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A unified framework for evaluating the resilience of critical infrastructure: Delphi survey approach

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ABSTRACT

This study advocates establishing an indicator system for Critical Infrastructure (CI) resilience assessment to ensure consistency and comparability in future endeavors. Resilience has emerged as a fundamental framework for effectively managing the performance of CIs in response to the challenges posed by disaster events. However, it is evident that a lack of uniformity exists in the choice and standardization of resilience assessment across the identified frameworks. This paper proposes key attributes for facilitating resilience assessment of CIs using an in-depth literature survey for identification and two rounds of Delphi survey in the Sri Lankan context for their verification. The literature survey has analyzed the resilience assessment attributes under four types of capacities: planning (anticipative), absorptive, restorative, and adaptive. Twenty-seven resilience attributes (Planning: 6; Absorptive: 12; Restorative: 6; Adaptive: 3) under different capacities were identified, including sub-indicators for evaluating each resilience attribute. Outcomes of the Delphi survey were analyzed through descriptive statistics. The proposed attributes received high levels of agreement from the experts, indicating their suitability and applicability for assessing the resilience of the CIs. The mean ratings of the attributes varied from 4.0 to 5.0, with the majority exceeding 4.5 out of 5. The evaluation of these attributes will be useful for assessing the resilience capacity of the CIs and thereby to model the overall resilience of the CIs. The results of this study will provide a solid basis for formulating hypotheses in future research aimed at assessing CI resilience.

1. Introduction

Critical infrastructures (CIs) are intricate and complex networks which non-linearly work together with multiple components to

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sustain societies [1–5]. They are created to meet specific social needs and must maintain the integrity and functionality of modern societies, including the supply of vital services such as electricity, gas, water, transportation, and telecommunication services [5–7]. Nonetheless, due to their importance and exposure, CIs are susceptible to various threats and disturbances, such as natural disasters, accidents, cyber-attacks, terrorism, mischievous behavior, criminal activities, and negligence. Therefore, ensuring the resilience of CIs through reliable assessments is crucial to the survival of modern communities [4–6,8,9].

The concept of resilience in the built environment first appeared in the late 90s and gained importance after many catastrophic events [10–12]. The objective of resilience was to create more robust, secure, and adaptable infrastructures [6,8,13,14]. Resilience takes into account not only the physical and technical aspects of CIs but also, more recently, the social, ecological, and economic consequences by adopting a "hybrid socio-ecological-technical" approach [15–18]. This approach recognizes that urban resilience is multi-dimensional and interconnected [18–22]. Social aspects, such as community cohesion and social networks, play a vital role in disaster response and recovery [18,20,21]. Ecological aspects, including green infrastructure and ecosystem services, are crucial for urban resilience as they contribute to climate regulation, water management, and biodiversity support. Technological advancements enable efficient monitoring, response, and recovery operations by enhancing overall system robustness [23–25]. Economic resilience ensures that resources are available for recovery and adaptation efforts, supporting the sustainability of communities in the face of disruptions [18,26]. Acknowledging and integrating these interlinkages allow for a more comprehensive and effective resilience strategy, ensuring that all facets of urban systems are considered and reinforced [18–21,26,27]. These dimensions are interdependent [18–22,26]; for example, technological innovations can improve ecological monitoring and management, while strong social networks can enhance the effectiveness of technological solutions. This holistic approach not only improves the immediate response to crises but also fosters long-term sustainability and adaptability of urban environments [18,19,21].

Resilience refers to a system's ability to withstand and recover from a disruptive event by absorbing a specific shock or threat and minimizing the time required to restore balance [5,28–31]. A resilient society can endure unexpected events by efficiently and quickly planning, absorbing, recovering, and adapting all its essential functions and structures. Therefore, it is necessary to assess the resilience of CIs before, during, and after a disruption [4,32,33]. Evaluating resilience before a disruption and implementing appropriate preventive measures will enhance a system's resilience and improve its functionality, leading to economic benefits. A failure in CIs could have a significant impact on the built environment, public health, and society [10,34,35]. Given that climate change is affecting weather patterns and the availability of natural resources, and with 70 % of the world's population expected to live in urban areas by 2050 [36], it is crucial for developing countries to improve the resilience of CIs by adopting proper planning and adaptation strategies to recover from adversity.

A resilient system embodies sustainability principles and aligns with the three pillars of sustainability: society, economy, and the environment [33,37]. It is in accordance with the 9th and 11th Sustainable Development Goals (SDGs) established by the United Nations (UN), focusing on building resilient infrastructure, inclusive and sustainable industrialization, innovation, and creating safe, resilient, and sustainable cities [4,33]. The UN recognizes the importance of reducing the risk of CI failure by understanding vulnerabilities and threats, enabling the development of effective risk mitigation plans to manage and minimize the impact of adverse events [4,37]. By understanding these risks, effective plans for risk mitigation can be developed to manage and minimize the potential impact of adverse events. This approach is crucial for ensuring the long-term sustainability and resilience of CIs [4,33].

The assessment of CI resilience has been the subject of various metrics and definitions proposed in previous literature. Previous approaches have involved the use of quantitative and qualitative methods, as well as empirical methods based on data and hypothetical scenarios [8,24,38–40]. However, these methods have limitations, such as evaluating resilience based on available information and data, subjectivity in the responses provided, and their specificity to particular CIs or scenarios, which restricts their generalizability [13,39–41]. Primarily, the resilience of CIs in the context of disruptions was evaluated under three distinct approaches in the literature: engineering, ecological, or socioecological perspectives. By considering multiple perspectives, these approaches offer more comprehensive and in-depth insights into assessing CI resilience, allowing researchers to gain a deeper understanding of the complex dynamics involved [5,15,42].

Previous research studies have extensively explored the determination and assurance of CI resilience [13,15,43,44]. However, the available knowledge is scattered across various research contexts, and while several resilience assessment frameworks exist, they are often domain-specific and do not adequately address the interdependencies among infrastructures such as water, transport, and electricity [8,25,45–47]. An individual infrastructure operates as an interconnected system of systems. Therefore, a disruption in one infrastructure can affect the others and cause cascading failures. Thus, to model and comprehensively assess the resilience, a common framework is required in order to recognize the interdependencies [5,14,48]. To facilitate that, a comprehensive resilience assessment that can evaluate resilience across different systems and levels is much needed. Establishment of a unified framework would facilitate the study of interdependencies among CIs and enable the benchmarking of resilience across CIs. This, in turn, would enhance the capability to manage and mitigate the effects of disruptions [49,50]. Therefore, there is a need for a thorough assessment of the current literature on CI resilience assessment criteria and standards to establish a foundation for relevant hypotheses in future research.

The specific objective of this study is to propose a resilience assessment framework and verify it through a Delphi survey in the context of road, water, and electricity infrastructure considering Sri Lanka as a case point. By addressing these objectives, this study seeks to provide a comprehensive analysis of the existing literature on CI resilience and propose a framework that can guide future research and practice in assessing and enhancing the resilience of CIs. Furthermore, the present study will assist in identifying a standard resilience assessment methodology for CI systems from an engineering perspective. CI operators and managers will gain valuable awareness regarding the key standards and criteria necessary to ensure the resilience of CI and its associated systems. Importantly, these findings initiate a discourse on the importance of proactive measures in developing and implementing CI resilience, emphasizing the significance of prevention rather than relying solely on corrective actions. A common set of criteria will enable

benchmarking resilience across CIs, which is a significant advantage over the current state of practice. As a consequence of benchmarking, policymakers can justify scarce resource allocation among CIs. The evaluated attributes of resilience will serve as valuable tools for assessing CI resilience in real-world applications and improving the overall resilience of CI.

2. Literature review

The concept of "resilience" originated within ecological studies, aiming to strengthen systems against disturbances [24,25]. Over the last four decades, this idea has expanded across various fields such as engineering, ecology, sociology, and the economy, offering a more thorough examination of risks and uncertainties [13,24,25,40,51]. Recently, the resilience of urban areas has gained attention due to the significant impacts of disaster, where most interactions between humans and nature take place [20,52,53]. The notion of urban resilience, which has its roots in ecological resilience introduced by Holling in 1973, is defined as a system's capacity to absorb disturbances, reorganize, and continue functioning while undergoing change [54]. Holling and Gunderson later introduced the Panarchy Model, describing evolving hierarchical systems with interconnected elements to help understand and solve complex issues. This model redefines the focus on resilient cities, not just maintaining essential functions during disturbances but also leveraging these disturbances for potential transformation [20,21,53].

In 1996, Holling proposed the concept of engineering resilience, derived from ecological resilience, which describes urban infrastructure's ability to withstand natural disasters [13,25]. The resilience of the engineering systems is well connected to the robustness of the urban infrastructure systems by its capabilities of maintaining desired functioning during disturbances, its responsiveness, and its efficiency in transforming to minimize loss and prevent dysfunction [20,21,53,55]. This concept has influenced planners and decision-makers to focus on strengthening urban infrastructure resilience against disasters. Urban resilience has thus become a fundamental principle in urban planning and development to prepare better for such disasters [53,55–57]. The urban resilience can be defined as the capacity of an urban system, including its socio-ecological and socio-technical networks across different timeframes and areas, to uphold or swiftly resume desired operations when confronted with disruption, adjust to shifts, and promptly alter systems that impede present or future adaptability [21,57–59]. This characterization lays the groundwork for improving urban systems' ability to endure, adjust to, and thrive amidst variations and uncertainties, shedding light on the interconnections within urban systems and pinpointing crucial factors influencing urban resilience [18,19,26,52,56,57].

Even with the growing attention to urban resilience, evaluation techniques have frequently been employed in a limited manner, targeting specific aspects of urban systems [52,53,56,57]. Given the continuous and extensive impacts of disaster and rapid urban growth, there's a need for a comprehensive approach to resilience assessment, one that grasps the interconnectedness, vulnerabilities, and capabilities of urban systems [20,21,52,53,58]. A thorough method is vital for grasping interactions between humans and nature, establishing suitable timeframes for analyzing the lifecycle of disasters, and facilitating effective interventions. The developing idea of urban resilience, which incorporates various disciplines, necessitates meticulously planned assessment techniques to enhance comprehension of the complexity and dynamics of urban ecosystems [18–21,26,52,53,58].

Considering the significant consequences of disasters, urban planners, and policymakers regard resilience as a critical aspect of urban systems. The examination of urban resilience enables a comprehensive evaluation of the risks associated with disasters and the ability of urban systems to endure these challenges [18,19,21,26,53,56,58]. Five fundamental traits preparedness, absorption, recovery, adaptability, and transformability depict the varied and interconnected capacities of urban systems across different phases of resilience [18,21,26,53,57]. The monitoring of these traits reflects the level of resilience within a system and informs strategies to bolster resilience. Preparedness entails the capability to plan and prepare for foreseeable or unforeseeable disasters, essential for decision-making prior to disaster events [20,21,56,57]. Absorption denotes the capacity to withstand a disturbance, manage its impacts, and sustain functionality without deterioration, indicating the inherent strength of urban systems, such as resilience, diversity, and redundancy [60–62]. Recovery involves swiftly recovering from a disturbance, reorganizing within defined parameters, and restoring functionality through rapid response mechanisms and self-directed initiatives. Recovery encompasses not only the repair of physical infrastructure but also the reconstruction of social bonds [30,63–65]. Adaptation involves the agility to seize opportunities and implement informed, long-term adjustments in response to changing circumstances to uphold desired functionalities. Transformability represents the capacity to develop a fundamentally new system when existing ecological, economic, or social structures become untenable, achieved through significant alterations in infrastructure, functionalities, and relationships [19–22,26,52,56,57].

Urban resilience and the methods used for evaluation offer essential analyses spanning within ecology, sociology, and the economical domains. Grasping the connections among these domains can inform strategies aimed at strengthening the resilience of urban ecosystems [21,52,56]. Five key aspects can be identified for assessing urban resilience from the study carried out by Sharifi & Yamagata(2016), as materials and environmental resources, society and well-being, economy, built environment and infrastructure, and governance and institutions [56]. Materials and environmental resources pertain to the presence and accessibility of clean and affordable resources, crucial for recovering from disasters. Society and well-being encompass social capital, place attachment, safe communities, equity, and knowledge for learning processes [52,56,57]. A resilient economy ensures the distribution of resources for recovery. The built environment and infrastructure dimension covers the vulnerability and efficiency of infrastructure, ensuring the provision of essential services. Governance and institutions include leadership, resource management, contingency planning, collaboration, regulations, and education, crucial for continuous urban system operations [56,57]. Researchers have developed various methods for urban resilience assessment, categorized into quantitative, qualitative, and mixed methods. These include conceptual frameworks, mapping, Delphi, interviews, indicators, indices, numerical methods, and surveys, each with its resilience metrics and limitations [19,52,57,58].

With the increasing concentration of people, activities, and resources in urban areas, the sustainable management of cities

encounters considerable hurdles. This issue has propelled the concept of community resilience into prominence over the past four decades within both scientific and policy-making circles [59,66–69]. The growing emphasis on community resilience recognizes that not all threats can be entirely avoided, highlighting the need for mechanisms to mitigate disturbances. Additionally, resilience involves learning from disruptive events and implementing adaptive and transformative strategies which promote the system's gradual, long-term evolution [56,57,59].

As the idea of community resilience has evolved, there has been a growing emphasis on developing techniques and instruments for evaluating it. Community Resilience Assessment (CRA) has emerged as a vital component of resilience evaluation, especially in the last decades [18,21,26,48,53,59]. The heightened interest in CRA is due to a better understanding of climate change impacts, increased funding for resilience enhancement, the reliance of donor organizations on assessment outcomes for funding decisions, and the necessity to measure progress against international risk reduction targets [60,67,68,70,71]. Assessing community resilience is essential for reducing disaster risk and preparing for a wide range of natural and human-induced disasters. CRA tools make resilience a tangible and measurable concept, helping to understand what constitutes community resilience by examining environmental, social, economic, physical, and institutional elements [59,60,67,68]. These tools encourage future-oriented thinking and provide a framework to understand the complexities of communities as socio-ecological systems. Viewing communities this way implies that ecological and socio-economic factors are interlinked across various spatial and temporal scales [53,58,59]. CRA tools also serve as benchmarking instruments, enabling communities to compare their resilience status with peers and best-practice standards. This comparison can foster competition and knowledge sharing among communities. As ex-ante decision support systems, CRA tools help planners and decision-makers identify vulnerable areas, suggest intervention points, and prioritize resource allocation. As ex-post decision support systems, these tools allow organizations to monitor the effectiveness and efficiency of resilience and disaster risk reduction plans [53,56,57,59].

Conducting assessments and disseminating results enhance transparency and accountability in the planning process. Involving stakeholders in the assessment process empowers citizens and improves their role in decision-making, enhances risk communication, and establishes social networks essential for resilience [19,21,52,56,58]. Despite the numerous CRA tools available, few researchers have thoroughly examined them, often providing only overviews of existing tools and their structures [19,21,56–58]. For instance, Irajifar et al. (2013), found that existing assessment frameworks lack specific variables and attributes suitable for community-level measurement [72]. Monaghan et al. (2014), listed six CRA toolkits, highlighting their main features [72]. Pfefferbaum et al. (2014), outlined the similarities and differences of six CRA tools, indicating that while these tools promote resilience assessment, more research is needed to provide communities with more resilient development pathways [73]. Larkin et al. (2015), reviewed resilience assessment efforts by various U.S. agencies, arguing that these frameworks help communities identify weaknesses but need more specific guiding standards for local use [73]. Cutter (2016), provided the most detailed investigation, reviewing 27 assessment tools and discussing their spatial orientation, dimensions addressed, and assessment approaches [74]. This study highlighted that the existence of multiple solutions to the assessment issue stems from varying interpretations of resilience and different motivations of assessment proponents. Cutter (2016), emphasized the need for co-designed assessment tools that acknowledge the social dynamism of communities [74].

The integration of social dimensions into resilience studies underscores the need to understand social-ecological systems [58,59]. Sharifi (2016), analyzed 36 community resilience assessment tools, identifying six performance evaluation criteria. The findings revealed that these tools have limited success in addressing the criteria comprehensively, particularly the environmental dimension, despite its significance for building community resilience [59]. Sharifi emphasized the need for cross-fertilization among tools to create more comprehensive and informative assessment instruments. Sharifi and Yamagata (2016), further evaluated these tools for guiding communities toward disaster resilience, developing a framework to measure planning, absorption, recovery, and adaptation abilities. They found that only a few tools effectively address these resilience measures [75]. In conclusion, community resilience assessment tools are indispensable for understanding and enhancing resilience in urban areas. These tools enable planners and policymakers to identify vulnerable areas, set priorities, allocate resources, and design effective interventions [52,58,75–78]. The integration of social and ecological dimensions in resilience studies highlights the importance of viewing communities as complex, dynamic systems that require continuous assessment and adaptation. As urban areas face increasing challenges from disaster and other threats, developing and utilizing robust community resilience assessment tools will be crucial for building sustainable, resilient communities [53,56,59,78,79].

CI plays a crucial role in built environment by maintaining urban systems and providing essential services to communities, particularly during disasters [18,20,53,80]. Disasters significantly impact these CIs, underscoring the importance of ensuring their resilience. Infrastructure resilience, although lacking a unified definition, generally refers to the ability of CIs to withstand and recover from disruptive events [13,24,81]. Ensuring the resilience of infrastructure systems involves measures such as incorporating safety margins in engineering design codes and guidelines. During disaster event, vital services like electricity, transportation, water, and healthcare are often disrupted, emphasizing the critical role of resilient infrastructure in providing for community needs [5,13,24,82].

Assessing the resilience of CIs involves various qualitative and quantitative approaches. Some methodologies focus on quantitative evaluations, aiming to reduce disaster risk by assessing infrastructure resilience and interdependencies through virtual city models and damage assessments for different disaster scenarios [18,30,48,65]. Performance-based design, Bayesian networks, fragility functions, and restoration curves are among the quantitative methods used to assess CI functionality during and after disasters. Qualitative assessments are also employed to evaluate CI functionality, particularly in understanding the broader context of resilience. Many resilience assessment frameworks have been developed with specific geographic focuses, tailored to particular regions or communities [18,24,30,40,48,65]. While being successful within their designated contexts, these frameworks often lack inclusivity and adaptability to different settings. This limitation hinders their application and replication potential across diverse geographic contexts. To address

this challenge, there is a growing need for an integrated framework that incorporates adaptable indicators for assessing CI resilience across multiple geographic contexts and hierarchical levels, from local communities to national infrastructures concerning the interdependencies between CIs [5,24]. An integrated framework for assessing CI resilience would facilitate consistent operationalization across diverse contexts, enabling more effective resilience investment decisions. Such a framework should incorporate a set of potentially adaptable indicators that account for variations in geographic, socioeconomic, and institutional settings [24,40,65]. By providing a standardized approach to resilience assessment, this integrated framework would enhance comparability across regions and support informed decision-making regarding resilience investments [10,24,48,52,83]. In conclusion, ensuring the resilience of CIs is essential for maintaining the functionality of urban systems and safeguarding the well-being of communities, particularly in times of crises. To effectively assess CI resilience, it is imperative to employ a combination of qualitative and quantitative approaches tailored to diverse geographic contexts. An integrated framework that incorporates adaptable indicators holds the potential to enhance resilience assessment efforts and support more informed decision-making regarding infrastructure investments [40,50,83].

3. Methodology

This study has employed a systematic literature review to identify the resilience attributes and sub-indicators for evaluating the attributes of resilience of the selected CI system, and a two-stage Delphi survey to validate the identified attributes. The content analysis technique is used to identify the relevant resilience attributes from screened literature sources. The PRISMA method was followed for selecting literature from scientific databases. This research study has been designed to explore which attributes could effectively be used for resilience assessment. The above research question was designed to encompass the development of fundamental concepts and theories of CI resilience. The search queries were developed using the combination of key terms in Table 1. Available articles in the research domain of disaster resilience of CIs were examined.

Fig. 1 demonstrates the utilization of exclusion criteria to refine the selection of articles. Specifically, articles which focused on disaster resilience in the context of CI and were published in journals between 2010 and 2023 in both "Scopus" and "Web of Science" databases, were considered for inclusion. The screening stage involved three steps: title and keywords screening, abstract screening, and full-text screening. Out of 1582 records, 1325 were manually screened based on the label and keywords, resulting in 614 records for further analysis. These records were screened based on the abstract, leaving 245 full texts for the final stage. In the final screening stage, 245 full texts were read with the inclusion criterion of focusing on disaster resilience assessment in the context of CIs, which was aligned with the objective of the study. Out of 245 full texts, only 50 articles met this criterion, and 4 articles were added after a manual search. 54 were selected and analyzed in this study.

After identifying relevant literature sources, the selected studies were subjected to thorough content analysis to extract critical data. A spreadsheet was created to organize the data on studied methodologies, attributes, and sub indicators and categories used for resilience assessment. Separate columns were allocated to record definitions of various attributes, sub-indicators for measuring the attributes, focused CI sectors, and hazard types. An inductive approach guided the content analysis, with iterative coding of the extracted data. Initial codes were developed based on the first reviewed paper, and new codes were added to the data extraction sheet as needed after reviewing each subsequent paper. This process continued until all papers in the database were reviewed. Finally, the synthesized data was used to develop the initial attributes of resilience.

Afterwards, a two-stage Delphi survey was conducted to validate the identified resilience attributes. In the Delphi survey, 30 experts were selected from the three infrastructure sectors in Sri Lanka (Electricity, Water distribution, and Road) as a case point. The "purposive sampling technique" was utilized for the selection of the experts for the interview, as this method was preferred by most of the studies [11,84,85]. Conducting two rounds in a Delphi survey serves various crucial purposes. The initial round allows participants to generate diverse responses, while the second round facilitates the refinement and clarification of these ideas based on feedback from the group. This iterative process aids in building consensus, identifying areas of agreement or disagreement, and incorporating the collective expertise of participants. Additionally, the two-round structure helps to address ambiguities, prioritize options, and allow for the validation and refinement of decisions in scenarios involving forecasting.

The process fosters a dynamic learning environment where participants can adapt their opinions based on the insights shared by others, resulting in a more comprehensive and informed decision-making outcome. The same type of selection criteria as used and proposed by the previous scholars for the expert selection has been used in this study [86–89]. Accordingly, the selected panelists comprised professionals in the field of infrastructure planning, design, construction, and maintenance from the respective organizations. When selecting the panel members, their experience in working in infrastructure sector, education level and their ability to

Table 1
Key terms used for developing the search query.

Key terms	Category
Critical Infrastructures, CIs, Critical infrastructure network, Critical infrastructure system, CI network, CI system, energy infrastructure, energy system, energy network, transportation infrastructure, transportation systems, transportation network, electricity infrastructure, electricity system, electricity network, water infrastructure, water infrastructure system, water distribution network, assets	The articles related to the CIs
Disaster, Climate change, Disaster risk, Resilience	The articles related to the Disaster Risk and resilience domain
Indicators, Criteria, Standards, Index, Matrix	The articles related to the indicators, criteria, and standards

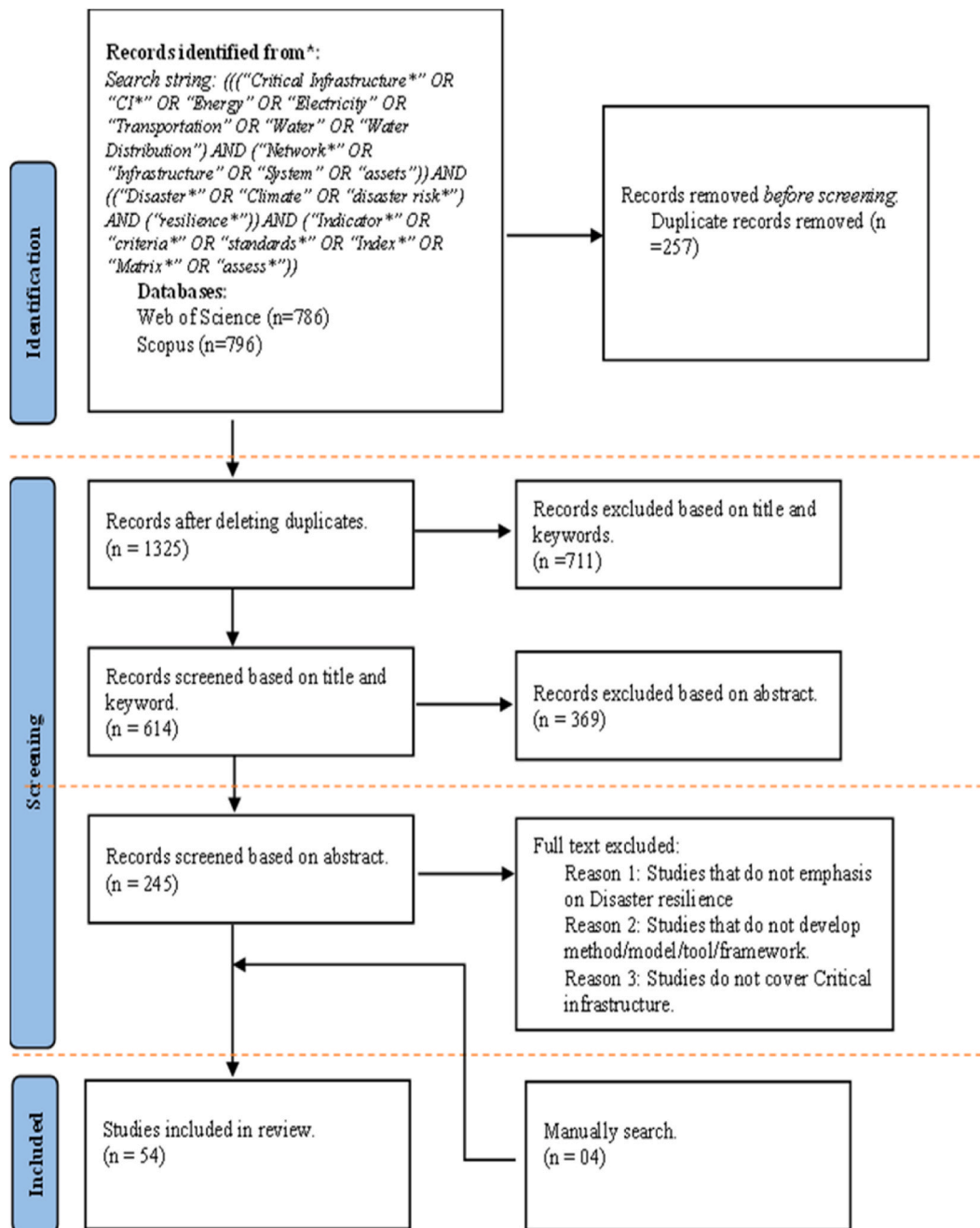


Fig. 1. Literature Screening process.

understand the research’s objectives were considered. Each member had minimum 5 years of working experience in respected infrastructure sector. Accordingly, ten experts were selected from each infrastructure sector (i.e., transportation, water, and electricity sectors). All panel members had bachelor’s degrees in engineering and 25 out of the 30 members had followed post graduate degrees. Among the experts selected from the water infrastructure sector, 30 % hold a PhD, while 40 % hold a postgraduate qualification. In the context of electrical infrastructure, 10 % of experts hold a PhD, while 50 % have postgraduate qualifications. In the road infrastructure sector, 40 % of experts hold a PhD, while 60 % hold postgraduate qualifications. Experts represent different organizations, including Electricity organization 1 (13 %), Electricity organization 2 (10 %), Road infrastructure related organization (RDA) (34 %), Water infrastructure related organization (33 %) and other private organizations and academia (10 %). Furthermore, these experts comprise 3 individuals in the role of Assistant General Manager, 10 professionals designated as planning engineers, 11 individuals specializing in civil engineering, and 6 professionals specializing in electrical engineering. The working experiences of the experts are presented in

Table 2.

4. Results

4.1. Resilience assessment and assessment methods

Resilience assessment methods for CIs encompass various approaches, capacities, and dimensions to comprehensively evaluate the system’s ability to withstand and recover from disruptive events. Assessment is a process of obtaining information, such as data or indicators, in relation to a specific objective or goal [30,40,90,91]. These assessment methods employ a combination of quantitative, qualitative, and hybrid approaches to capture the multifaceted nature of resilience. Quantitative methods focus on performance metrics and system interdependencies, while qualitative approaches emphasize expert judgment and scenario-based analyses [48, 92–97]. Hybrid approaches integrate data-driven modeling with stakeholder inputs. Resilience assessment frameworks, whether quantitative, qualitative, or semi-quantitative, often rely on indicators [24,30,60,64,92–97]. Quantitative approaches utilize measures not specific to a particular domain and employ structural-based modeling techniques to represent domain-specific features. Semi-quantitative approaches provide a broad numerical description of classifications without extensive formulas or models. On the other hand, qualitative approaches rely on judgments and analysis from experts or operators and graphical representations to illustrate the value or change of indicators without numerical calculations [24].

Even after extensive research on the resilience of CIs, researchers still have no consensus regarding a specific approach for resilience assessment. Over the years, multiple approaches have been suggested, each offering its perspective on the resilience of CIs [13,24,31, 98]. Some approaches focus solely on preparedness or recovery activities, while others consider both aspects. From the studies reviewed, the resilience assessment approaches for technological CIs can be broadly categorized into four main groups: empirical, qualitative, index-based, and simulation approaches [13,24,98]. However, within these approaches, different aspects of resilience have been considered. These assessments can be divided mainly into three types, as presented in Fig. 2.

Among these three types of studies, the assessment of resilience capacities is crucial for several reasons. These capacities provide valuable insights into the system’s ability to withstand and recover from disruptions, ensuring the continuous delivery of essential services to society [100,101]. The importance of resilience assessment capacities can be discussed from several perspectives such as risk mitigation, effective resource allocation, preparedness and response planning.

4.2. Attributes of the resilience capacities

This section discusses resilience attributes identified from the literature analysis. The identified resilience attributes have been discussed under four capacities of resilience.

4.2.1. Resilience attributes under planning (anticipative) capacity

In the context of CIs, the planning capacity plays a critical role in ensuring resilience. It encompasses the ability to anticipate and prepare for potential disruptions or failures that may affect the functioning of CI systems [101,102,103]. The significance of planning capacity is evident in its ability to enhance preparedness and proactive measures to mitigate risks. By analyzing relevant literature, this study has identified a range of attributes that fall under the planning capacity domain. These attributes have been proposed and utilized in resilience assessments of various CI systems. Table 3 provides a visual representation of the identified resilience attributes under the planning capacity. The subsequent sections will provide an in-depth discussion of each attribute, shedding light on their specific characteristics and implications for CI resilience. Examining these resilience attributes individually enable comprehensive evaluation of planning capacity of CI systems and identify areas for improvement [101,104,105].

4.2.1.1. Failure probability. The ‘Failure probability’ attribute is crucial for assessing the resilience of CIs [43,94,95]. It indicates how likely disruptions or failures could occur within the system. A higher probability of failure under a given distress level suggests vulnerability, while a lower failure probability implies robustness against disruptions of a certain magnitude [6,17,121–123]. By using historical data, expert opinions, and predictive models, this attribute helps to identify vulnerabilities. It aids in proactive risk management by helping stakeholders to prioritize efforts and resources to minimize the likelihood of disruptions [24,106,107,124,125]. Historical data shows past incidents, are guiding for improvements in resilience. Expert opinions and predictive models provide insights into system complexities. Regularly reassessing failure probability is essential to maintain resilience [24,31,124,107,108,125, 126].

4.2.1.2. Quality of infrastructure. This examines the strength and condition of physical components, evaluating their ability to anticipate and handle disruptions. It involves analyzing factors like design, robustness, adaptability, and redundancy [8,16,79–84]. CI system resilience greatly depends on infrastructure quality, involving the assessment of structural integrity, durability, and

Table 2 Working experience of the experts.

Working experience (x) in years	Number of experts		
	Transportation	Water	Electricity
x < 15	0	0	0
15 ≤ x < 20	1	2	2
20 ≤ x < 25	2	3	2
25 ≤ x < 30	5	2	3
30 ≤ x	2	3	3

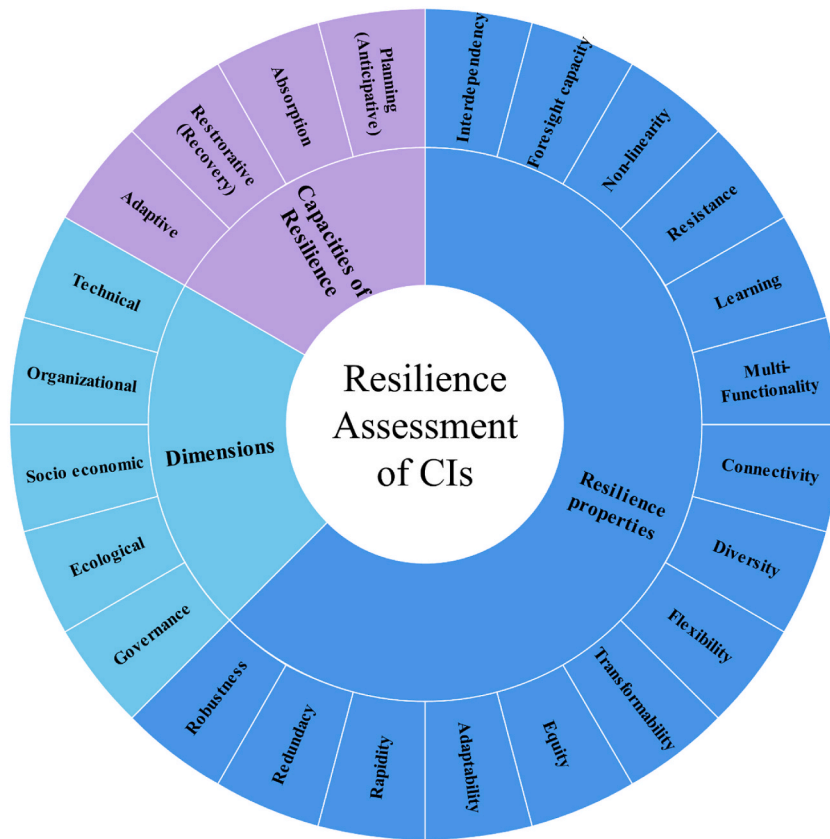


Fig. 2. Classification of resilience assessment studies based on the resilience aspects considered [15,18,24,25,27,40,96,99].

performance [73,74,85–87].

4.2.1.3. Pre-event functionality of infrastructure. This attribute focuses on the operational state of the CI system before disruptions occur [12,26,28]. Understanding baseline functionality is essential to quantify changes during and after disruptions [12,26,92–94]. Assessment of infrastructure under normal conditions involves measuring planning capacity by analyzing reliability, performance, and efficiency [26,28,57,95]. This identifies weaknesses which could worsen during adverse events [26,92–94]. Benchmarking pre-event functionality aids disaster preparedness and planning. It enables targeted strategies to strengthen vulnerable CI aspects, ensuring efficient crisis responses. Disruptions, whether natural or human-induced, highlight the need for assessing pre-event functionality [12,92–94].

4.2.1.4. Mitigation measures and features. This examines how well CIs are prepared to counteract potential disturbances [28,34,88]. Such assessment improves robustness by understanding the capacity to withstand and recover from disruptions. Mitigating features vary, including redundancy, backups, and contingency plans [9,12,28,34,88,94]. The effectiveness of these features depends on alignment with the CI and anticipated disruptions [9,34,57,89,92,96,97].

4.2.1.5. Disaster planning and response. In assessing resilience for CIs, it is vital to consider both technical aspects and organizational readiness. Technical evaluations focus on physical infrastructure, but assessing pre-defined policies for quality and functionality is an important resilience attribute [12,34,57,89,92,94]. Organizational preparedness is essential for effective disruption response. Evaluating policies, guidelines, and protocols enhance CI resilience and shows preparedness [34,57,89,92]. Beyond policies, organizational planning involves having repair facilities, resources, and trained personnel ready. The adequacy and efficiency of repair facilities can impact the recovery process [17,31,41,44,98]. Adequate resources ensure tools, equipment, and skilled personnel are available [31,41,44,98]. Personnel expertise, training, and readiness are crucial for expediting recovery [5,6,27,55]. Assessing collaboration among stakeholders (i.e., operators, agencies, services) improves cohesiveness during disruptions. Evaluating communication, information sharing, and collaboration enhance responsiveness [8,16,35,84,100]. This reveals that, along with technical evaluations, assessing organizational readiness and planning is key for CI resilience [41,51,98].

4.2.1.6. Communication and information sharing. Quality communication channels and coordination mechanisms are key attributes reflecting preparedness to manage disruptions [5,38,81,101]. This includes accessible, reliable communication systems and clear coordination protocols [6,30,99]. Evaluating communication involves robust, redundant systems for exchanging information sharing during normal and crisis situations [5,8,16,35]. Coordination mechanisms involve protocols, role clarity, and engagement among stakeholders [38,81,101]. These ensure effective response collaboration. Assessment of information sharing focuses on accessible, accurate, and timely data exchange within the CI system and externally [29,82,89,102]. This involves collecting, analyzing, and

Table 3
Summary of identified resilience attributes under Planning capacity.

	Resilience attributes	Related term used in literature	Assessment Methods	Sub indicators	Adopted infrastructure (from literature)	Focused hazard type	Reference
AN1	Failure Probability	<ul style="list-style-type: none"> • Likelihood of failure • Number of failures • Failure occurrence 	<ul style="list-style-type: none"> • Expert interview • Predictive modelling • Empirical data 	<ul style="list-style-type: none"> • Number of hazards related to the asset or network. • Return period of the hazard 	Water, Transportation, Electricity	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[17,30,31, 91,106, 107,108, 109]
AN2	Quality of Infrastructure	<ul style="list-style-type: none"> • Infrastructure quality • Service quality. 	<ul style="list-style-type: none"> • Expert interview • Empirical data 	<ul style="list-style-type: none"> • Existence of the equipment and procedures for hazard mitigation • Early warning system • Time that installed capacity exceeds demand 	Water, SCADA System, Transportation, Electricity	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[14,17,18, 110,111]
AN3	Pre-event functionality of Infrastructure	<ul style="list-style-type: none"> • Pre-event performance • Functionality before the disaster 	<ul style="list-style-type: none"> • Expert interview • Predictive modelling • Empirical data 	<ul style="list-style-type: none"> • Compliance Rate with codes, standards and regulations • Frequency of Maintenance and Inspections • Extent of Retrofitting Completed • Availability of Backup Systems • Alternative Routes and Connectivity Plans • Accessibility to Resources • Functionality of Early Warning Systems 	Water, SCADA System, Transportation, Energy and electricity infrastructure	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[14,17,18, 110,111]
AN4	Mitigation measures and features	<ul style="list-style-type: none"> • Mitigative action • Mitigation plan • Protective measures • Contingency plans • Risk reduction measures 	<ul style="list-style-type: none"> • Expert interview • Empirical data 	<ul style="list-style-type: none"> • Existence of the operational response plans • Coverage of the asset types by the planning and response • Type disasters covered by the plans. • Testing, Training, updating of the plans 	Water, SCADA System, Transportation, Electricity, and energy	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[14,17,18, 110,111]
AN5	Disaster planning and response	<ul style="list-style-type: none"> • Risk planning • Risk response 	<ul style="list-style-type: none"> • Expert interview • Empirical data 	<ul style="list-style-type: none"> • Existence of the operational response plans • Coverage of the asset types by the planning and response • Type disasters covered by the plans. • Testing, Training, updating of the plans 	Water, Transportation, electricity, Hospital, Emergency services	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[38, 112–114]
AN6	Communication and information sharing	<ul style="list-style-type: none"> • Information sharing • Communication • Internal and external communication strategies 	<ul style="list-style-type: none"> • Expert interview • Empirical data 	<ul style="list-style-type: none"> • Plans for the communication and information sharing is available. • Existences of the proper 	Water, Transportation, Electricity, Hospital, Emergency Services, Hospital	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[24,30,43, 63,97,112, 115–120]

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Table 3 (continued)

Resilience attributes	Related term used in literature	Assessment Methods	Sub indicators	Adopted infrastructure (from literature)	Focused hazard type	Reference	
AN7	Learnability	<ul style="list-style-type: none"> • Knowledge management • Learning from the past 	<ul style="list-style-type: none"> • Expert interview • Empirical data 	<ul style="list-style-type: none"> • Existence of the training system for the people work in the organization. • Number of training people • Collaborative training program with other CIs 	Water, Transportation, Electricity, SCADA system, Hospital, Emergency services	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[17,27,31,68,69]

disseminating relevant information for decision making during potential disruptions [29,82,89,102]. Quality communication extends to external stakeholders like government agencies, emergency response teams, and the general public [5,9,46,95,103–105].

4.2.1.7. Learnability. This attribute focuses on a system’s ability to capture and apply lessons from previous incidents, adapting strategies and implementing improvements over time. Assessing learnability involves evaluating a CI system’s effectiveness in collecting, analyzing, and sharing knowledge from past disruptions [46,55,89]. Robust knowledge management systems identify vulnerabilities, recognize effective responses, and share best practices. Learnability involves adapting strategies based on past experiences, refining protocols, and updating plans [8,17,27,29]. Implementing improvements based on lessons learned enhances resilience by investing in upgrades, technologies, training, partnerships, and coordination mechanisms [8,27,29,78]. Evaluating learnability fosters a culture of continuous improvement and knowledge sharing, encouraging stakeholders to enhance resilience through reflection, proactive measures, and vulnerability identification [8,27,55,74]. It promotes collaboration among operators, agencies, research institutions, and entities, facilitating innovative solutions and improved resilience [8,27,29,78].

4.2.2. Resilience attributes under absorption capacity

The resilience attributes under the absorption capacity focus on the system’s ability to absorb disruptions [60–62]. These attributes provide insights into how CI systems can withstand and recover from failures or disruptions. A total of twelve attributes under absorption capacity have been identified through the analysis. These attributes have been proposed and utilized in resilience assessment of various CI systems [15,122,127–129]. Table 4 provides a visual representation of the identified attributes.

4.2.2.1. System failure due to unavailability of assets. This attribute assesses the impact of asset unavailability during disruptions within a CI. It evaluates how the failure of critical assets affect overall functionality and absorption of the disruption [8,16], [28–30,82,126]. Asset unavailability during disruptions restricts CI operations, causing service interruptions and negative consequences for stakeholders [8,16]. Assessing this aspect reveals vulnerabilities and weak points, prompting attention and improvements [27,29,83,84,106]. Stakeholders prioritize mitigation, allocate resources, and implement measures for enhanced resilience [74,78,89,106,125]. Evaluating asset unavailability’s impact clarifies potential failure consequences, aiding both immediate and long-term recovery strategies and the need for redundancy [83,84,106]. Identifying areas for improvement enables targeted interventions like redundant systems or alternative strategies, ensuring continuity [78,89,106,125]. By understanding vulnerabilities, consequences, and implementing mitigation measures, CIs enhance their ability to absorb and recover from disruptions [78,106,125].

4.2.2.2. Severity of failure. The severity of failure assesses the extent of damage caused by a specific event or failure within a CI system [8,17,27–29]. By evaluating impact magnitude, such as downtime duration or affected users, it offers insights into the system’s recovery capability. Factors such as physical damage, service interruption duration, affected users, and broader consequences contribute to this assessment [8,27–29,74,78,83]. Assessing impacts helps to identify weaknesses and areas needing improvement or investment for enhanced resilience [74,78,83]. It guides planning and decision-making by projecting failure consequences. Strategies to mitigate projected severe outcomes include contingency plans, redundancy, and robust recovery mechanisms [17,27–29]. Severity assessment also aids in prioritizing mitigation efforts. High-impact scenarios drive resource allocation to reduce potential disruptions [8,27–29,74,78]. Strategies include improving vulnerable components, enhancing warning systems, and bolstering response capabilities [8,27–29,78]. Additionally, assessing severity should also consider cascading effects in complex CIs [8,27–29,78].

4.2.2.3. Reliability (Just-in-time delivery). This concept involves relying on timely and accurate delivery of resources, materials, or services within the CI system [8,17,27–29,68]. It encompasses efficient supply chain management and maintaining resource flow despite disruptions. Evaluating reliability focuses on the continuous availability of essential resources [8,17,27–29,68,92]. This includes supply chain resilience, logistics network robustness, and inventory system effectiveness [8,27–29,68,92]. By assessing reliability, resilience evaluations identify supply chain and resource management vulnerabilities [29,68,92]. Dependencies on external suppliers, transportation networks, and coordination among stakeholders are considered [29,68,92]. Identifying these vulnerabilities enhances absorption capacity through strategies like diversifying suppliers or establishing alternative sources [17,27–29,68]. Reliability assessment helps pinpoint bottlenecks and failure points in resource delivery [27–29,68,92].

Table 4
Summary of identified resilience attributes under absorptive capacity.

	Resilience attributes	Related term used in literature	Assessment methods	Sub indicator	Adopted infrastructure (from literature)	Focused hazard type	Reference
AB1	System Failure due to Unavailability of Assets	<ul style="list-style-type: none"> Asset unavailability. Failures 	<ul style="list-style-type: none"> Expert interviews Empirical data Predictive modelling 	<ul style="list-style-type: none"> Number of fully damaged assets Number of partially damaged asset Time of become dis functional Cost of damaged assets 	<ul style="list-style-type: none"> Water Transportation Hospital Emergency services Electricity and energy 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[64,65, 108,126, 130,131]
AB2	Severity of Failure	<ul style="list-style-type: none"> Failure magnitude Failure impacts Disruption of services Consequences of the failure 	<ul style="list-style-type: none"> Expert interviews Empirical data Predictive modelling 	<ul style="list-style-type: none"> Loss for certain hazard level Capacity reduction of the network Number of assets fail Number of fully damaged assets Number of partially damaged asset Loss of income due to the dis functionality of the assets Time spends without any CI services Time spends without one or more CI services Number of times CI threshold exceeded 	<ul style="list-style-type: none"> Water Transportation Hospital Emergency services Electricity and energy 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[64,65, 108,126, 130–132]
AB3	Reliability (Just-in-Time Delivery) -	<ul style="list-style-type: none"> Reliability 	<ul style="list-style-type: none"> Expert interviews Empirical data Predictive modelling 	<ul style="list-style-type: none"> Percentage of services made on or before the scheduled time Average number of hours per day service supply is uninterrupted Percentage of services meeting quality standards Average time taken to repair services Percentage of services on time and in full Number of times service levels fall to zero 	<ul style="list-style-type: none"> Water Transportation Hospital Emergency services Electricity and energy 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[46,55,74, 78]
AB4	Post-Event Functionality	<ul style="list-style-type: none"> Performance aftermath of disaster Functionality 	<ul style="list-style-type: none"> Expert interviews Empirical data Predictive modelling 	<ul style="list-style-type: none"> Average time taken to restore water supply after an event Number of emergency service distribution points set up post-event Percentage of emergency services provision capacity available post-event Identification of alternate services for replacement of services post-event 	<ul style="list-style-type: none"> Water Transportation Hospital Emergency services Electricity and energy 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[55,74,78, 89,100]
AB5	Resistance	<ul style="list-style-type: none"> Resistance 	<ul style="list-style-type: none"> Expert interviews Empirical data 	<ul style="list-style-type: none"> Failure probability Aging of CIs Adoption of safety design standards 	<ul style="list-style-type: none"> Water Transportation Hospital Emergency services 	Floods, Hurricane, Earthquakes, Landslides,	[55,74,78, 89,100]

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Table 4 (continued)

	Resilience attributes	Related term used in literature	Assessment methods	Sub indicator	Adopted infrastructure (from literature)	Focused hazard type	Reference
AB6	Robustness	<ul style="list-style-type: none"> Robustness 	<ul style="list-style-type: none"> Predictive modelling Expert interviews Predictive modelling 	<ul style="list-style-type: none"> Condition of regular maintenance Existence of backups Service replacement 	<ul style="list-style-type: none"> Electricity and energy Water Transportation Hospital Emergency services Electricity and energy 	Industrial accident Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[55,74,78,89,100]
AB7	Ability to Withstand	<ul style="list-style-type: none"> Withstand Resistance 	<ul style="list-style-type: none"> Expert interviews Empirical data Predictive modelling 	<ul style="list-style-type: none"> Level of infrastructure integrity Average duration and frequency of services outages per customer Capacity of backup facilities relative to peak demand 	<ul style="list-style-type: none"> Water Transportation Hospital Emergency services Electricity and energy SCADA system 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[14,17,18,58,59]
AB8	Redundancy	<ul style="list-style-type: none"> Alternative availability Redundancy Redundant system Redundance 	<ul style="list-style-type: none"> Expert interviews Empirical data Predictive modelling 	<ul style="list-style-type: none"> Number of assets that have backups Time of the availability of the backups Time taken backups become functional 	<ul style="list-style-type: none"> Water Transportation Hospital Emergency services Electricity and energy SCADA system 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[46,55,74,78,89,100]
AB9	Resourcefulness	<ul style="list-style-type: none"> Resources availability Resourcefulness 	<ul style="list-style-type: none"> Expert interviews Empirical data 	<ul style="list-style-type: none"> Availability of the interconnected assets 	<ul style="list-style-type: none"> Water Transportation Hospital Emergency services Electricity and energy SCADA system 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[55,74,78,89,100]
AB10	Response	<ul style="list-style-type: none"> Response plan Contingency plan 	<ul style="list-style-type: none"> Expert interviews Empirical data 	<ul style="list-style-type: none"> Existence of the special response plan Time required for response Emergency response plans for different type of disasters Business continuity plans for different types of disaster 	<ul style="list-style-type: none"> Water Transportation Hospital Emergency services Electricity and energy SCADA system 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[46,55,74,78,100]
AB11	Economic sustainability	<ul style="list-style-type: none"> Economic sustainability Financial availability for repairing, recovery, and replacement 	<ul style="list-style-type: none"> Expert interviews Empirical data Predictive modelling 	<ul style="list-style-type: none"> Associated cost for the response Associated cost for the replacement of services Cost of backup system 	<ul style="list-style-type: none"> Water Transportation Hospital Emergency services Electricity and energy SCADA system 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[46,55,74,78,89,100]
AB12	Interoperability	<ul style="list-style-type: none"> Emergency plan Communication with public Interoperability 	<ul style="list-style-type: none"> Expert interviews Empirical data Predictive modelling 	<ul style="list-style-type: none"> Procedure exists for interoperability with the public Communication system availability Joint action plans existence 	<ul style="list-style-type: none"> Water Transportation Hospital Emergency services Electricity and energy SCADA system 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[46,55,74,78,89,100]

4.2.2.4. Post-event functionality. The post-event functionality attribute assesses how quickly and effectively a system can restore operations following a disruption. It considers factors like service restoration time, recovery procedure efficiency, and achieved service levels [8,17,28,29,35]. It includes analyzing recovery processes, resource availability, and coordination [7,8,17,27–29]. Analyzing post-event functionality involves assessing response mechanisms, resource allocation, and coordination among stakeholders [7,8,17]. This evaluation guides investments in resilient designs, comprehensive recovery plans, stakeholder collaboration, and resource availability to enhance CI's ability to recover quickly and withstand disruptions [8,28,29,35].

4.2.2.5. Resistance. Resistance refers to the ability of the CI system to withstand the initial impact of a disruption without experiencing significant failures or service disruptions [10,24,30,40,41,51,133]. It revolves around the CI system's capacity to endure and withstand the initial impact of a disruption, all while avoiding substantial failures or disruptions in its services [8,17,27–29]. When evaluating resistance, one aims to delve deeper into the system's inherent ability to absorb the impact of a disruption, acting as the first line of defense against potential failures [8,17,27–29]. Through the evaluation of system's ability to resist failure and maintain functionality even under adverse conditions, it is possible to gain insights into the system's absorption capacity—the extent to which it can absorb and manage the initial shock without leading to a cascading failures that could potentially cripple the critical services [7,8,17,27].

4.2.2.6. Robustness. This attribute refers to its inherent strength in withstanding and recovering from disruptions by dynamically adapting its operations. This attribute assesses the system's ability to absorb shocks while minimizing significant disruptions to critical services [7–9,17,26–29]. It focuses on the system's adaptability during and after a disruption, encompassing resilience, agility, and flexibility in adverse conditions [7–9,17]. It goes beyond immediate responses, considering the system's ability to adapt operations over time to ensure continued functionality [17,26–29]. Robustness also involves learning from disruptions, enhancing future resilience by adapting operations, procedures, and infrastructure [9,17,26–29].

4.2.2.7. Ability to withstand. This attribute evaluates the CI's ability to endure disruptions without significant failures or service interruptions [7–9,17,26–29]. It assesses the physical strength, structural integrity, and durability of infrastructure components, aiming to gauge resilience against external shocks [17,26–29]. This assessment involves examining the robustness and reliability of infrastructure elements such as buildings, bridges, power grids, and communication networks [7–9,17,27–29]. Factors such as design features, materials, and maintenance practices are considered to determine the system's capability to withstand various disruptions. A robust withstanding capacity reduces the risk of critical failures, enabling the system to maintain functionality and provide essential services [27,29]. This attribute is essential for CIs to withstand diverse challenges, including natural disasters and cyber-attacks [7–9,17]. It also evaluates the system's capacity to withstand multiple or simultaneous disruptions, identifying vulnerabilities and areas for improvement [17,27–29].

4.2.2.8. Redundancy. This attribute assesses the extent of redundancy in critical components and infrastructure, identifying areas with alternative pathways or duplicate systems [7–9,27–29]. Redundancy ensures continued functionality during disruptions by swiftly switching to backup mechanisms, mitigating single points of failure, and maintaining essential services [7–9,17,27–29]. Evaluating redundancy also includes assessing the effectiveness and reliability of these backup components, requiring proper maintenance and testing to strengthen absorptive capacity [7,27–29]. By incorporating redundancy, decision-makers bolster the system's absorptive capacity, providing a safety net for rapid recovery, and minimizing disruptions [7–9,17,27–29]. Redundancy ensures uninterrupted critical service delivery, adapting and functioning during unexpected events, reducing the potential for widespread failures, and enhancing overall resilience [7–9,17,27–29].

4.2.2.9. Resourcefulness. This attribute refers to a CI system's ability to efficiently use available resources during disruptions, adapting and optimizing allocation to sustain operations. It assesses how well the system strategically employs resources like personnel, equipment, and supplies amidst disruptions [8,9,28,29,35,63,107]. The focus is on optimizing allocation, considering skills, equipment deployment, and material use. Enhancing resourcefulness helps improve absorptive capacity through proactive measures [8,9,28,29,35]. Beyond allocation, it includes agility in reallocating resources as circumstances change, sustaining services without compromising overall functionality [8,9,28,107]. By promoting resourcefulness, stakeholders bolster absorptive capacity, reducing strain on resources, minimizing service disruptions, and maintaining functionality [8,9,28,107].

4.2.2.10. Response. The response attribute assesses a CI system's speed, efficiency, and effectiveness in addressing disruptions. Experts evaluate the preparedness and coordination of emergency plans and protocols. This evaluation provides insights into the system's ability to handle disruptions through timely and well-coordinated responses. The attribute encompasses resource mobilization, activating emergency plans, efficient protocols, collaboration among stakeholders, and learning from past events [7–9,17,27–29]. A coordinated response minimizes disruptions, reduces cascading failures, and speeds up recovery, lessening socioeconomic impacts [8,29,35,63,107]. This evaluation also considers the system's adaptability by analyzing post-event assessments and implementing improvements over time, enhancing overall resilience [7–9,17,27–29]. Preparedness and coordination minimize disruption impacts, allocate resources efficiently, and facilitate swift recovery [8,29,35,63,107].

4.2.2.11. Economic sustainability. Economic sustainability evaluates a CI system's capacity to remain financially viable during disruptions. This attribute examines financial aspects such as revenue generation, cost-effectiveness, and financial reserves [8,9,35,63,107]. It helps gauge absorptive ability by ensuring the system can endure financial shocks, uphold essential services, and recover efficiently. Experts analyze revenue sources, resource efficiency, and reserves to comprehend how the system sustains financially during disruptions [8,9,28,29,35,63,107]. The assessment encompasses revenue mechanisms, like user fees and funding sources, ensuring income sufficiency despite disruptions [8,9,28,29,35,63]. Cost-effectiveness and resource allocation efficiency are also scrutinized. Additionally, the presence of financial reserves, like contingency funds or insurance, is evaluated. Strong reserves aid rapid resource allocation during recovery [8,9,28,29,35,63]. Financially stable systems endure shocks, maintain services, and recover efficiently, minimizing socioeconomic impacts [8,9,35,63]. Long-term perspectives should be considered for identifying vulnerabilities and enhancing future resilience. Diversifying revenue streams, implementing cost-saving measures, and exploring innovative financing options can contribute to improved financial resilience [8,9,28,107].

4.2.2.12. Interoperability. Interoperability evaluates the seamless cooperation of different CI systems and organizations during disruptions. This attribute assesses coordination, information sharing, and collaboration among stakeholders to enhance the system's resilience [8,9,35,63,107]. By analyzing interoperability, experts ensure effective joint response and recovery efforts, promoting absorptive capacity and minimizing disruptions [8,9,28,29]. The assessment scrutinizes coordination and collaboration among CI

systems, examining information exchange, communication protocols, and resource sharing [28,29,35,107].

Interoperability evaluation considers various dimensions, including command structures and technical system compatibility. Sharing resources and expertise ensures a comprehensive response [8,9,107]. It reduces redundancy, optimizes resource allocation, and minimizes service gaps by fostering coordinated efforts among stakeholders [8,9,28,29,35,63,107]. This resilience attribute extends beyond immediate response, requiring long-term coordination. Strengthening interoperability involves shared protocols, joint training, and interoperable systems [8,35,63,107].

4.2.3. Resilience attributes under restoration capacity

Restoration capacity is a fundamental aspect of resilience within the context of CI systems which holds paramount importance. It encompasses the vital ability to recover and restore full functionality efficiently and effectively following any disruptive event or incident [30,63–65]. This capacity determines the extent to which a CI system can bounce back from adverse circumstances, minimizing downtime and enabling swift reestablishment of normal operations [30,40,63,65]. Comprehensive evaluation of restoration capacity require to identify specific attributes that provide insights into the system’s resilience. Table 5, presented herewith, showcases a comprehensive set of attributes that have been meticulously identified and classified under the restoration capacity domain. These attributes serve as valuable benchmarks and reference points for evaluating the robustness and effectiveness of the restoration processes [30,40,63–65].

4.2.3.1. Post-event damage assessment. This attribute assesses the ability to accurately and comprehensively evaluate the extent and nature of damage caused by a disruptive event [27,28,89,92]. Thorough evaluation is essential for the assessment of restoration capacity [28,68,89]. This assessment analyzes physical damage, infrastructure impairment, and equipment conditions, guiding the prioritization of restoration efforts [27,28,68,89,92]. Post-event damage assessment aids in recovery decision-making. It reveals the full extent of damage, guiding resource allocation and setting realistic restoration timelines [27,28,68]. It identifies necessary resources and expertise for efficient recovery, enabling proactive planning [27,68]. The identification of interdependencies facilitates streamlined and efficient recovery efforts [27,28,89,92]. Additionally, damage assessment drives resilience improvement. The analysis of assessment data identifies vulnerabilities, assesses risk reduction measures, and informs future enhancements [27,28,68,89,92].

4.2.3.2. Recovery time in post-event. "Recovery time in post-event" refers to the period needed to restore a CI system to its pre-disruption functionality. It gauges restoration efficiency, with shorter times indicating higher restoration capacity and reduced societal and economic disruption [5,8,27,28,68,89,92]. Shorter recovery times reflect resilience and swift restoration capability [5,8,89,

Table 5
Summary of identified resilience attributes under restorative capacity.

	Resilience attributes	Related term used in literature	Assessment method	Sub indicators	Adopted infrastructure from literature	Focused hazard type	Reference
RS1	Post event damage assessment	<ul style="list-style-type: none"> • Damage assessment. • Post disaster impact assessment 	<ul style="list-style-type: none"> • Empirical data • Predictive modelling 	<ul style="list-style-type: none"> • Number of fully damaged asset • Number of partially damaged asset • How long the intended service being unavailable 	<ul style="list-style-type: none"> • Water • Transportation • Hospital • Emergency services • Electricity and energy • SCADA system 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[14,17,18, 58,59]
RS2	Recovery time in post event	<ul style="list-style-type: none"> • Post recover time. • Recovery time 	<ul style="list-style-type: none"> • Expert interviews • Empirical data • Predictive modelling 	<ul style="list-style-type: none"> • Existence of the special recovery plan • Time needed to recovery 	<ul style="list-style-type: none"> • Water • Transportation • Hospital • Emergency services • Electricity and energy • SCADA system 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[46,55,74, 78,89,100]
RS3	Recovery/loss ratio	<ul style="list-style-type: none"> • Restoration cost • Income lost. • Repairing cost 	<ul style="list-style-type: none"> • Expert interviews • Empirical data 	<ul style="list-style-type: none"> • Cost of restoration • Loss of income during restoration • Loss due to penalties • Replacement cost • Cost of maintenance after disaster • Reputation cost • Insurance cost 	<ul style="list-style-type: none"> • Water • Transportation • Hospital • Emergency services • Electricity and energy • SCADA system 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[55,74,78, 89,100]
RS4	Cost of reinstating functionality	<ul style="list-style-type: none"> • Reconstruction cost • Recovery expenses • Recovery financing 	<ul style="list-style-type: none"> • Expert interviews • Empirical data 	<ul style="list-style-type: none"> • Material and Labor Costs • Equipment and Machinery Cost • Transportation and Logistics Costs • Consultant and Professional Fees 	<ul style="list-style-type: none"> • Water • Transportation • Hospital • Emergency services • Electricity and energy • SCADA system 	Floods, Hurricane, Earthquakes, Landslides, Industrial accident	[46,55,74, 78,100]

92]. Efficient restoration includes quick damage assessment, prioritized resource allocation, rapid repair/replacement, and skilled personnel deployment [5,28,68,89,92]. This streamlining minimizes service downtime, providing critical advantages [5,68,89,92]. Timely restoration benefits public safety, healthcare, and emergency services [5,8,27,28]. Swift resumption of critical services reduces financial losses, maintains supply chains, and bolster economic stability [5,8,68,92]. It also enhances social cohesion, boosts public trust, and accelerates community recovery [8,27,68,89,92].

4.2.3.3. *Recovery/loss ratio.* The recovery/loss ratio is a financial metric comparing recovery costs to overall losses to assess the restoration effectiveness [5,27,28,89]. A higher ratio indicates efficient restoration, where recovery costs are proportionally lower than losses. This metric guide cost-effective strategies [8,27,68,92]. The recovery/loss ratio offers insights into financial impact and restoration success [5,8,27,92]. Higher ratios signify effective restoration, reducing overall economic disruption. Efficient strategies optimize resource use and prioritize critical functions [68,89,92]. Efficient restoration efforts contribute to higher recovery/loss ratios [5,8,92]. Swift damage assessment, prioritized resource allocation, and effective coordination minimize losses. A higher ratio indicates strategic resource allocation, emphasizing critical services [5,27,28,92]. The recovery/loss ratio not only gauges financial efficiency but also enhances system resilience [5,27,28,89,92].

4.2.3.4. *Cost of reinstating functionality.* This attribute encompasses the costs of repairing or replacing damaged infrastructure, obtaining necessary equipment, and restoring services. Evaluating reinstatement costs determines restoration feasibility and sustainability [5,8,27,28,68,92]. This assessment examines expenses tied to repairing or replacing infrastructure, including labor, materials, and equipment costs [5,8,92]. Procurement and installation expenses for new components are considered [5,8,92]. Expenses for acquiring needed equipment, specialized tools, and technology are included [5,8,27,89,92]. It also considers costs for reestablishing critical services like communication, power, and transportation. It also involves personnel training, system configuration, and testing [5,8,27,68,92]. Evaluating reinstatement costs informs financial planning, resource allocation, and strategy prioritization [5,8,27,68,92]. It aids in making informed decisions by identifying cost-effective restoration approaches [5,27,28,89,92].

4.2.4. *Resilience attributes under adaptation capacity*

Adaptation capacity stands as a pivotal and indispensable aspect within the realm of resilience when considering CI systems. It encapsulates the inherent capability of a CI system to respond flexibly and adept to dynamic and evolving conditions, as well as to emerging threats that may pose risks to its functionality and integrity [5,28,68,89,92]. This capacity not only enables the CI system to withstand the pressures of change but also empowers it to proactively adjust its operations, strategies, and infrastructure components to ensure sustained performance and mitigate potential disruptions [5,8,92]. To holistically evaluate and gauge the adaptation capacity of CI systems, it is imperative to identify and delineate specific attributes that provide a comprehensive picture of the system’s resilience in the face of evolving challenges [5,68,89,92]. Table 6 presents the four key attributes identified and categorized under the adaptation capacity domain. These attributes serve as valuable signposts, enabling stakeholders to assess and monitor the system’s ability to adapt and respond effectively to changing circumstances.

4.2.4.1. *Substitutability (Replacement of Service).* Substitutability refers to a system’s ability to replace disrupted primary services with alternatives. This indicator gauges backup systems, redundancy, or alternate resources available to maintain critical functions during disruptions [5,8,89,92]. The evaluation of substitutability involves assessing backup systems, redundant components, and the

Table 6
Summary of identified resilience attributes under adaptive capacity.

	Resilience attributes	Related key terms	Assessment method	Sub indicators	Adopted infrastructure from literature	Focused hazard type	Reference
AD1	Substitutability (Replacement of Service)	<ul style="list-style-type: none"> • Replacement of services • Availability of the backup system 	<ul style="list-style-type: none"> • Empirical data • Predictive modelling 	<ul style="list-style-type: none"> • Technical and financial possibility of replacement of the assets • Technical and financial possibility of replacement of the services 	<ul style="list-style-type: none"> • Water • Transportation • Hospital • Emergency services • Electricity and energy • SCADA system 	Flood, Earthquake, Hurricane, Landslides, Industrial accidents	[14,17,18, 58,59]
AD2	Adaptability/ Flexibility	<ul style="list-style-type: none"> • Adaptivity • Flexibility 	<ul style="list-style-type: none"> • Expert interviews • Empirical data • Predictive modelling 	<ul style="list-style-type: none"> • Possibility of timely adapt to the new disruptive event • Existence of adaptation plans 	<ul style="list-style-type: none"> • Water • Transportation • Hospital • Emergency services • Electricity and energy • SCADA system 	Flood, Earthquake, Hurricane, Landslides, Industrial accidents	[46,55,74, 78,89,100]
AD3	Impact and consequences reduction measures availability	<ul style="list-style-type: none"> • Mitigative measures • Impact mitigation measures • Adaptation measures 	<ul style="list-style-type: none"> • Expert interviews • Empirical data 	<ul style="list-style-type: none"> • Possibility of relocating the facilities • Number of new facilities according to the standards 	<ul style="list-style-type: none"> • Water • Transportation • Hospital • Emergency services • Electricity and energy • SCADA system 	Flood, Earthquake, Hurricane, Landslides, Industrial accidents	[46,55,74, 78,89,100]

availability of spare capacity [5,8,68,89,92]. Substitutability fosters flexibility and responsiveness, allowing dynamic resource allocation and redirection during disruptions [5,27,28,89,92]. It acts as a safety net, ensuring service availability despite impacts on the primary system [28,68,89,92]. Enhancing substitutability involves identifying redundancy needs and allocating resources to improve adaptive capacity [5,8,68,89,92].

4.2.4.2. *Adaptability/flexibility.* This attribute showcases the system’s aptitude for altering operations, protocols, or configurations to accommodate new circumstances or counter disruptions [5,8,92]. Adaptability emphasizes the system’s agility in evolving scenarios, involving the recognition of risks, anticipation of disruptions, and swift modification of operations to sustain critical functions. This attribute encompasses both reactive and proactive strategies, enabling effective responses to unexpected events and proactive mitigation [5,68,89,92]. Evaluating adaptability involves assessing the system’s capacity to alter operations in response to changes [5,89,92]. This includes examining alternative strategies, contingency plans, and flexible operational frameworks that can address emerging challenges [28,68,89,92]. A highly adaptable CI system can swiftly allocate resources and implement solutions to maintain crucial functions during disruptions [5,68,89,92], minimizing vulnerability and ensuring functionality in rapidly changing environments. Furthermore, adaptability allows the system to embrace innovation, incorporating new technologies or practices to enhance resilience and efficiency [5,8,68,89,92].

4.2.4.3. *Impact and consequences reduction measures availability.* Impact reduction measures involve resources and measures that effectively minimize the effects of disruptions, such as early warning systems and protective infrastructure [5,8,27,28,68,89,92]. Conversely, consequences-reduction measures focus on resources and measures that mitigate the aftermath of disruptions on CI systems and their broader context. This includes recovery plans, emergency response capabilities, and strategies to reduce socio-economic and environmental impacts. By assessing recovery capacity, functionality restoration, and broader consequences, this indicator strengthens overall resilience [5,8,27,28,68,89,92].

Together, these attributes cultivate resilience and improvement within CI systems. They encourage risk reduction, innovation, and collaboration to enhance adaptability [5,8,27,28,68,89,92]. Prioritizing these attributes allows for optimal resource allocation, fortified infrastructure planning, and sustainable CI systems. By assessing and strengthening these attributes within the adaptive capacity, stakeholders enhance CI systems’ ability to adapt. Substitutability ensures backup systems, while adaptability recalibrates operations for emerging challenges [5,8,27,92]. Impact-reducing measures mitigate disruption effects, and consequences-reducing measures expedite recovery. These strategies bolster adaptive capacity, yielding a resilient CI system that adeptly navigates challenges and consistently provides essential services [5,92].

4.3. Validation of identified resilience attributes

This section presents the validation of the proposed framework. The validation process was conducted through two rounds of



Fig. 3. Average rating for the resilience attributes during 1st and 2nd round of Delphi survey.

Delphi survey. Fig. 3 illustrates the average score for the applicability of the pre-identified resilience attributes within each capacity during the first round and second round. Notably, the majority of experts evaluated all attributes as "Applicable" or "Highly Applicable." Additionally, comments were received for the revision of these attributes during this initial round. A noteworthy suggestion from several experts was to combine "Disaster planning and response" with "Mitigation measures and features" into a single attribute, as these two attributes were found to share a similar interpretation. In assessing the applicability of these identified attributes for evaluating the resilience of CIs, certain key attributes emerged as prominent during the first round of the Delphi survey. In the context of planning capacity, "Mitigation measures and features" (with an average rating of 4.70), "Learnability" (4.60), and "Disaster planning and response" (4.57) demonstrated their strong suitability. For absorptive capacity, "Severity of Failure" and "Reliability of Just-in-Time Delivery" received the highest ratings (4.67 and 4.70). Similarly, "Redundancy" (4.67), "Robustness" (4.63), "Economic sustainability" (4.63) played pivotal roles, "Response" (4.53), "Post-Event Functionality" (4.53) and "Resourcefulness" (4.57) were found to be relevant within the absorptive capacity category. In the context of restorative capacity, "Recovery/loss ratio" (4.70) proved crucial for evaluating recovery efficiency, alongside "Recovery time in post event" (4.50) and "Cost of reinstating functionality" (4.43). Lastly, within the adaptive capacity category, "Substitutability (Replacement of Service)" emerged as the top-rated indicator (with an average rating of 4.77), underscoring its paramount importance. "Adaptability/Flexibility" and "Impact and consequences reduction measures availability" also demonstrated strong performance, with an average rating of 4.67. These findings offer valuable insights into the selection and refinement of attributes of CI resilience. In the second round of the validation process, all the attributes received the highest rating for applicability. Fig. 3 shows that the average ratings increased in all attributes from the first round to the second round, except for mitigation measures and features and just-in-time delivery reliability, which remained the same. This suggests that the experts revised their opinions and became more positive about the applicability of resilience attributes. The largest increases in average ratings were observed in infrastructure quality, failure probability, systems failure, ability to withstand, resistance, interoperability, post-event damage assessment, cost of reinstating functionality, and adaptability/flexibility, which improved by 0.5 points.

5. Discussion

The results of this study indicate that the identified attributes employed in previous studies differ in terms of the attributes used, criteria applied, and assessment methods. Moreover, attributes and criteria are often misused. Many existing studies in the literature fail to conduct a comprehensive assessment of CI resilience, as they neglect various capabilities, stages, interdependencies, and implementation actions. These issues are widespread in indicator-based assessments of CI resilience, resulting in incomparable and

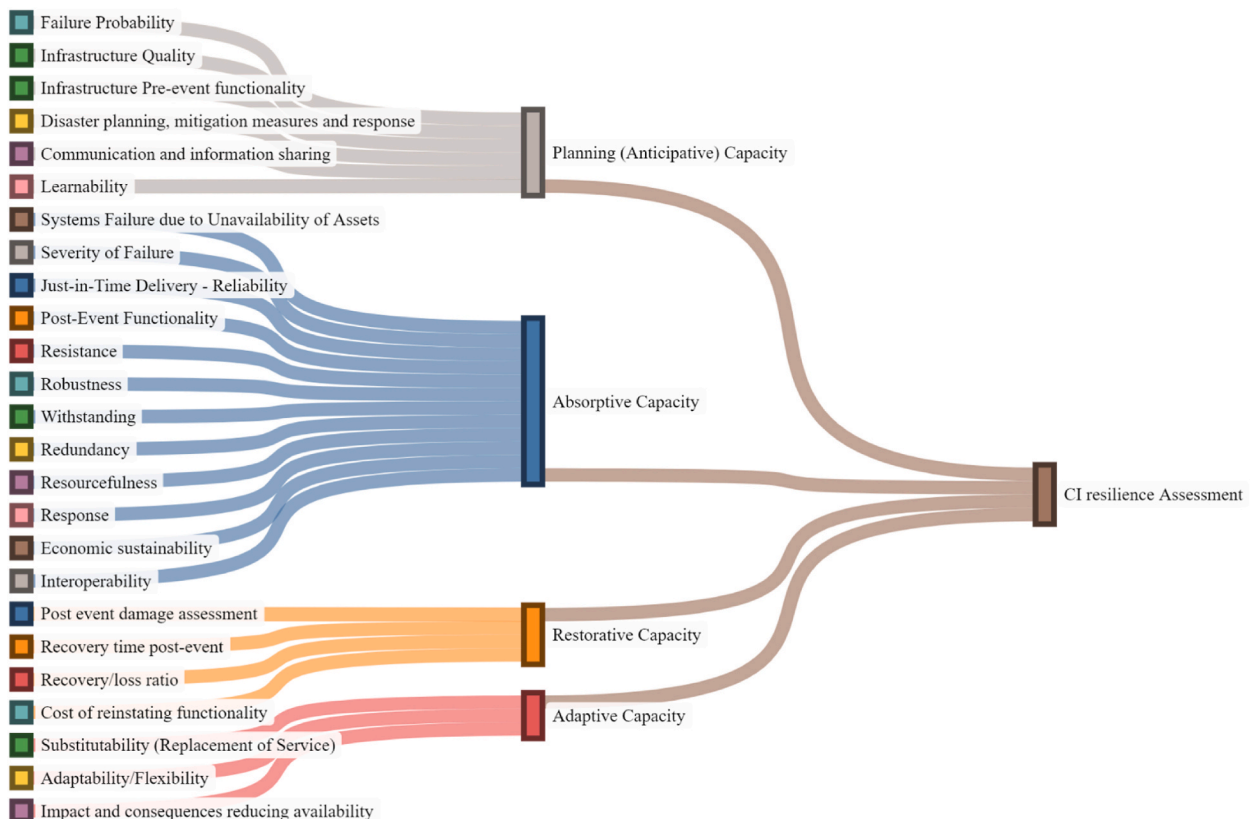


Fig. 4. Proposed resilience assessment framework.

incomplete outcomes. To achieve comparable assessment results, it is essential to establish consistent criteria and metrics for evaluating the resilience of different CIs. Addressing these challenges necessitates the development of a framework aimed at improving the assessment of CI resilience. Fig. 4 presents the proposed resilience assessment framework as an outcome of the study.

In 2022, UNDRR has introduced the principles for the resilient infrastructures [134,135]. This report outlines a series of principles, important steps, and recommendations aimed at enhancing national-level resilience and bolstering the uninterrupted delivery of CI's

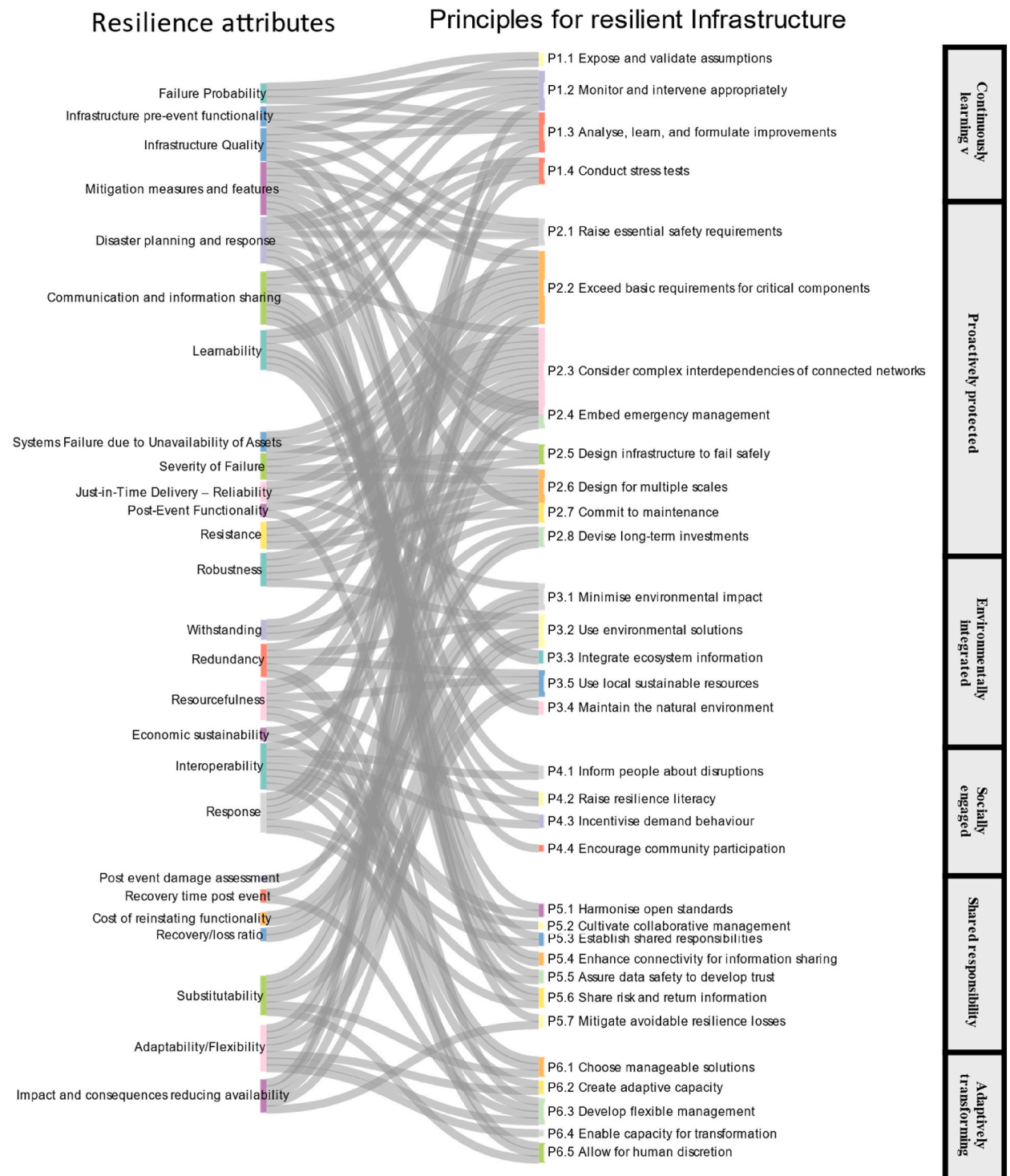


Fig. 5. Alignment of main attributes with UN principles for Resilient Infrastructure.

services through economic infrastructure systems [134]. The proposed framework for the resilience assessment of CIs is also aligned with the UN principles for resilient infrastructure as well as depicted in Fig. 5. The previously mentioned methods for evaluating resilience in CIs include a range of approaches, capabilities, and aspects aimed at thoroughly assessing the system's capacity to endure and bounce back from disruptive incidents. Assessment involves gathering relevant information, such as data or indicators, to address a particular objective or goal [30,40,90]. These assessment methods employ a combination of quantitative, qualitative, and hybrid approaches to capture the multifaceted nature of resilience. Quantitative methods focus on performance metrics and system interdependencies, while qualitative approaches emphasize expert judgment and scenario-based analyses [92–97]. Hybrid approaches integrate data-driven modeling with stakeholder inputs. Resilience assessment frameworks, whether quantitative, qualitative, or semi-quantitative, often rely on indicators [10,24,30,60,64,92–97]. Quantitative approaches utilize measures not specific to a particular domain and employ structural-based modeling techniques to represent domain-specific features. Semi-quantitative approaches provide a broad numerical description of classifications without extensive formulas or models. On the other hand, qualitative approaches rely on judgments and analysis from experts or operators and graphical representations to illustrate the value or change of indicators without numerical calculations [24].

Different researchers have also used numerical models for developing the resilience assessment tools of the CIs. Ouyang, 2014 classified these modelling and simulation techniques mainly into six categories; empirical approaches, agent-based approaches, system dynamic based approaches, economic theory-based approaches and network-based approaches [51]. Quantitative resilience assessment methods, utilizing probabilistic models, offer quantitative estimates of risk, although they may struggle with complex, cascading failures [40,136,137]. Network-based approaches, rooted in network theory, analyze infrastructures as complex systems, capturing interdependencies but facing challenges in scalability and computational complexity. Resilience indicators and metrics provide a holistic assessment of resilience dynamics, facilitating benchmarking and comparison but requiring careful selection and integration of qualitative insights [40,138]. Dynamic systems modeling, employing techniques like system dynamics and agent-based modeling, simulate complex system behaviors, offering insights into leverage points for resilience enhancement but demanding significant computational resources and expertise [40,51]. Multi-Criteria Decision Analysis (MCDA) methods integrate diverse criteria to prioritize investment decisions, considering stakeholder perspectives and trade-offs, yet relying on subjective judgments. Integrating multiple methods and perspectives can enhance the robustness of resilience assessments, supporting informed decision-making for CI resilience enhancement [139,140]. In these modelling techniques, scholars have used these resilience indicators in different ways to assess the resilience of the CIs.

One must consider foundational resilience attributes that span across different CI sectors. These may include factors such as physical integrity of infrastructure, redundancy of critical components, and the capacity to withstand natural or man-made disasters. These attributes provide a baseline for assessing resilience across various infrastructure types. However, the challenge arises when attempting to apply certain attributes universally. Therefore, the identification of common attributes necessitates a thorough review of each infrastructure type to determine its unique vulnerabilities and dependencies. This process should involve experts from different sectors, policymakers, and stakeholders to ensure comprehensive coverage. The objective is not to rigidly apply attributes but instead to establish a versatile framework that can be adjusted to suit the unique circumstances of each sector within competitive intelligence. In conclusion, while common framework for resilience assessment across all infrastructure types are desirable, it is crucial to recognize that some attributes may not be universally applicable. A thoughtful and collaborative approach is required to strike a balance between commonality and adaptability, ensuring that resilience assessments effectively address the unique characteristics and challenges of each CI sector.

On the other hand, dependencies exist among the identified attributes. In the context of developing a robust resilience assessment framework for CI, it is imperative to acknowledge and address these dependencies. Overlaps and interconnections among various attributes across CI sectors have significant implications for the accuracy and effectiveness of the framework. For example, higher failure probability indicates low infrastructure quality. Identifying and understanding these dependencies constitute foundational steps. Rigorous analysis and documentation of these interrelationships are essential. This process should be collaborative, involving experts from diverse CI sectors, to gain a comprehensive understanding of how specific attributes influence each other and collectively contribute to overall resilience. Quantification of these dependencies represents the next critical phase. By employing statistical methodologies or modeling techniques, it becomes possible to gauge the strength and nature of the relationships between resilience attributes. Quantitative analysis is invaluable for prioritizing attributes within the proposed framework, allowing the recognition of attributes that wield greater influence or exhibit cross-sector relevance. Additionally, it may be necessary to embark on further research endeavors when significant dependencies remain inadequately understood or quantified. Collaborative efforts with academic institutions, research organizations, and industry experts can facilitate the refinement of the framework and the delivery of more precise resilience assessments. Furthermore, redundancy reduction becomes imperative when attributes either duplicate information or possess strong dependencies. The removal or consolidation of redundant attributes simplifies the framework, making it more practical for implementation. Finally, the framework must embrace a philosophy of continuous improvement. Recognizing that the CI landscape is dynamic, it is essential to accommodate new research findings, real-world experiences, and evolving CI dynamics through regular reviews and updates.

While recent studies have identified the dimensions, capacities, and indicators of CI resilience, there is a notable absence of a practical rating method to evaluate all categories of these attributes and sub indicators. Existing ratings primarily focus on some resilience indicators. However, some of these attributes lack a scientifically based rating system that assesses their contribution to CI resilience. Therefore, it is crucial and necessary to develop a rating approach capable of evaluating all attributes of CI resilience. This approach would unveil the relative importance of each attributes' contribution to resilience, enabling CIs to determine the priority of certain attributes over others. The resilience capacities of the CIs can be assessed through the major attributes mentioned above.

Different scholars have assessed these major attributes using sub-indicators. The preceding sections outline various attributes and sub-indicators that can be used to assess the capacity of CI systems. Moreover, as outlined in the previous sections, these attributes are amenable to measurement using both quantitative and qualitative methods. The versatility in assessment methods is another advantage. Depending on the specific context and available data, these attributes can be empirically measured through data analysis, predictive modeling to anticipate future resilience, or expert opinions that draw on the knowledge and insights of subject matter experts. This adaptability in assessment methodologies ensures that the evaluation process is tailored to the unique characteristics and needs of individual CI systems, enhancing the overall effectiveness of resilience building efforts. Also, it should be noted that there is a lack of guidelines for choosing and selecting appropriate attributes and sub indicators for resilience assessment. A brief guideline as shown in Fig. 6 can be used to select appropriate attributes and sub indicators for resilience assessment. By following these guidelines, stakeholders can effectively select and apply appropriate resilience attributes and sub indicators to assess infrastructure resilience, thereby supporting informed decision-making, risk management, and investment prioritization efforts aimed at enhancing the resilience of CI systems. However, it should be noted that providing comprehensive guidelines is beyond the objective of this study.

6. Conclusion

The lack of uniformity and standardization in the selection of resilience attributes across existing frameworks has been identified as a significant challenge in the field. To overcome this challenge, this study proposes a framework for CI resilience assessment, with the goal of ensuring consistency and comparability in future endeavors. These findings are crucial for future research and the development of a comprehensive CI resilience assessment framework. They reveal disparities in current assessments and offer valuable insights for further research, hypotheses, and global discussions on CI resilience. In conclusion, this study emphasizes the need for a standardized CI resilience assessment framework system. However, several questions arising from this study can be considered in future research.

- Given that the results indicate that attributes can exhibit both broad and precise characteristics, how can we create a universal framework that is adaptable for all CIs while also remaining specific and practical for diverse CIs and situations? Is it advisable to categorize the framework into multiple tiers to address this issue?
- How to design framework that consider the execution of actions, as well as the interdependencies among CIs, their internal elements, and their interactions with other urban components?
- How to define effective criteria for evaluating resilience and standardize the approaches for both 'resilience assessment' and 'attribute assessment'.

However, it is essential to acknowledge certain limitations that should be considered in the present study. These limitations include,

- Firstly, the screening process resulted in the inclusion of 54 articles, providing a substantial body of literature to analyze. Nonetheless, the scope of the study was constrained by the inclusion of studies published between 2010 and 2023. As a result, there is a possibility that relevant studies addressing CI resilience assessment, particularly those published prior to 2010 or after 2023, may not have been incorporated into our analysis. This temporal limitation may have excluded insights and perspectives from earlier research or emerging trends that have developed since the conclusion of our data collection.
- The proposed framework has been identified through existing literature on the CI disaster resilience domain, and it can be used in developing resilience assessment systems for CIs. It is worth noting that this study does not intend to prioritize the resilience attributes. However, to use the framework in resilience assessment, prioritizing them is necessary, as some attributes and sub indicators may significantly affect the overall resilience assessment. While the validation of the identified indicators were conducted utilizing the Sri Lankan experts, it can also be applied for different geographic context after a proper validation process.

As the field of CI resilience continues to evolve, future studies should consider broadening the temporal scope to encompass a more comprehensive range of literature, ensuring a thorough and up-to-date understanding of the subject matter is maintained. Moreover, while we endeavored to compile a comprehensive set of relevant articles through a rigorous screening process, the inherent diversity and complexity of CI sectors may have led to the omission of studies that use different terminology or approaches to resilience assessment. This underscores the need for ongoing efforts to identify and incorporate diverse perspectives from a wide array of CI sectors to ensure a holistic understanding of resilience assessment practices.

CRedit authorship contribution statement

Bawantha Rathnayaka: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Dilan Robert:** Writing – review & editing, Supervision, Resources, Conceptualization. **Varuna Adikariwattage:** Writing – review & editing, Supervision. **Chandana Siriwardana:** Writing – review & editing, Supervision. **Lasantha Meegahapola:** Writing – review & editing, Resources. **Sujeewa Setunge:** Writing – review & editing, Supervision, Resources. **Dilanthi Amarungu:** Writing – review & editing, Resources.

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.

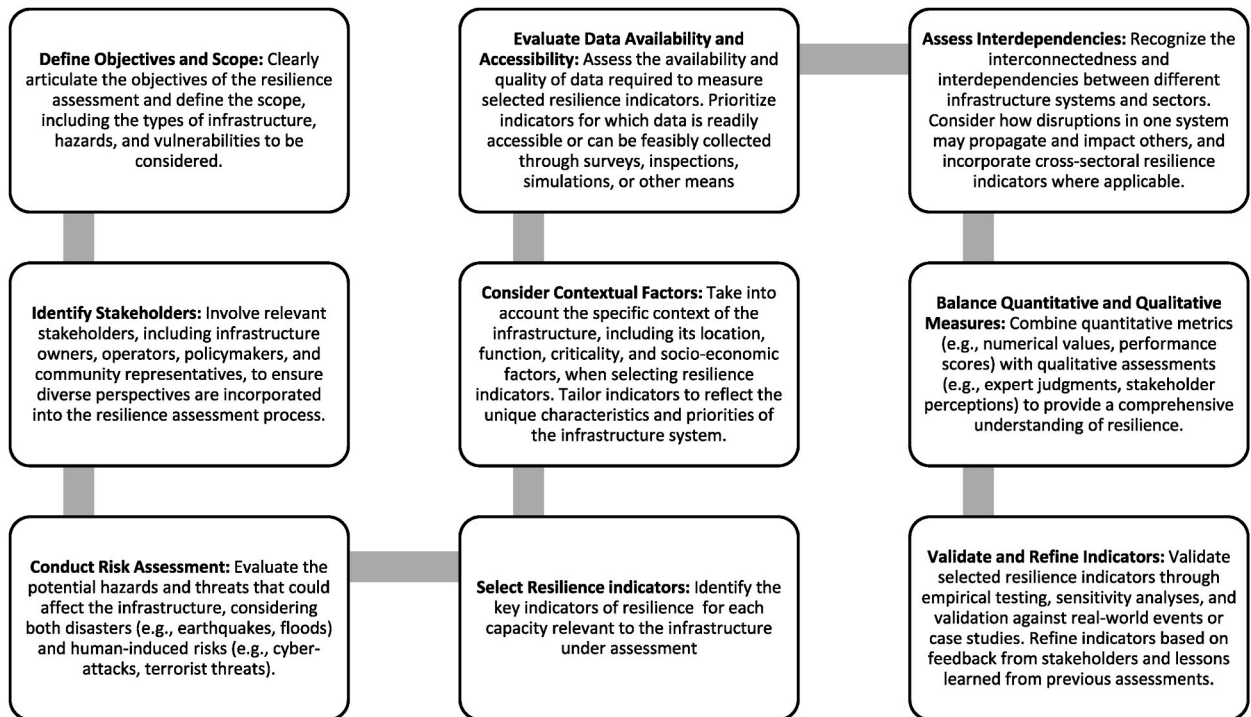


Fig. 6. Proposed guideline for choosing attributes for resilience assessment.

Data availability

Data will be made available on request.

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