

Review

Resilience Assessment Frameworks of Critical Infrastructures: State-of-the-Art Review

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Abstract: During the past two decades, critical infrastructures (CIs) faced a growing number of challenges worldwide due to natural disasters and other disruptive events. To respond to and handle these disasters and disruptive events, the concept of resilience was introduced to CIs. Particularly, many institutions and scholars developed various types of frameworks to assess and enhance CI resilience. The purpose of this paper is to review the resilience assessment frameworks of the CIs proposed by quality papers published in the past decade, determine and analyze the common dimensions and the key indicators of resilience assessment frameworks of CIs, and propose possible opportunities for future research. To achieve these goals, a comprehensive literature review was conducted, which identified 24 resilience assessment frameworks from 24 quality papers. This paper contributes to the current body of resilience research by identifying the common dimensions and the key indicators of the resilience assessment frameworks proposed for CIs. In addition, this paper is beneficial to the practice, because it provides a comprehensive view of the resilience assessment frameworks of CIs from the perspective of implementation, and the indicators are pragmatic and actionable in practice.

Keywords: resilience assessment framework; critical infrastructure; dimension; indicator

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1. Introduction

Critical infrastructures (CIs) are essential for the function of human societies and provision of vital societal services [1–4]. CIs consist of various components and physical or virtual goods, including electric power, water supply, wastewater, telecommunication, and transportation (e.g., rail, roads, bridges, highways, road tunnels, ports, waterways, and pipelines) [5]. CIs are crucial for the nation and community, and their destruction or damage will cause extensive losses for the health, economy, safety or security of the society [6–8]. However, CIs are inevitably exposed to disruptive events and hazards such as floods, earthquakes, tsunamis, landslides, hurricanes, wildfires, extreme temperatures, winter storms, and debris flows [9–11]. For instance, the severe floods that occurred in the UK in 2007 resulted in the failure of transport networks, the shutdown of emergency facilities, and the lack of water and electricity supply for nearly half a million people [12]. The 2011 Tohoku earthquake and the resulting tsunami in Japan drastically affected railways and highways, swept away 23 stations, and buried or eroded many piers and tracks [13]. During the devastating hurricanes Katrina in 2005 and Sandy in 2012 in the US, CIs suffered serious losses, especially in terms of electricity supply, and more than eight million users in 21 states suffered serious and large-scale power outages, which brought daily production and life to a standstill [14,15].

Obviously, recent disasters worldwide have demonstrated that not all the hazards can be predicted and averted [16,17]. To manage crisis and minimize the detrimental effects to CIs, the academia and the practice have started to direct their attention to CI

resilience [18,19]. Resilience was first introduced by Holling [20] in the field of ecosystems and defined as “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables,” which is considered as the origin of “modern resilience theory” [21–23]. From the early 2000s onward, the concept of resilience was widely applied in diverse domains, including economics [24,25], organization [26–28], engineering [29–31], and psychology [32–34]. The introduction of resilience to the CI sector was relatively late, but it is developing rapidly. By 2010s, CI resilience gained a prominent role and replaced the earlier focus on CI protection in scientific research and relevant policy documents. Several definitions of CI resilience have been proposed and discussed in the existing literature. For instance, the United Nation’s International Strategy for Disaster Reduction provided a generic definition applicable to CIs, namely, “resilience is the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions” [35]. According to the National Infrastructure Advisory Council, CI resilience is defined as “the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event” [36]. Similarly, Bocchini et al. [37] defined CI resilience as “the ability to deliver a certain service level even after the occurrence of a disruptive event, such as an earthquake, and to recover the desired functionality as fast as possible.” Among the multitude of definitions found, there were two main commonalities of CI resilience, namely, maintaining a minimum level of service and recovering after a disruptive event quickly [38].

In line with the grown concern of enhancing and managing CI resilience, the issue of measuring resilience has become a primary concern. Thus, as a basic method and operational tool to measure CI resilience, resilience assessment framework has captured considerable research attention in recent years [8,9,39–41]. The existing literature shows that resilience assessment framework must consist of several dimensions and indicators to comprehensively and effectively measure resilience [42,43]. In 2003, Bruneau et al. [44] were the first researchers to develop a resilience assessment framework. Their framework consisted of four essential dimensions: technical, organizational, social, and economic. In recent years, an increasing number of frameworks based on multidimensional indicators have been raised to evaluate the resilience of different CIs worldwide. For example, in 2014, the New Zealand Transport Agency published a research report with AECOM New Zealand Ltd., which proposed a framework utilizing technical and organizational dimensions to measure transport infrastructure resilience [45]. In 2015, the Los Angeles County Metropolitan Transportation Authority released a resilience assessment framework for transportation, which agreed that the technical and organizational dimensions are applicable to transportation [46]. In the same year, Labaka et al. [47] developed a framework and implemented it in a nuclear plant in southern Europe, which divided resilience into two categories, namely, internal and external resilience. In 2019, a resilience framework was offered for worldwide rural power systems in emerging economies, which consisted of technological, social and economic resilience components [48]. Balaei et al. [49] proposed a framework for global water supply systems, which contained four dimensions, namely, technical, organizational, social, and economic. Similarly, Sweya et al. [50] developed a framework of water supply systems in Tanzania, and added an environmental dimension to the framework of Balaei [49]. All these resilience assessment frameworks have played a major part in gauging and building up CI resilience worldwide.

There are some currently released review studies on CI resilience. These studies have varying focuses, including the concept of resilience, the methods of resilience analysis, modeling, simulation and evaluation, and the hazards affecting the building of CI resilience. For instance, Twumasi-Boakye and Sobanjo [51] reviewed the concept of resilience and its applications in various domains, with special emphasis in transport infrastructure. Mot-

tahedi et al. [52] conducted a systematic review, presented definitions of resilience in the discipline of CIs, identified 20 factors contributing to CIs resilience, and grouped and discussed resilience analysis approaches. Hosseini et al. [53] summarized several definitions of resilience in different domains and focused on qualitative and quantitative assessment approaches and their subcategories. Similarly, Quitana [6] and Cantelmi et al. [54] both aimed to provide synthetic reviews on resilience assessment methods used in the field of CI. Unlike assessment methodologies, Ouyang [55] focused on existing modeling and simulation approaches of CI resilience, and broadly categorized them into six groups. Liu and Song [56] analyzed the resilience of six different types of CIs respectively, including their definitions, hazard categories, research method, and enhancement strategies. Osei-Kyei et al. [57] provided a critical review of the hazards/threats affecting the building of CI resilience. Furthermore, several reviews are available in literature about resilience assessment frameworks, which have mainly focused on community and social resilience. For example, Serfilippi and Ramnath [58] reviewed resilience measurement and conceptual frameworks, which developed a series of critical indicators to measure community resilience. Examining 17 resilience assessment frameworks, Bulti [39] analyzed community resilience measurement tools in flood disaster management and defined seven evaluation criteria considering the multifaceted nature of resilience. Similarly, Almutairi et al. [59] provided a synthetical review of resilience frameworks for disaster risk management in coastal communities. Saja et al. [60] critically reviewed existent social assessment resilience frameworks and social resilience characteristics and indicators. Sepúlveda Estay et al. [61] focused on cyber-resilience assessment frameworks and analyzed a sample representing 36 industries and 25 research areas. However, none of these studies reviewed existing resilience assessment frameworks of CIs from a comprehensive perspective.

The aim of this paper is to conduct a comprehensive review of the resilience assessment frameworks of CI adopted by the extant literature. In addition, this review has a specific objective to summarize the assessment dimensions and sub-dimensions /indicators used in existing resilience assessment frameworks of CIs developed over the past decade. In this review, an in-depth analysis of the significant dimensions and sub-dimensions/indicators of 24 identified resilience assessment frameworks of CIs are presented. This paper also proposes future research opportunities for the resilience assessment frameworks of CIs. Thus, this paper can contribute to the current body of knowledge of resilience research. Furthermore, the research findings of this paper are beneficial to the practice, because this review can provide industry practitioners and related institutions with a holistic view of CI resilience and enhance their understanding in this regard.

2. Analysis of Resilience Assessment Frameworks of CIs

A systematic search of quality papers in the domain of CI resilience was conducted to discover and provide a comprehensive overview of resilience assessment frameworks adopted by the CI research. Furthermore, 24 papers containing resilience assessment frameworks were identified for this review.

2.1. Overview of Resilience Assessment Frameworks of CIs

Table 1 presents the details of 24 identified papers, as well as the assessment frameworks they proposed. According to Table 1, 19 out of 24 identified resilience assessment frameworks of CIs were released in the past seven years (i.e., 2015–2021), indicating that an increasing number of researchers have shifted their attention to assessment frameworks of CI resilience. These frameworks targeted diverse regions. About half of them focused mainly on evaluating CI resilience of Western countries, covering United States [46,62,63], New Zealand [45,64], Italy [65,66], and Czech Republic [67]. The infrastructure systems in Western countries were designed and maintained well, that is, researchers can assess their resilience easily and accurately [68–70]. Only Sweya [50] and Sen et al. [71] discussed CI resilience and its assessment framework of developing countries, Tanzania and India. The rest of the assessment frameworks were not targeted to specific countries or regions. These

scholars attempted to develop frameworks that can be universally applicable in Europe and even globally, especially Labaka, who has committed to build a practical and holistic framework to assess CI resilience [47,72–75].

In addition, the identified frameworks revolved around CIs, and some of them concentrate on a specific infrastructure. For instance, Balaei [49], Pagano [65], and Sweya [50] proposed frameworks for measuring water supply resilience. Mazur [48] provided a resilience framework of rural power infrastructure in emerging economies. Sen [71] developed a resilience framework against a flood hazard for housing infrastructure, which was then implemented in Barak valley North-East India to quantify the valley's resilience. Labaka [47] presented a holistic resilience framework of CIs, and used a nuclear power plant example to implement the framework in practice. Transportation infrastructure is one of CIs that is particularly crucial in guaranteeing the normal operation of cities [76,77]. Thus, the Los Angeles County Metropolitan Transportation Authority released the Resiliency Indicator Framework of the Metro's transit programs to address climate change [46]. Tonn [62] conducted a case study with Amtrak, a US rail passenger service provider, which developed a metrics framework to measure transportation infrastructure resilience. Patel et al. [78] used multicriteria decision-making techniques to establish a bridge resilience index framework, which aided in evaluating and enhancing bridge resilience to flood impacts. Freckleton [63], Hughes and Healy [45], and [62] also worked on the resilience assessment frameworks of transportation infrastructure.

Table 1. Basic information of identified resilience assessment frameworks of CI for analysis.

No.	Reference	Framework	Type	Country/Region	Year
1.	Freckleton [63]	Transportation Networks Resiliency Evaluation Framework	Transport	Salt Lake City	2012
2.	Labaka [72]	Resilience Framework of CIs	CIs	Global	2013
3.	Labaka [73]	Resilience Building Policies and Influence	CIs	Global	2013
4.	Hughes and Healy [45]	The Measurement Framework of Transport Resilience	Transport	New Zealand	2014
5.	Imran [64]	Transport Resilience Indicator Framework	Transport	Manawatu-Wanganui	2014
6.	AECOM [46]	Resiliency Indicator Framework	Transport	Los Angeles	2015
7.	Labaka [47]	A Holistic Resilience Framework of CIs	Nuclear plant	Europe	2015
8.	Labaka [74]	Framework to Improve the resilience of CIs	CIs	Europe	2015
9.	Bertocchi [66]	CIs Resilience Evaluation Guidelines	CIs	Italy	2016
10.	Labaka [75]	Framework of Building CIs Resilience	Nuclear plant; Water supply	Europe	2016
11.	Balaei [49]	Water Supply Resilience Measurement Tool	Water supply	Global	2018
12.	Pagano [65]	Water Distribution Systems Assessment Framework	Water supply	L'Aquila	2018
13.	Petrenj et al. [79]	READ framework	CIs	Europe	2018
14.	Mazur [48]	Rural Power Systems Resilience Framework	Power	Global	2019
15.	Rehak et al. [80]	CI Elements Resilience Assessment Framework	CIs	Czech	2019
16.	Patel [78]	Bridge Resilience Index	Transport -bridge	Global	2020

Table 1. *Cont.*

No.	Reference	Framework	Type	Country/Region	Year
17.	Splichalova [67]	CIs Elements Resilience Assessment Framework	CIs	Czech	2020
18.	Sweya [50]	The Tool to Measure Resilience of WSS	Water supply	Tanzania	2020
19.	Tonn [62]	Transport Resilience Index	Transport-rail	US	2020
20.	Jovanovic et al. [81]	The Approach to Assess Healthcare Infrastructure Resilience	Healthcare infrastructure	Global	2020
21.	Jhan et al. [82]	Socioeconomic Vulnerability Indicator Framework	Infrastructure	Taiwan	2020
22.	Mottahedi et al. [83]	Assessment of Green Infrastructure	Green Infrastructure	Global	2021
23.	Fu et al. [84]	Resilience Estimation of CI systems	CIs	Global	2021
24.	Sen [71]	Resilience Quantification Framework for Housing Infrastructure	Housing Infrastructure	India	2021

2.2. Dimensions of Resilience Assessment Frameworks of CIs

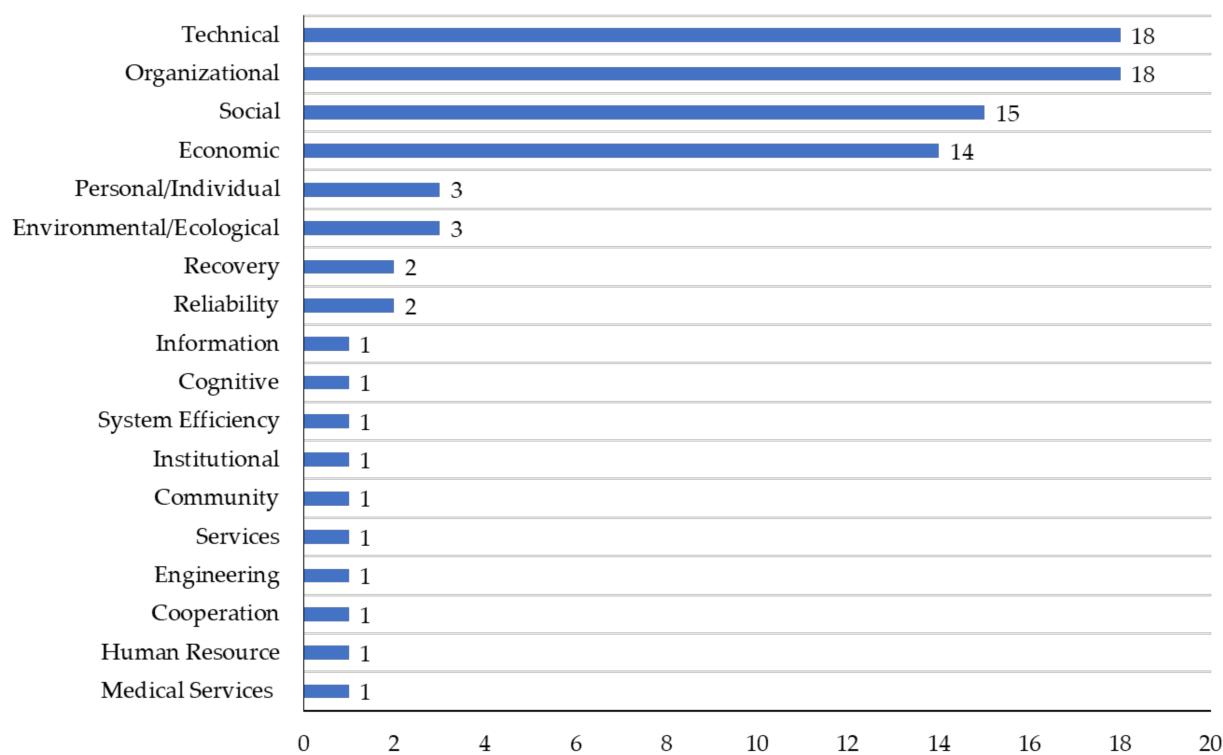
CI resilience is a complex concept and cannot be assessed from one aspect alone [49,85]. Therefore, the frameworks of evaluating CI resilience have formed various dimensions. To supply a complete picture of CI resilience evaluation dimensions, this paper extracted and summarized all the evaluation dimensions from 24 identified frameworks. Finally, a total of 16 dimensions were identified, as shown in Table 2. Among the 16 dimensions, technical, organizational, social, and economic dimensions could be the four most essential evaluation dimensions as they were mentioned frequently. The technical dimension was the most prevalently analyzed in literature, which was proposed in 18 assessment frameworks. Organizational dimension was valued by researchers as well as the technical dimension, which also appeared 18 times. The other two dimensions, social and economic, appeared 15 times and 14 times, respectively. The number of occurrences of each dimension in 24 identified resilience assessment frameworks is shown in Figure 1. According to the figure, in addition to these top four essential dimensions, the other 14 dimensions only appeared three times or less. Due to the limitation of words and space, this paper primarily discussed and analyzed technical, organizational, social, and economic dimensions, ignoring the uncommon dimensions that only occurred three times or less.

According to the review, the technical dimension of resilience mainly refers to the capability of the physical systems to perform to an acceptable/desirable level when subject to a disruptive event [44,86,87]. This dimension is a core aspect in CI resilience, and it focuses on the vulnerability and recovery of hard systems of CIs, encompassing components, their interconnections and interactions, and the entire systems.

The organizational dimension of resilience relates to the capacity of organizations to decide and take actions to prepare for and respond to a disruptive event [44]. When the infrastructures do inevitably fail, the timely and successful restoration relies on organizations to respond effectively, thus, the organizational dimension is a vital element of CI resilience [3,88]. The organizations refer to all those that manage critical facilities and are responsible for performing critical functions related to disasters, including public and private sectors. Their performance affects the availability of CIs when subject to a disruptive event. In addition, the organizational domain of CI resilience emphasizes the effects of institutional conditions on infrastructure flexibility and resilience [49].

Table 2. Dimensions of the identified resilience assessment frameworks of CIs for analysis.

No.	Dimension	Total
1.	Technical	18
2.	Organizational	18
3.	Social	15
4.	Economic	14
5.	Environmental/Ecological	3
6.	Personal/Individual	3
7.	Reliability	2
8.	Recovery	2
9.	Engineering	2
10.	Services	1
11.	Cooperation	1
12.	Community	1
13.	Institutional	1
14.	System Efficiency	1
15.	Cognitive	1
16.	Information	1
17.	Human Resource	1
18.	Medical Services	1

**Figure 1.** The number of occurrences of each dimension in 24 resilience assessment frameworks.

The social dimension of resilience looks at the capacity of social relationships and networks to lessen the negative effects of catastrophes, explaining society's response to disruptive events [89,90]. Social resilience is described by Adger [91] as the ability of groups

or communities to cope with external pressures and disturbances caused by social, political, and environmental changes. Following Labaka [75], social resilience is the capability of society to reduce the impacts of disasters by helping first responders or acting as volunteers. Pagano [65] divided CI resilience into “hard” and “soft” infrastructural resilience, and regarded the social domain as soft infrastructural resilience.

The economic dimension of resilience refers to the capability to minimize direct and indirect financial losses resulting from a crisis [44,65]. Economic resilience is defined by Labaka [74] as the ability of organizations to absorb and balance the additional costs that arise from disruptive events. According to Balaei [49], resilience is greatly affected by the economic domain, including the country’s overall economic status and average economic situation at the individual level.

2.3. Indicators of Resilience Assessment Frameworks of CIs

To gauge resilience, indicators of resilience assessment frameworks of CIs must be developed and identified, which is one of the most prominent methods of disaster resilience assessment [92]. Estimating CI resilience using only the technical, organizational, social, and economic dimensions is difficult. The indicators of each dimension must be determined and standardized. Indicators are the fundamental tools of the frameworks and evaluation process and are quantitative attributes of the dimensions, capabilities, and characteristics of the infrastructure being assessed [49,66]. In the 24 identified frameworks, the indicator has different names, such as guideline [66], attribute [63], principle [45], metrics [62,65], and capacity [79]. Indicators have different definitions, because when considering the general concept of indicators, ambiguities and contradictions are likely to arise. This paper only focuses on resilience indicators, which were defined by Balaei [49] as operational variables that represent the availability, quality, or features of the system in terms of technology, organization, society, or the economy; these variables also affect the system’s resilience to destructive disasters. Throughout all the frameworks, 87 indicators of technical, organizational, social, and economic dimensions were identified. This paper discusses indicators with universal applicability; thus, only indicators that appear more than three times were identified and reviewed due to space constraints. Table 3 shows the indicators that meet the requirements. The following sections will review and discuss these indicators in detail.

Table 3. Identified indicators of technical, organizational, social, and economic dimensions.

Dimensions	Indicators	Frequency
Technical	1.1. Robustness	9
	1.2. Maintenance	6
	1.3. Safety design and construction	5
	1.4. Data acquisition and monitoring system	5
	1.5. Emergency equipment	5
	1.6. Redundancy	5
	1.7. Recoverability	5
Organizational	2.1. Adaptability	6
	2.2. Government preparation	5
	2.3. Crisis regulation and legislation	5
	2.4. First responder preparation	5
	2.5. Change readiness	4
	2.6. Leadership and culture	4
Social	3.1. Societal situation awareness/ preparation	5
Economic	4.1. Crisis response budget	5
	4.2. Public crisis response budget	5

2.3.1. Indicators of Technical Dimension

Robustness—Robustness is the most commonly used principle as it appears nine times, more than all other principles of the four dimensions. Robustness refers to strength, or the capacity of the system to withstand shock and pressure without performance degradation or loss of functionality [44,48,65,78,93–95]. In other words, to withstand destructive events, hardware components can be reinforced or replaced with more durable alternatives in the process called “hardening” or “resilience engineering” [96,97], aiming to enhance the robustness of vulnerable parts. From a technical perspective, when the robustness level of the hard infrastructure reaches 100%, the relevant components will be able to completely resist the effects of disruptive events without perceptible negative effects [98]. To measure the level of robustness, different studies have different classification methods. For example, Hughes and Healy [45] divided the robustness principles into three measurement categories of structural, procedural, and interdependencies and then scored them separately. However, Rehak [94] considered that robustness is determined by five variables, namely, crisis preparedness, redundancy, detection ability, responsiveness, and physical resistance. Although the measurement categories are not the same, the significance of technical robustness is the same.

Maintenance—Maintenance is the second most important evaluation indicator because its frequency of appearance ranks second. Tonn [62] described maintenance as standard operating procedures for sustaining assets and ensuring safe and reliable operations, including post-accident procedures. CIs need regular high-quality maintenance to ensure high efficiency and reliability of the components and systems. A good level of maintenance helps resist disruptive events and can also decrease the impact and recovery time [74,75,99]. From a technical perspective, indicator maintenance can be divided into two sub-indicators: preventive and corrective maintenance [47,72]. Preventive maintenance refers to the means used to withstand major threats and avoid failures prior to the occurrence of events. The components of CIs require regular maintenance and update of old parts and technical features in time to guarantee that they are in the correct state. Well-maintained infrastructures help identify early warning signs and deal with them before incidents occur. Conversely, corrective maintenance refers to activities performed to repair malfunctioning components or systems after an accident. Once a failure occurs, the cause must be analyzed and corrective actions are determined to avoid recurrence.

Safety design and construction—Safety design and construction appeared five times and ranked third, becoming the third most important evaluation criterion of CI resilience. This indicator refers to the security level of CIs and their ability to avoid crises and effectively absorb the impacts. Having a security subsystem and redundant components and subsystems can prevent crises and ensure the functionality of CIs [44,75]. The design of CIs should have appropriate complexity according to requirements to ensure a high level of resilience. At the same time, the design should meet the current normative specifications and requirements. In addition, construction should be performed based on the design and establishment to meet all established requirements and enhance the safety of CIs. Based on the review, the lifecycle of resilience consisted of three stages, namely, prevention, absorption, and recovery. The effects of the indicators at each stage were evaluated in the range of 0–5 (0 means no impact, 5 means strong impact). The average scores of safety design and construction in three stages are 4.3, 4.1, and 3.8, indicating that this indicator has a high contribution to CI resilience [74,75]. To better define its scope, four sub-indicators were identified: safety systems, redundancy, simplicity and loose coupling, and audits [47,72].

Data acquisition and monitoring system—Data acquisition and monitoring system and safety design and construction appear at the same frequency; however, their contribution to resilience is different. The average scores of data acquisition and monitoring system in three resilience stages (prevention, absorption, and recovery stage) are 3.9, 3.8, and 2.8, which are slightly lower than safety design and construction [74,75]. This indicator looks at gathering CI data information and monitoring system operating status, which should be

implemented throughout the process. This indicator has two sub-indicators, namely, data acquisition equipment and information monitoring equipment [47,72]. Data acquisition equipment (e.g., sensors) is used to collect key data to monitor the normal operation of CIs. Data collection must determine the critical parts of CIs to ascertain the specific data required for the proper functioning of these key parts. Information monitoring equipment refers to the processing, transmission, storage, and monitoring of different points of CIs after the data are collected to check whether the data are within the correct value range; otherwise, it will trigger an alarm to notify the staff.

Emergency equipment—Emergency equipment refers to the response to crises to absorb the impact and ensure the safety of staff [47,72–75]. This indicator can be used to measure internal and external resilience of CIs. Thus, not only the internal equipment of CIs is needed but external stakeholders, such as emergency personnel, government, and society, should also have reliable and sufficient technical equipment to deal with the plight. Internal and external crisis emergency equipment shall be reliable to guarantee properly function when necessary. In addition, the technical department should ensure that the equipment is always available in a disruptive event. When scoring emergency equipment in the range of 0–5 on the three resilience lifecycle stages (prevention, absorption, and recovery stage), the scores of internal emergency equipment of CIs are 2.8, 4.4, and 3.9, whereas the scores of external emergency equipment are 2.3, 3.7, and 3.6 [74,75]. The scores indicate that internal and external emergency equipment have relatively low impacts in the prevention stage and high impacts in the absorption and recovery stages. Generally, the impact of internal emergency equipment is higher than that of the external on the resilience lifecycle stages.

Redundancy—Redundancy refers to the degree to which substitutable elements, systems, or other infrastructures are present, that is, the ability to meet functional requirements in the event of interruption, degradation, or loss of functionality [44,51,65,78,100]. It describes the availability of alternative resources, including backup/replicate systems, materials, equipment, and alternative routes in the CI (e.g., transportation or backup power). Bruneau [44] first recommended that research should consider four attributes of resilience robustness, rapidity, resourcefulness, and redundancy, combined with technical, organizational, social, and economic dimensions to evaluate the resilience of any infrastructure. From a technical perspective, more replaceable elements and technical components are needed to make CIs more resilient. Thus, the redundancy principle is proposed for assessing the CI resilience in the technical dimension.

Recoverability—Recoverability, or restorative, has been used to measure resilience in the five identified frameworks. With regard to CIs, recoverability is understood as reparability, which refers to the capacity of a system or component to restore its function to either its original, required performance, or in combination, level after the effects of disruptive events have worn off [66,67]. On the basis of the review, recoverability is determined by four variables, namely, material resources, financial resources, human resources, and recovery processes [67]. Material resources refer to the availability of parts needed to repair or replace damaged or aging components. Financial resources depend on whether financial resources or reserves are available to fund the fast recovery of this element. Human resources look at the availability of human resources with the required qualification level. Recovery processes are key processes in helping to quickly restore the required performance of the component. If the above four attributes meet the demand, then the infrastructure will be highly recoverable, which can strengthen resilience.

2.3.2. Indicators of Organizational Dimension

Adaptability—Adaptability is the resilience indicator of the organizational dimension that appears most frequently in the identified frameworks, ranking first with the government preparedness indicator, with five occurrences each. Adaptability refers to the dynamic ability of a system to adapt to undesirable circumstances by undergoing some changes [36,40,66,67,94,101]. In essence, resilience is the capacity of a CI organization to

plan and adapt to an emergency for survival and development in an uncertain environment [3,101]. Moreover, the level of resilience of infrastructures relies upon their ability to predict, and absorb, adapt and quickly recover from potentially disruptive events [36,40]. Thus, adaptability is a crucial indicator to gauge organizational resilience. Adaptive and absorptive capacities should be distinguished. Absorptive capacity is the ability of the system to absorb interference, whereas adaptive capacity indicates that the system undergoes some changes to adapt to the dilemma, generally when the absorptivity fails. Improving the adaptability of CIs to disruptive events is divided into three stages: risk management, innovation process, and education and development process.

First responder preparation—First responder preparation refers to how first responders (e.g., firefighters, emergency forces, police, and military) are prepared and trained to face a dire situation prior to its occurrence [47,72,74,75,99]. It can be divided into two sub-indicators: first responder training and first responder situation awareness and commitment. First responders have to be trained the emergency response procedures established before a disruptive event arises, such that they can respond to emergency circumstances and assure social security quickly and effectively. First responder situation awareness and commitment are also essential, as they must always be aware of possible accidents and commit themselves to the process of building CI resilience [102]. In addition, CIs can significantly improve the situational awareness and commitment level of first responders by performing training programs and reminding them of possible crises.

Government preparation—Government preparation indicates that the governments have to figure out and anticipate the possible events that may trigger crises and make full preparations for crisis management [72–75,99,103,104]. Similar to first responders, the government acts as a pivotal part in the CI's response to dilemmas and should also determine emergency response procedures prior to the critical situations to clearly comprehend how to act quickly when a severe crisis occurs. Conversely, the government has the power and ability to enhance the awareness and commitment of organizations and first responders to the process of building resilience and can provide resources to help CIs resolve crises. On the basis of the review, five major sub-indicators under this resilience metric are about government situation awareness and commitment, government training, government communication capacity, government leadership capacity, and coordination of the response agents.

Crisis regulation and legislation—Crisis regulation and legislation looks at the maturity and compliance level of regulations and laws. Legislation is a law approved by the government body, whereas regulations are guidelines formulated by government agencies or other authorities that describe how to implement the legislation in detail. With clear and updated regulations and legislation, CIs can be more secure, better guard against the occurrence of a crisis, and better deal with one when it happens. In addition, regulations and laws should be regularly updated and examined to determine who is responsible in the event of a crisis [47,72–75]. This indicator basically depends on the level of crisis awareness of the government and organization, and assisting its development is difficult for CIs. Moreover, crisis regulation and legislation can be disaggregated into two sub-indicators: regulations and law revisions and updates, and the compliance level of regulations and laws.

Change readiness—Change readiness in organizational resilience is widely defined by scholars and has rich connotations. This indicator mainly looks at the organizations' ability to perceive and predict dangers, identify problems and breakdowns, and provide early warning of interference threats and their effects by improving alertness and understanding the vulnerability of CIs. At the same time, it includes the ability to be flexible, able to change, develop or adopt alternative strategies in accordance with the ever-changing environment, and learn from it. Resourcefulness is also included in the concept of change readiness, which is defined as the capacity to adjust materials and human resources to prepare for, respond to, and manage crises or destruction [30,36,44–46,105]. Given its broad definition, change readiness has many sub-indicators as follows: warnings for the

general public, communication systems for the staff, sensor installation and use, collection of current weather data, backup critical information, risk assessment, scenario planning, business continuity procedures, combined/joint external planning, internal understanding of emerging threats and new stressors, and training/drills [46,62]. Following Sweya [50], the sub-indicators also include awareness, emergency response plan, communication and warning, and planning strategies.

Leadership and culture—Leadership and culture, also known as resilient leadership and organizational culture, refers to the ability to cultivate an organizational mentality/culture that is passionate about challenges, agility, flexibility, adaptability, and innovation and takes advantage of opportunities [45,46]. A resilient organization should cultivate these capabilities by building trust, clarifying goals, empowering employees, and encouraging employees to improve their personal resilience. It should also promote a consistent and transparent organizational commitment to a resilient culture, value, and vision. In addition, the establishment of organizational culture has become an indispensable index for enterprises to be resilient and sustainable [106]. On the basis of the review, leadership and culture have the following sub-indicators: leadership, decision making, situational awareness, innovation and creativity, political will, and staff engagement and involvement [46,50].

2.3.3. Indicators of Social Dimension

Societal situation awareness/preparation—Societal situation awareness/preparation refers to the public's awareness level of the risks and vulnerabilities they face in unfavorable situations. Its commitment to avoiding crises lessens the possibility and degree of impact of emergency and advances society's capacity to respond to crises [47,74,75,102]. In addition to the government and first responders being prepared to deal with crises, the society can also play a key role in resolving crises [107]. Moreover, the society can provide cooperation and resources, which are essential to strengthen crisis management. According to Labaka [47], two sub-indicators have been defined within this indicator: societal situation awareness and commitment, and societal training. CIs should inform the society of the risk, and the society should be aware of the possibility of incidents and be committed to crisis management. In addition to being conscious, the public should also be trained by CIs to understand how to act or help in handling crises. The importance of this indicator is reflected in the Prestige disaster. In this case, the proper response of social volunteers not only helped clean up Galicia's expenses, but also enabled more organizations and governments to participate [108].

2.3.4. Indicators of Economic Dimension

CI crisis response budget—CI crisis response budget indicated that while a disruptive event occurs, CIs need to reserve currency to absorb the impact and repair and replace facilities, so as to restore the acceptable state as soon as possible [47,72,73,75,99]. In order to improve economic resilience, the CI should have a response budget to repair damages in time, purchase new components, and employ workers and equipment temporarily. If the CI crisis response budget is lacking, CIs will need more time and funds to restore to initial state after encountering a crisis, and the economic resilience will be reduced.

Societal situation awareness/preparation—Public crisis response budget is similar to CI crisis response budget, but the subjects of reserved response funds are different. Similarly, as the CI should have a crisis response budget, public institutions should also set aside a crisis response budget to help stakeholders and society in times of crisis [47,72,73,75,99]. This additional funding enables organizations, the society and first responders to obtain monetary resources within a reasonable period of time after the crisis, such that they can perform repair and reconstruction activities and compensate the affected CIs and people. The government's commitment and awareness level may affect the establishment of this funding, thereby affecting this indicator.

Based on the literature review above, this paper summarized a typical framework that could be used to assess CI resilience, as presented in Figure 2.

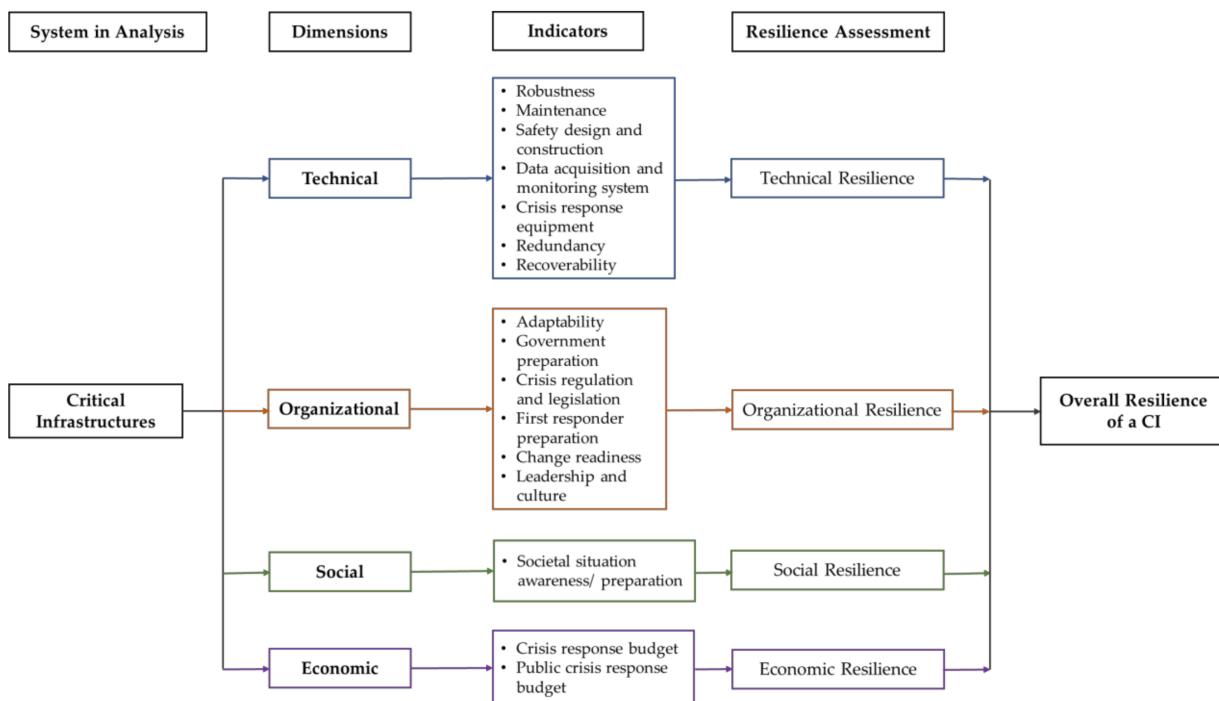


Figure 2. Typical framework for measuring CI resilience.

3. Future Research Opportunities

3.1. Implementation of Resilience Assessment Frameworks

On the basis of the review, the existing research on resilience assessment frameworks generally presents an analysis of the state of the art on definition and assessment frameworks of resilience [6,51,58,60], as well as the development and comparison of resilience measurement dimensions, metrics, and approaches [2,39,43]. In comparison, studies on the implementation of resilience assessment frameworks are limited. In fact, a systemic study of the implementation of resilience assessment frameworks is essential. Moreover, studying how many CIs have adopted resilience assessment frameworks worldwide and checking their implementation and results in different situations are necessary. Only by putting the proposed frameworks to CIs in practice can researchers check the applicability and reliability of the indicators. Furthermore, the obstacles and limitations to the implementation of resilience assessment frameworks in CI industries must be analyzed, and some corresponding effective and workable solutions must be proposed.

3.2. The Adjustment and Correction of the Existing Dimensions and Indicators

This paper analyzes 16 indicators under the technical, organizational, social, and economic dimensions based on 24 identified resilience assessment frameworks, but they may not be feasible and applicable to all situations. For different CIs, different countries or regions, different types of geographically specific communities (e.g., coastal, rural, and urban), and even different disruptive events, the meaning and priority of resilience indicators may change. Therefore, future research should adjust, revise, and update the resilience indicators of the framework based on specific circumstances.

3.3. The Investigation of Environmental Impact Dimension of CI Resilience Assessment

Over the past decade, in addition to technical, organizational, social, and economic dimensions, environmental impact has become a core dimension in measuring resilience [109,110]. The life-cycle environmental dimension of resilience has significant impacts on the sus-

tainability and robustness of a CI [111]. In particular, when considering climate change consequences, environmental impacts are critical to risk assessment and CI resilience [112]. However, only three of the identified 24 resilience assessment frameworks of CIs in this paper considered the environmental dimension [50,64,84]. According to Imran [64], disruptive events also have environmental impacts on CI resilience, but it was proved difficult to quantify environmental dimension and determining its indicators. Therefore, the environmental impact dimension of CI resilience should be investigated and emphasized in future research, apart from four core dimensions analyzed in this paper.

3.4. Development of a Rating Approach to Evaluate CI Resilience Indicators

Although the dimensions and indicators of CI resilience have been identified in recent studies [40,49], there is a lack of an applicable rating approach to evaluate all categories of indicators on CI resilience. According to the literature review in this paper, the rating mainly focused on these resilience indicators: ‘Safety and construction’, ‘Data acquisition and monitoring system’, and ‘Emergency equipment’. Some indicators like ‘Robustness’, ‘Maintenance’, and ‘Adaptability’ lack a scientific rating with regards to their contribution to the resilience of CI. Thus, it would be important and necessary to develop a rating approach that can evaluate all indicators of CI resilience. By doing so, the relative importance of the contribution of different indicators to resilience could be revealed, and it also allows CIs to determine which indicators should take precedence over others.

4. Conclusions

Resilience refers to the capacity of a system to maintain its function in the face of destruction, and it has been studied and applied in many different disciplines in recent years. In response to crises, CI resilience has become a hot topic in recent academic research. The framework for measuring resilience is important as it reveals how well a given CI behaves in front of disruptive events. This paper provides a comprehensive review of 24 resilience assessment frameworks published from 2011 to 2021. It analyzes the dimensions and indicators included in the identified frameworks and proposes future research opportunities.

First, this paper reviewed the origin and importance of resilience, as well as the definition of resilience proposed by authority agencies and scholars in recent years. It adopted the definition of CI resilience as the ability to reduce either the magnitude, duration, or both, of disruptive events. The paper then conducted a systematic literature search and identified 24 resilience assessment frameworks. This paper reviewed the dimensions and indicators of the identified assessment frameworks and found that the indicators from the frameworks are multidimensional, and the common dimensions are technical, organizational, social, economic, environmental, personal, and community. Particularly, technical, organizational, social, and economic are the four dimensions used most by the identified frameworks and thus are considered as the four basic measurement dimensions of CI resilience.

This paper also reviewed and analyzed the indicators under each basic dimension. The review found that many indicators exist in the technical and organizational dimensions, whereas relatively few indicators are present in the social and economic dimensions. Particularly, the review identified seven main indicators of the technical dimension, which are robustness, maintenance, safety design and construction, data acquisition and monitoring system, emergency equipment, redundancy, and recoverability. The review then summarized six major indicators of the organizational dimension, which are first responder preparation, government preparation, crisis regulation and legislation, adaptability, change readiness, and leadership and culture. In addition, this paper found that the most important indicator of the social dimension is societal situation awareness/preparation, and the two most important indicators of the economic dimension are crisis response budget and public crisis response budget. Furthermore, this paper proposed four major future research opportunities of resilience assessment frameworks, that is, research on the implementation

of resilience frameworks to CIs, adjustment and correction of the existing dimensions and indicators, investigation of environmental impact dimension of CI resilience assessment, and development of a rating approach to evaluate CI resilience indicators.

Although efforts have been made to review the resilience assessment frameworks of CIs, inevitably, some limitations still exist. First, due to limited time and space, this paper cannot cover all the dimensions, indicators, and even sub-indicators of every proposed resilience assessment framework of CIs. Second, because of the limit of the search code and scope, some studies that investigated resilience assessment frameworks of a specific CI might be omitted. In spite of the limitations, the findings of this review are still valuable. This is the first study reviewing resilience assessment frameworks of CIs, summarizing the significant dimensions and indicators of existing resilience assessment frameworks of CIs, and proposing future research opportunities. In addition, combining practice with theory, this paper has practical implications as well. Because it analyzes practical assessment dimensions and indicators used in resilience frameworks of CIs, it reveals the implementation status of the different resilience assessment frameworks of CIs in the real world. Moreover, the findings of the review suggest that the authorities and industry practitioners should adjust the resilience assessment framework in the light of the actual situations and consider using multi-dimensional indicators to evaluate CI resilience instead of a single dimension.

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