services/year; excess toxicity in incoming water; etc. (for details see the list in references)			
16	Kammouh et al. (2018)	NA	NA	No	No	accessibility; Road density; Road width; Road lanes; Link (road, track, etc.) condition; etc. (for details see the list in references)	21	NA	Quantitative
17	Cimellaro et al. (2016)	Performance function	PrES DES PoES NEPS	No	No	the number of equivalent households without service loss function the tank water level loss function	10	Quantitative	Quantitative
18	Tachaudomdach et al. (2021)	Robustness	PrES	No	No	water quality levels of floods; the damaged area; the number of affected links; the number of affected nodes and the number of affected cars	21	Quantitative	Quantitative
19	Murino, et al. (2019)	Performance	DES PoES	No	No	the height of the nitrification-oxidation process tank; The power delivered to the pump; The outlet mass flow rate	10	Quantitative	Quantitative
20	Johnsen and Veen (2013)	Safety, Security culture	DES PoES NEPS	No	No	the technical "up time'' and stability of decentralised communication equipment; The number of unwanted incidents related to communication failures; The regularity of railway operations and delays due to incidents.	A	Qualitative	NA
21	De Vivo et al. (2022)	Vulnerability,	NA	No	No	score of culture rating based on the survey extreme temperatures (Increase in frequency of	2	NA	NA

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Table 5 (*continued*)

N°	References	I Capabilities or properties	II Temporal stages	III Implementing action	IV Interdependence	V Indicators	VI CI Sectors	VII Assessment methods	VIII
								Resilience	Indicator
		Sensitivity, Adaptive capacity				extreme temperatures; Increase in intensity of extreme temperatures), extreme rainfall (Increase in rainfall frequency; Increase in rainfall intensity); sea level rise; Soil sealing; Air traffic, etc. (for details see the list in references)			
22	Pietrucha-Urbanik et al. (2020)	reliability	DES	No	No	disruption frequency; network downtime; network repair time and network back-to-service time; unavoidable annual real water losses and the infrastructure leakage	10	Qualitative	Quantitative

assessment for a CI, as well as for several interdependent urban components. Therefore, both the aspects concerning CIs' interdependence and effects caused by implemented actions should be taken into account for resilience assessment. However, among these selected papers, only 6 articles mention interdependence, while 13 papers relate to the implementing actions concerning cost, resources, effectiveness and safety of actions.

6.4. Indicators (V)

The identification of indicators is a complex process. Firstly, only 30 of the 58 articles use the term "indicator" and specifically explain what they are. Some papers apply the function of "indicator" to its synonyms or related vocabularies, like parameter Hromada and Lukas, 2012; Liu et al.,2021), variable Roe and Schulman, 2012; Murino, et al., 2019; Baroud et al., 2014b; Morlok and Chang, 2004, metric (Ghosn et al., 2016; Shafieezadeh and Ivey Burden, 2014; Ouyang and Wang, 2015; Ouyang and Duenas-Osorio, 2014; Vugrin et al., 2010; Henry and Ramirez-Marquez, 2012; Pant et al., 2014; Cavalieri et al., 2012; Ayyub, 2013), index Ghosn et al., 2020; Cimellaro et al. 2016; Ayyub, 2014), etc. These vocabularies are closely associated with indicator-based assessment, but have various definitions in different contexts. If they have the function of "indicator" in reviewed papers, they are presented in Table 5, 6 and 7. On the other hand, some mentioned indicators in reviewed papers are not for assessing resilience. For example, two papers consider "resilience" as an indicator for assessing risk-cost trade-offs in water resources system Li and Lence, 2017 and for assessing recovery capability in Intermodal Freight Transport Chen and Miller-Hooks, 2012. In these cases, we chose the information assessing "indicator resilience" as indicators.

Sometimes the 'indicators' are not presented in an obvious way. For example, Johnsen and Veen (2013) calculate the scores of three issues relating to safety culture, based on a questionnaire-based survey, and the number of scores could be considered as an indicator. Vugrin ED et al. (2010) use a number of metrics to assess performance, whose values in different periods change into the values of "recovery path" and "recovery effort". Then interviewers present these results to experts, who use them to assess the resilience of CIs. Finally, CI resilience is classified as high, medium or low-level. Therefore, what could be considered as a resilience indicator in the whole assessment process of Vugrin ED et al., (2010) is the "results of interviews", which are an assessment of performance, recovery path and recovery effort. Some papers Faturechi and Miller-Hooks, 2014; Reed et al., 2009; Ip and Wang, 2011; Sun et al., 2006; Omer et al., 2015; Li and Lence, 2017; Miller-Hooks et al., 2012; Winkler et al., 2010; Chang, 2003) provide mathematical formulas to calculate resilience or elastic capacity, and this study records the variables needed for the calculation as an indicator. In some other papers Carvalho et al., 2008; Ouyang and Dueñas-Osorio, 2012-b.; Gilbo, 1993, the indicators were obtained from the authors' analysis.

The results also show that the term "indicator" is sometime misused. Adams et al. (2012) apply "redundancies," "recovery activities" and "travel speed" as indicators, but the former two are not objective enough to be an indicator. This problem occurs in many other papers, such as Shirali et al. (2012), Shirali et al. (2013), LaLone et al. (2017), Liu et al. (2021), Shafieezadeh and Ivey Burden, (2014), etc. The subjective terms like availability, resilience, mitigation and recovery are related to ideal expectations of stakeholders, which cannot be an indicator since it must be objective. Such as the "availability of cranes and berths" indicator in Liu et al. (2021), whether it should correspond to crane volumes or quantity of vehicle berths, since the value that is considered to represent the expected performance of that road infrastructure depends on the subjective judgment of stakeholders. Human judgement for expected performance is based on their means, objectives and results Bescos et al., 1997. Therefore, the non-objective terms are not indicators, but called criteria that are used to distinguish a thing or a concept, and to make a judgment of appreciation.

6.5. Suitable CI sectors (VI)

36 papers present the indicators that could be applied to all types of CIs. These indicators are relatively general in comparing the indicators only suitable for specific sectors. Moreover, this study identifies more indicators specific to two CI sectors: transportation systems, Drinking Water and Water Treatment. Specific indicators for 10 sectors are not present in the results: Banking, Commercial Facilities, Critical Manufacturing, Defence, Government Facilities, Industrial Base, Materials and Waste, National Monuments and Icons, and Nuclear Reactors. This result does not indicate a low level of interest in these sectors. For example, although we did not identify indicators applicable only to Industrial Base sectors, the studies on industrial plants could be found in some review papers, like Shirali et al. (2012), and Shirali et al. (2013). It can only be said that the indicators they use are also applicable to other CI sectors. A hypothesis is proposed, but it needs to be proven: more specific indicators are needed to assess the infrastructure in several sectors, like transport and water systems, where such needs do not exist in other sectors. Meanwhile, when reading the paper, we found that some CI sectors are indeed less discussed for resilience assessment, especially National Monuments and Icons, Materials and Waste, Banking, and Government Facilities.

Table 6
Results summary for the paper selected through first reference search.

N°	References	I Capabilities or properties	II Temporal stages	III Interdependence	IV Implementing action	V Indicators	VI CI Sectors	VII Assessment methods	VIII
								Resilience	Indicator
1	Shafieezadeh and Ivey Burden, (2014)	available capacity Performance	DES PoES	No	No	availability of cranes and berths time required and service provided (sub-indictor: the number of berthed ships, the delay time (i.e., the time in between ship arrival and docking), the number of displaced ships (i.e., the number of ships within the arrival stream that cannot be accommodated at the port on a given day due to large delay times), and the number of TEUs handled by the seaport.)	20	Quantitative	Quantitative
2	Ouyang and Wang (2015)	Restoration, Performance, Fragility (of components)	DES PoES	yes	No	event occurrence number; total number of event occurrences; occurrence time of the event; impact area; expected impact area under the hazards accounting for all possible intensities; occurrence rate of the hazards per year	A	Quantitative	Quantitative
3	Ouyang and Dueñas-Osorio, (2014)	Restoration, Performance, Fragility (of components)	DES PoES	No	No	event occurrence number; total number of event occurrences; occurrence time of the event; impact area; expected impact area under the hazards accounting for all possible intensities; occurrence rate of the hazards per year	A	Quantitative	Quantitative
4	Vugrin et al. (2010)	Absorptive capacity, Adaptive capacity, Restorative capacity Performance	DES PoES	No	No	results of the interviews of experts	A	Qualitative	Qualitative
						the profitability of power companies; the percentage of customers with working electric power	11		
						rates of and population exposure to food contamination; average consumer price of food	1		
						shipments to critical chemical-based commodities	4.18		
						lives saved; average response time	8		
						barrels of refined petroleum product transported to the Midwest; price of domestic refined products; profitability of energy companies	11		
						number and efficacies of cyber attacks	14		
						rates of morbidity and mortality; cost per vaccine given	19		
						average speed and cost of shipments; number of disrupted shipments	20		
						number of dropped telephone calls	6		
5	Shirali et al. (2012)	Safety culture	PrES DES PoES NEPS	No	No	schedule delays; (frequency of) safety committees; meeting effectiveness; safety education; worker's involvement; competence; safety training	A	Qualitative	Qualitative
6	Shirali et al. (2013)	Safety culture	PrES DES PoES NEPS	No	No	top management; commitment; learning culture; awareness; preparedness; and flexibility.	A	NA	Qualitative
7	Adams et al. (2012)	Reduction, Recovery, Performance	DES PoES	No	No	redundancies; recovery activities; travel speed (sub-indictor: the severity of damage on travel speed and truck counts, reduction period time, recovery period time)	21	Quantitative	Quantitative
8	Henry and Emmanuel Ramirez-Marquez, (2012)	NA	DES PoES	No	No	function; time; cost of resilience	A	Quantitative	NA
9	Pant et al. (2014)	Vulnerability, Recoverability	DES PoES	No	No	time to Total System Restoration; Time to Full System Service Resilience; and Time to 100 % Resilience.	A	Quantitative	Quantitative
10	Baroud et al., (2014b)	Reliability, Vulnerability, Recoverability	PrES DES PoES	No	No	time to total system restoration; time to full system service resilience; and time to a specific % resilience; the number of links recovered	A	Quantitative	Quantitative

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Table 6 (*continued*)

N°	References	I Capabilities or properties	II Temporal stages	III Interdependence	IV Implementing action	V Indicators	VI CI Sectors	VII Assessment methods	VIII
								Resilience	Indicator
11	Chen and Miller-Hooks (2012)	Redundancy, Recovery	DES PoES	No	yes	post-disruption expected fraction of demand (time, cost, resources); redundancies; recovery activities	A	Quantitative	Quantitative
12	Ayyub (2014)	Performance, Quality	DES PoES	No	No	time of incident or disturbance occurrence; time to full recovery; The probability of cost; standard normal cumulative distribution function	A	Quantitative	Quantitative
						space availability	A		
						throughput traffic	2.18.20.21		
						water production capacity	10		
						water available for consumption	10		
						power delivered	11		
13	Hashimoto et al., (1982)	Reliability, Vulnerability, Performance	PrES DES PoES	No	No	average level and average squared of water deviation	10	Quantitative	NA
14	Franchin and Cavalieri (2015)	Efficiency	PoES	No	No	function	A	Quantitative	Quantitative
15	Faturechi et al. (2014)	NA	PoES	No	yes	post-repair capacity rates for take-offs and landings	2	Quantitative	Quantitative
16	Faturechi and Miller-Hooks (2014)	NA	PrES DES PoES	No	No	travel time	21	Quantitative	Quantitative
17	Adjetey-Bahun et al.(2014)	Performance	DES PoES	No	No	the number of passengers that reach their destination; the total delay of passengers after a serious perturbation.	21	Qualitative	Quantitative
18	Enjalbert et al. (2011)	Performance, Safety	PrES DES PoES	No	Yes	the evolution of performances (sub-indictor: time period during which the performance improvement occurs or remains; the consequences of human actions in order to compare performance levels between two dates; the effect of disturbance on the system	A	Quantitative	NA
19	Curt et al., (2010)	Performance	NA	No	No	sinkhole–Subsidence cone; Differential movement; Concrete quality; Visual state of drain outlet; Visual state of drain collector; etc. (for details see the list in references)	8	Quantitative, Semi-quantitative	Semi-quantitative
20	Lhomme et al. (2013)	Redundancy	PoES	No	No	clustering coefficient; connection points	A	NA	NA

6.6. *Resilience and indicator assessment (VII and VIII)*

Most reviewed papers use a quantitative assessment approach, both in the indicator and resilience assessment phases. In the "Resilience assessment" phase, the quantitative approach is 44 times higher than the semi-qualitative method, and 6.3 times higher than the qualitative approach. In the "Indicator assessment" phase, these values were 19.5 and 9.75 respectively. Quantitative assessment is frequently related to modelling, simulation and general mathematic equations, while Qualitative assessment is generally based on questionnaires Vugrin et al., 2010; Shirali et al., 2012; Shirali et al. 2013) and graphical comparisons Pietrucha-Urbanik et al., 2020; Adjetey-Bahun et al., 2014; Carvalho et al., 2008). For example, LaLone et al. (2017) draw the change of social indicators based on the data of Tweets per hour that mention keywords and Customers affected by Power Outages during hurricanes.

The assessment for the same capabilities or properties may have different approaches. One example comes from the reliability assessment of the water supply network, related to three articles. Zhan et al. (2020) and Li and Lence (2007) apply the quantitative assessment method in both resilience and indicator assessment phases. Pietrucha-Urbanik et al. (2020) use quantitative methods to calculate the values of two indicators (failure rates and water losses), and then compare graphically the change of indicators to qualitatively assess the reliability of the water supply network during different periods. Besides, for the same capabilities or properties, applied indicators are also different. For example, both relating to CI quality, Reed et al. (2009) present a greater number of indicators, including "inoperability", "wind speed for the hurricane", "capacity", "time in days post-event", etc., while Hromada and Lukas (2012) apply indicators including "delay of breaking resistance", "information and probability of successful communication", "total number of risk", etc. The selection of indicators that are more accurate or practical should be an invaluable issue.

From a psychological point of view, assessing an object is a process that involves judgment and decision-making, which apply certain criteria, principles or standards to form an assessment Sun et al., 2019. For example, Hollnagel (2015) classifies "Potential of Resilience Performance" into five levels: Excellent, Satisfactory, Acceptable, Unacceptable and Deficient. The "Potential of Resilience Performance" is subjective, and can be considered as a criterion that can be used to make judgements about system resilience. However, "criterion" and "criteria" for resilience indicators are discussed only in 12 papers Liu et al., 2021; Upadhyaya et al., 2018; Ghosn et al, 2016; Hashimoto et al., 1982; Kamissoko et al., 2020; Tachaudomdach et al., 2021; Adams et al., 2012; Enjalbert et al., 2011; Curt et al., 2010; Cavalieri et al., 2012; Gilbo, 1993; and Chang, 2003. What's more, in these papers the criteria or indicators may be somewhat confusing, due to the misuse of terms or unclear expressions. For example, Kamissoko et al. (2020) present 6 criteria for three interdependent CIs: "the Quantity of Produced Electricity", "the Number of Incoming Trucks", "the Quantity of Required Electricity", "the Performance", "the Safety" and "the Number of Circulating Trucks". But apart from Performance and Safety, all the other elements could be supposed to be objective information and should be called indicators. Conversely, many expressions are not objective enough to be an indicator, but are used as such.

Table 7
Results summary for the paper selected through second reference search.

N°	References	I Capabilities or properties	II Temporal stages	III Interdependence	IV Implementing action	V Indicators	VI CI Sectors	VII Assessment methods	VIII
								Resilience	Indicator
1	Serre (2018)	Resistance, Absorptive, Recovery	PrES DES PoES	No	yes	contribution of the urban design features in DS3 (spatial decision support system) model	A	Qualitative	NA
2	Fisher et al. (2010)	15 factors in two levels (see level 1 and 2 in references)	PrES DES PoES NEPS	No	yes	Answers (yes or no) for level 5 in this study, for example: if "Multiple service lines" are in different geographic locations. (for details see the list in references)	A	Quantitative	NA
3	Reed et al. (2009)	Fragility Quality	DES PoES	yes	No	interdependency matrix between the various subsystems; disturbance or perturbation; wind speed for the hurricane; time in days post-event	A	Quantitative	Quantitative
4	Carvalho et al. (2008)	Safety	PrES	No	yes	possibilities for Micro incidents to escalate and reach negative consequences (loss of control, incidents or accidents); actions under operators' control (use of procedures, training, equipment)	A	Quantitative	Quantitative
5	Ip and Wang (2011)	Recovery ability, Performance, Friability	DES PoES	No	No	the number of reliable passageways between any pair of nodes; reduction in network performance caused by the removal of nodes or edges (based on performance)	A	Quantitative	Quantitative
6	Morlok and Chang (2004)	Capacity, Flexibility	NA	No	No	traffic flow; cost of operation; Traffic Pattern Deviation	21	Quantitative	Quantitative
7	Sun et al. (2006)	Degraded-condition, Performance, Capacity, Flexibility	NA	No	No	number of empty containers per time period; number of loaded containers per time period; number of trains per time period; number of carloads per time period; number of loaded containers per time period for origin–destination (O-D) pairs	21	Quantitative	Quantitative
8	Cox et al. (2011)	Vulnerability, Flexibility, Resource availability	DES PoES	No	yes	the percentage of maximum disruption avoided by resilience behaviours (sub-indictor: Changes in passenger journeys)	2.20.21	NA	NA
9	Omer et al. (2009)	NA	DES	No	No	the total demand of the node (sub-indictor: total information that needs to be carried through the network to the node); the total information loss	14	Quantitative	Quantitative
10	Cavalieri et al. (2012)	Performance, Emergency response planning, Preparedness, Vulnerability	DES	yes	yes	number of casualties and fatalities; number of displaced people	A	Quantitative	Quantitative
11	Ouyang and Dueñas-Osorio, (2012-b.)	Performance	DES PoES	No	No	time; function	A	Quantitative	Quantitative
12	Li and Lence (2007)	Reliability, Performance function	PoES	No	No	the number of failures; the number of successes	A	Quantitative	Quantitative
13	Miller-Hooks et al. (2012)	Performance	PrES DES PoES	No	No	change of demand for O–D pair (sub-indictor: original pre-disaster demand for O–D pair; the post-disaster maximum demand that can be satisfied for O–D pair)	21	Quantitative	Quantitative
14	Gilbo (1993)	Capacity	NA	No	No	number of arrivals and departures at the airport during a fixed time	2	Quantitative	NA
15	Winkler et al. (2010)	Fragility (of component), Performance	NA	No	No	the order or number of generators (power plants) and substations, and the size or number of substations, generator edges (transmission lines) for each network; total edge length/	11	Quantitative	Quantitative

(*continued on next page*)

Table 7 (*continued*)

N°	References	I Capabilities or properties	II Temporal stages	III Interdependence	IV Implementing action	V Indicators	VI CI Sectors	VII Assessment methods	VIII
								Resilience	Indicator
16	Chang (2003)	Cost-benefit	DES PoES NEPS	No	yes	number of substation-substation edges, average substation degree, Generators total life cycle costs (sub-indictor: planned costs undertaken by the lifeline agency (maintenance investments and mitigation investment costs), any associated costs imposed on society (e.g., societal disruptions related to maintenance and mitigation activities), expected costs from seismic events (repair costs and revenue loss), the associated expected costs imposed on society (direct economic losses or business interruption°	A	Quantitative	Quantitative

7. Discussion

7.1. Necessity of an indicators system

The analysis in this study helps find a significant problem with the existing indicators of CI resilience: existing indicators do not assess resilience according to a uniform and well-defined indicator system. Indicator-based assessment needs an indicators system Shavelson, 1987; Shavelson et al, 1990; UNESCO-LearningPortal). More than just a collection of indicator statistics, indicator systems are usually designed to generate more and more accurate information about conditions Shavelson et al, 1990. Ideally, an indicator system will provide a framework for focus aspects, criteria, and how individual indicator components work together Eurostat, 2014; UNESCO-LearningPortal). However, as can be seen from the results, although these identified indicators are all designed to assess the CI resilience, the indicators systems used by reviewed papers are different due to different indicators, criteria, and assessment methods. In addition, Indicators and criteria are frequently misused. In most of the papers, the resilience assessment is incomplete, as they assess CI's resilience without consideration of various capabilities, and all stages, especially without interdependencies and implementing actions. The problems described above are quite common in indicator-based assessment for CI resilience, which directly leads to results that are not comparable or comprehensive. Comparable assessment results require that the assessment process for different CIs follow uniform criteria and metrics. Comprehensive assessment needs consideration on as many aspects as possible. The establishment of an indicators system aiming at these problems would help improve the indicator-based assessment for CIs resilience.

7.2. Limit of aspects

This paper is constructed according to the concepts and aspects presented in part 3. These approaches are presented from a scientific position, founded on a hypothesis that all the aspects presented are compatible with each other. However, these aspects may have a conceptual inconsistency.

To understand and model complex systems, the concept of resilience is often associated with the need for much less centralised control-based, deterministic, and linear approaches. The model grounded on a timeline of a linear transition between stages or levels of system performance or function is one of the examples. However, several mentioned capabilities, such as the capacities in the face of uncertainty and complexity could be contradictory to linear and deterministic models. Being in a complex environment, the performance or function of the infrastructure may be constantly changing at all stages, and is difficult to be presented as an ideal single linear. In addition, for many researchers, function or performance is no longer a priority property for studying the resilience of CIs. Many properties or capabilities that are not based on simple linearity are becoming increasingly popular in complex systems, such as reliability, resource (cost)-effectiveness, and safety culture.

Nevertheless, it is undeniable that deterministic and linear approaches occupy a very important place in resilience studies. Moreover, the opinion, that deterministic and linear approaches could be combined with the capability in the face of uncertainty, is also accepted by many studies.

7.3. Use of results

Meanwhile, this work establishes an initial mapping of resilience indicators and builds a state of the art. For each indicator, this study defines:

- the temporal stage of resilience as noted by PrES (Pre-Event Stage), DES (During Event Stage), PoES (Post-Even Stage) and NEPS (New Event Preparation Stage);
- the suitable CI sectors of indicators;
- the resilience and assessment approaches of indicators.

This type of identification allows stakeholders and scientists to quickly select applicable indicators for their situations and find desired assessment methods through the papers reviewed in the study. For example, for an assessment aiming at the PrES of resilience scenario, based on the tables and Fig. 6, 18 relevant articles could easily be found based on the tables 5, 6, and 7, and Fig. 6. For a study focusing on transport resilience indicators, 48 relevant papers could also be quickly found, 36 of which propose indicators applicable to all CI sectors. Moreover, based on the results, future studies could establish an indicator system at a relatively higher level by observing important areas and existing shortcomings.

7.4. Limitation of literature review

The limitations of this study concern the literature review and the elements that aren't viable. Firstly, the "reference search method" is applied by noting only the articles in the existing scientific bibliographies. This led to a lack of investigation of the articles published after the three original review papers Table 3. Secondly, the information about capabilities or properties in several papers is missing (noted with NA in Table 5, 6 and 7). For some papers because the article does not address

Table A1
Appendix 1: Papers Selected Through First Reference Search.

N° a	Source	Title	step: Keyword for Screening			Step: Abstract screening
			Type 1	Type 2	Type 3	
1	Shafieezadeh and Ivey Burden, (2014)	Scenario-based resilience assessment framework for critical infrastructure systems: case study for seismic resilience of seaports.	resilience	Critical infrastructure/ seaport	assessment	X
	Vugrin and Camphouse (2011-a)	Infrastructure resilience assessment through control design.	resilience	infrastructure	assessment	No indicator
	MacKenzie and Barker (2013)	Empirical data and regression analysis for estimation of infrastructure resilience with applications to electric power outages	resilience	Infrastructure, electric power	estimation	No indicator
2	Ouyang and Wang (2015)	Resilience assessment of interdependent infrastructure systems: with a focus on joint restoration modeling and analysis	resilience	infrastructure systems	assessment	X
3	Ouyang and Dueñas-Osorio, (2014)	Multi-dimensional hurricane resilience assessment of electrical power systems	resilience	electrical power system	assessment	X
4	Vugrin et al., (2010)	A framework for assessing the resilience of infrastructure and economic systems	resilience	infrastructure	assessing	X
5	Shirali et al. (2012)	Assessing resilience engineering based on safety culture and managerial factors.	Resilience, safety	engineering	assessing	X
6	Shirali et al. (2013)	A new method for quantitative assessment of resilience engineering by PCA and NT approach: a case study in a process industry.	resilience	engineering	assessment	X
7	Adams et al. (2012)	Freight Resilience Measures.	resilience	Freight	measure	X
8	Henry and Emmanuel Ramirez-Marquez, (2012)	Generic metrics and quantitative approaches for system resilience as a function of time	resilience	System	Metrics, quantitative	X
	Barker et al. (2013)	Resilience-based network component importance measure.	resilience	network	measure	Measuring the importance of components
9	Pant et al. (2014)	Stochastic measures of resilience and their application to container terminals.	resilience	container terminal	measure	X
	Baroud et al., (2014a)	Importance measures for inland waterway network resilience.	resilience	inland waterway network	measure	Measuring the importance of critical waterway links
10	Baroud et al., (2014b)	Stochastic Measures of Network Resilience: Applications to Waterway Commodity Flows.	resilience	Network	measuring	X
	Wang et al., (2010)	Measurement of resilience and its application to enterprise information systems.	resilience	system	Measurement	No suitable for infrastructures
11	Chen and Miller-Hooks (2012)	Resilience: an indicator of recovery capability in intermodal freight transport.	Resilience, recovery capacity	intermodal freight transport	indicator	X
	Janic (2015)	Modeling the resilience, friability and costs of an air transport network affected by a large-scale disruptive event	resilience, friability and costs	transport network	Modelling	No indicator
12	Ayyub, (2014)	Systems resilience for multihazard environments: definition, metrics, and valuation for decision making	resilience	system	metric	X
13	Hashimoto et al., (1982)	Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation	Reliability, resiliency, vulnerability, performance	water resource system	Criteria, Evaluation	X
14	Franchin and Cavalieri, (2015)	Probabilistic assessment of civil infrastructure resilience to earthquakes	resilience	infrastructure	Assessment	X
	Attoh-Okine et al., (2009)	Formulation of resilience index of urban infrastructures using belief functions	resilience	Urban infrastructure	index	No indicator
15	Faturechi et al. (2014)	Evaluating and optimizing resilience of airport pavement networks	resilience		Evaluating	X
16	Faturechi and Miller-Hooks (2014)	Travel time resilience of roadway networks under disaster	resilience	Road network	Travel time	X (travail time)
	Azadeh et al. (2014)	Performance evaluation of integrated resilience engineering factors by data envelopment analysis: the case of a petrochemical plant	performance	Engineering, petrochemical plant	Evaluation	Assessing the reliability of indicators, not the resilience
	Cardoso et al. (2014)	Resilience assessment of supply chains under different types of disruption	resilience	supply chains	assessment	supply chains are not infrastructures
	Khaled et al. (2015)	Train design and routing optimization for evaluating criticality of freight railroad infrastructures	Criticality	freight railroad infrastructures	Evaluation	Identifying critical rail infrastructures
	(Spiegler et al., 2012)	A control engineering approach to the assessment of supply chain resilience	resilience	supply chain, engineering	assessment	supply chains are not infrastructures

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Table A1 (*continued*)

N° a	Source	Title	step: Keyword for Screening			Step: Abstract screening
			Type 1	Type 2	Type 3	
17	Adjetey-Bahun et al. (2014)	Planchet, A simulation-based approach to quantifying resilience indicators in a mass transportation system	resilience	transportation system	Indicator, quantifying	X
	Azadeh et al. (2014)	Assessment of resilience engineering factors in high-risk environments by fuzzy cognitive maps: a petrochemical plant	resilience	Engineering, petrochemical plant	assessment	supply chains are not infrastructures
	Muller (2012)	Fuzzy architecture assessment for critical infrastructure resilience	resilience	Critical infrastructure	assessment	presents an approach for the selection of alternative architectures in a connected infrastructure system
18	Enjalbert et al. (2011)	Assessment of transportation system resilience	Resilience	Transportation system	assessment	X
	Francis and Bekera (2014)	A metric and frameworks for resilience analysis of engineered and infrastructure systems	resilience	engineered and infrastructure system	metric	No indicator
19	Curt et al., (2010)	A knowledge formalization and aggregation-based method for the assessment of dam performance	performance	dam	assessment	X
	Petit et al., (2013)	Resilience Measurement Index: an indicator of critical infrastructure resilience.	resilience	Critical infrastructure	Measurement, index, indicator	No indicator
	Rosati and Touzinsky, (2015)	Quantifying coastal system resilience for the US Army Corps of Engineers	resilience	coastal system	Quantifying	Community resilience
20	Lhomme et al. (2013)	Urban technical networks resilience assessment	resilience	Technical network	assessment	X

the information sought, and for others because the message is not clear. In the spirit of furthering this work, the future idea could be to formalise a criterion and analyse all studies against this, eventually filling the "NA" in Fig. 6. Moreover, the future study could also suggest possible assessment methods for the articles that do not address the information intended.Table 4.

8. Conclusion

To investigate the existing resilience indicators for CIs, this paper undertook the following steps:

- define the elements to be identified for this study by presenting current studies for indicator-based assessment of CI resilience.

- screen the relevant scientific papers with two search methods, including the method for indicators identification;

- analyse the target elements based on results.

The results of the study contribute to a comprehensive understanding and application of resilience indicators for CIs. Meanwhile, it provides a clear orientation for further research (i.e., establishing an indicator system for CI resilience assessment). For this goal, several questions are highlighted based on the results of this review work:

- since the results show that indicators can be both general and specific, how develop general indicators systems that could be suitable for all CIs, at the same time specific and practical for applying to different CIs and contexts? Should the indicator system be classified into several levels for this issue?
- how to develop the general indicator systems that could be suitable for all CIs, which are also specific and practical for applying to different CIs and contexts? Should the indicator system be classified in several levels for this issue?
- how to construct the indicator systems that take into account implementing actions and interdependencies between CIs, internal components and also between CIs and other urban components?
- how does the indicator system address the shortcomings of existing indicators, like the lack of assessment relating to the Next Event Preparation Stage;
- how to establish efficient criteria for resilience assessment;
- how to formalise the methods for "resilience assessment" and "indicator assessment";

All of these questions are worth considering in the future.

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CRediT authorship contribution statement

Zhuyu Yang: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Bruno Barroca:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Alexandre Weppe:** Writing – original draft, Visualization, Investigation. **Aurélia Bony-Dandrieux:** Writing – review & editing, Supervision. **Katia Laffréchine:** Writing – review & editing, Supervision. **Nicolas Daclin:** Writing – review & editing, Supervision. **Valérie November:** Validation. **Khaled Omrane:** Validation. **Daouda Kamissoko:** Funding acquisition. **Frederick Benaben:** Validation, Methodology. **Hélène Dolidon:** Validation. **Jérôme Tixier:** Validation. **Vincent**

Table A2
Appendix 2: Papers Selected Through Second Reference Search.

N° b	Source	Title	Step 3: Keyword for Screening			Step 4: Abstract screening
			Type 1	Type 2	Type 3	
	Jovanović et al. (2018)	An indicator-based approach to assessing resilience of smart critical infrastructures	resilience	critical infrastructure	assessing	No source
1	Serre (2018)	DS3 Model Testing: Assessing Critical Infrastructure Network Flood Resilience at the Neighbourhood Scale	resilience	Critical Infrastructure	assessing	X
2	Fisher et al. (2010)	Constructing a resilience index for the enhanced critical infrastructure protection program	resilience	critical infrastructure	index	X
3	Reed et al. (2009)	Methodology for assessing the resilience of networked infrastructure	resilience	infrastructure	assessing	X
	Khazai et al. (2013)	An Integrated Indicator Framework for Spatial Assessment of Industrial and Social Vulnerability to Indirect Disaster Losses	Vulnerability	Industrial	Assessment	Social community resilience
	Molyneaux et al. (2016)	Measuring Resilience in Energy Systems: Insights from a Range of Disciplines	Resilience	Energy System	measuring	Assess security of oil supplies which is not infrastructure
	Vugrin et al., (2011)	A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane	Resilience	Infrastructure, petrochemical supply chains	assessment	Not for CIs
	Costella et al. (2009)	A method for assessing health and safety management systems from the resilience engineering perspective	Safety, resilience	System	Assessment	health and safety management systems
4	Carvalho et al. (2008)	Micro incident analysis framework to assess safety and resilience in the operation of safe critical systems: a case study in a nuclear power plant.	Safety, resilience	Systems, nuclear power plant	assess	X
	Saurin et al., (2011)	Evaluation and improvement of a method for assessing HSMS from the resilience engineering perspective: a case study of an electricity distributor	Resilience	electricity distributor, engineering	Evaluation, assessing	No infrastructure
5	Ip and Wang (2011)	Resilience and friability of transportation networks: evaluation, analysis and optimization	Resilience, friability	transportation networks	Evaluation	x
	Miller et al. (2004)	Evaluation of network reliability calculation methods	Reliability	network	Evaluation	It discusses network, not infrastructure
	Dutuit and Rauzy, (2005)	Approximate estimation of system reliability via fault trees.	Reliability	system	Estimation	It discusses network, not infrastructure
	Zhang et al. (2011)	A new holistic method for reliability performance assessment and critical components detection in complex networks.	reliability performance	network	Assessment	No indicator
	Kalyoncu and Sankur (1992)	Estimation of survivability of communication networks.	survivability	communication network	Estimation	No resource
	Cho (2002)	Three papers on measuring the reliability and flexibility of transportation system capacity	Reliability, flexibility, capacity	transportation system	Measuring	No resource
6	Morlok and Chang (2004)	Measuring capacity flexibility of a transportation system	capacity flexibility	transportation system	Measuring	Socio-economic system: transportation network service
	Najjar and Gaudiot, (1990)	Network resilience: A measure of network fault tolerance.	Resilience	Network	measure	No suitable for infrastructures
	Srinivasan (2002)	Transportation network vulnerability assessment: A quantitative framework.	vulnerability	Transportation network	Assessment	No indicator
7	Sun et al. (2006)	Estimating freight transportation system capacity, flexibility, and degraded-condition performance	Capacity, performance	freight transportation system	Estimating	x
8	Cox et al. (2011)	Transportation security and the role of resilience: A foundation for operational metrics	Resilience	Transportation	metrics	X
	Garbin, and Shortle (2007)	Measuring Resilience in Network-Based Infrastructures	resilience	infrastructure	Measuring	No resource
9	Omer et al., (2009)	Measuring the Resilience of the Global Internet Infrastructure System	resilience	Infrastructure	Measuring	x
10	Cavalieri et al. (2012)	Quantitative assessment of social losses based on physical damage and interaction with infrastructural systems	damage, loss	Infrastructural system	Assessment	x
11	Ouyang and Dueñas-Osorio, (2012-b.)	Time-dependent resilience assessment and improvement of urban infrastructure systems	resilience	infrastructure	Assessment	x
12	Li and Lence, (2007)	Estimating Resilience of Water Resources Systems	Resilience	Water Resources Systems	Estimating	X
13	Miller-Hooks et al. (2012)	Measuring and maximizing resilience of freight transportation networks	resilience	networks	Measuring	X
	Xu (2009)	Evaluating sustainability and resilience of complex systems using network theory.	sustainability and resilience	complex systems	Evaluating	No resource
14	Gilbo (1993)	Airport capacity: representation, estimation, optimization.	capacity	Airport	estimation	X
15	Winkler et al., 2010	Performance assessment of topologically diverse power systems subjected to hurricane events.	Performance	diverse power systems	assessment	X
	Chen et al. (2005)	Cascading dynamics and mitigation assessment in power system disturbance via a hidden failure model	Cascading dynamics and mitigation	power system	assessment	Not related to resilience

(*continued on next page*)

Table A2 (*continued*)

N° b	Source	Title	Step 3: Keyword for Screening			Step 4: Abstract screening
			Type 1	Type 2	Type 3	
16	Chang (2003)	Evaluating disaster mitigations: methodology for urban infrastructure systems.	disaster mitigation	infrastructure	Evaluation	X
	Fisher et al. (2009)	Constructing Vulnerability and Protective Measures Indices for the Enhanced Critical Infrastructure Protection Program	Vulnerability	Critical Infrastructure	Measure, indices,	No indicator

Chapurlat: Validation.

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

No data was used for the research described in the article.

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