Combating Infrastructure Complexity

Developing a Comprehensive Set of Wellbeing and Resilience Indicators for the Transport Infrastructure System

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ABSTRACT: As modern societies become increasingly dependent on infrastructure systems, ensuring their functionality is paramount. Current simulation-based approaches for evaluating infrastructure wellbeing and resilience are known to be complex and time-consuming, making them unfeasible for practical applications. Indicators-based methods have been proposed as a promising alternative to simulations. However, a comprehensive set of indicators that cover all aspects of infrastructure systems has yet to be established. In this study, we performed an extensive literature review on wellbeing and resilience indicators specific to the transport infrastructure system. We filtered out duplications among the indicators and categorized them under distinct components and dimensions. These indicators can be tailored to fit specific circumstances and employed for/alongside advanced techniques such as Machine Learning, Bayesian Networks, and Fuzzy Logic. Acquiring a comprehensive set of wellbeing and resilience indicators can significantly improve stakeholder communication, empower communities in decision-making processes and adaptive management, and support resilience-strengthening strategies.

1. INTRODUCTION

Infrastructure systems, such as transport systems, are vital to modern societies. However, they are subject to various hazards, uncertainties, and transitions that can disrupt their operations and lead to negative social, economic, and environmental consequences. To minimize the impact of these disruptions and ensure the continued provision of essential services, improving the wellbeing and resilience of infrastructure systems is crucial. Resilience refers to the capacity of a system to withstand, adapt to, and recover from unfavorable events while maintaining its essential functions and services (Cimellaro et al., 2016). On the other hand, wellbeing is more concerned with the functionality of the infrastructure system under normal conditions, such as its ability to provide reliable and efficient services, support economic growth and development, and promote social equity and environmental sustainability.

Infrastructure systems are characterized as complex adaptive systems; hence, evaluating their performance requires carefully selecting appropriate methods. By "Infrastructure system", we do not refer to the physical infrastructure network but rather to the combination of the infrastructure network, the organization responsible for managing it, and the environment in which everything is embedded. The interactions between these components shape how the infrastructure system would respond to a hazardous event. These interactions are complex, and they change over time in response to new hazards, development, and technology. For example, the emergence of technology has changed the way the infrastructure is operated and the users interact with it.

Simulation-based methods are commonly used to assess the wellbeing and resilience of infrastructure systems, but they have some limitations. These methods require extensive data and significant computational resources, which can be time-consuming and challenging. Additionally, simulations often rely on assumptions that may not accurately represent real-world scenarios, making them less reliable for decision-making processes.

Indicators are a promising alternative approach to evaluating the wellbeing and resilience of complex systems such as infrastructure (Cutter et al., 2014). Unlike simulation-based methods, indicators provide a practical and straightforward way of measuring the wellbeing and resilience of infrastructure systems. They can be designed to capture all relevant aspects of the system's performance, such as its performance under normal operations and its ability to withstand disruptions, adapt to changing conditions, and recover from events that negatively impact the system's operations. Indicators are often perceived as a less complex alternative to measuring the wellbeing and resilience of infrastructure systems, making them a more accessible tool for decision-makers.

The development of a comprehensive set of infrastructure wellbeing/resilience (W/R) indicators has the potential to empower other research in various ways. One such way is through the use of Bayesian Networks and Fuzzy Logic. These techniques can be used to analyze the relationships between the various indicators and their impact on the wellbeing and resilience of the infrastructure system.

The use of these indicators can also empower other research to develop new and innovative methodologies for assessing infrastructure performance. For example, machine learning techniques can analyze the relationship between the different indicators and identify patterns and trends that may not be immediately apparent. This can result in more sophisticated models for assessing infrastructure performance and improving predictions' accuracy.

Several studies have investigated the use of indicators for measuring the wellbeing and resilience of infrastructure systems. Tachaudomdach et al. (2018) conducted a systematic literature review and identified two dimensions and ten principles of resilience assessment indicators, which can be used to measure the resilience of transport systems. Osei-Kyei et al. (2022) conducted a three-stage systematic review to explore the main standards and criteria used to assess the resilience of critical infrastructure and identified 28 resilience criteria, including organizational resilience, performance loss, and economic resilience. Jovanović et al. (2020) proposed an approach to assessing the resilience of healthcare infrastructure exposed to COVID-19, which included resilience indicators and international standards. Yang et al. (2022) reviewed the existing resilience indicators in urban transport infrastructures. Jovanovic et al. (2016) and Guo et al. (2021) conducted state-of-the-art reviews of resilience assessment frameworks for infrastructure systems. Kammouh et al. (2018) proposed two indicator-based methods for evaluating community resilience based on the PEOPLES framework, including a deterministic and a fuzzy-based method.

Despite the abundance of proposed indicators, there is little consensus on which indicators are most appropriate or comprehensive for assessing infrastructure performance. Some sets of indicators focus on specific aspects of the system, while others lack standardization or validation. Moreover, current literature focuses mostly on the physical aspect of the system neglecting the important role of humans and the environment. If we can capture the dynamics of such interactions, we can proactively prevent cascading failures, minimize losses, and boost recovery.

This paper aims to develop a comprehensive set of W/R indicators for the transport infrastructure system, covering all the relevant aspects of the system. Such indicators can facilitate communication among stakeholders, empower communities in decision-making processes and adaptive management, and support developing and implementing resilience-strengthening strategies.

2. METHODOLOGY

This section describes the process for identifying and selecting the W/R indicators for the transport infrastructure system. This includes collecting indicators, assigning measures to the indicators, and grouping the indicators under components and dimensions.

2.1. Collecting indicators

A systematic literature review was conducted to identify existing indicators to develop a comprehensive set of W/R indicators for the transport infrastructure system. The rigorous and systematic process used to collect and filter the proposed indicators involved a combination of literature review, expert consultation, and stakeholder feedback.

The search was conducted using several scientific databases, including Scopus, Web of Science, and Google Scholar, with search terms such as "infrastructure resilience," "infrastructure wellbeing," "network resilience," " transport systems," and "indicators." A total of 248 articles were initially identified and screened based on inclusion and exclusion criteria. Articles were included if they proposed indicators for measuring the resilience of infrastructure systems and were published in English between 2000 and 2022. Duplicate articles and those that were not relevant were excluded, resulting in 168 articles for full-text review.

After full-text review, a further 59 articles were excluded, resulting in 109 articles that were analyzed to identify eligible indicators. The identified indicators were evaluated based on their relevance to infrastructure resilience and their potential for redundancy. Redundant indicators that captured the same aspect were removed from the list. To further refine the set of indicators, the indicators were shared with experts and stakeholders in the field of infrastructure management and resilience, and their feedback was considered. This process ensured that the selected indicators were comprehensive, relevant, and non-redundant.

2.2. Identifying and assigning Measures

It is essential to identify measures for the indicators to allow their quantification. Measures provide a quantitative or measurable quantity that is more precise and objective than qualitative indicators. For instance, an indicator of the transport system's resilience could be the recovery speed after disruptions. To measure this indicator, the associated measure could be the time to restore transport services after an event. The measure is essential because it provides a quantifiable quantity that can be used to compare different disruptions and evaluate the transport system's resilience objectively.

In this study, each indicator was assigned only one measure to ensure that the measure accurately reflects the aspect of resilience that the indicator represents. For some indicators, measures were identified from the literature. These measures were carefully evaluated and selected to accurately reflect the indicator's intended meaning. In cases where measures could not be found, we proposed alternative measures based on our expertise and knowledge of infrastructure's wellbeing and resilience.

To further validate the identification and assignment of the measures, they were reviewed and discussed with experts in the field of (transport) infrastructure systems. Their feedback was incorporated into the final selection of measures to ensure that they were appropriate and relevant for evaluating the wellbeing and resilience of transport infrastructure systems.

2.3. Clustering indicators:

The collected W/R indicators were clustered under components and dimensions to make them more organized and easier to understand. This implies grouping similar indicators under the same component and similar components under the same dimension, resulting in a meaningful organization of the indicators.

The components were identified based on the commonalities in the proposed indicators. For example, a component could include all the indicators related to the physical structure of the infrastructure system, such as the age of the assets and the condition of the facilities. Similarly, the dimensions were identified based on the overarching aspects of the components.

3. RESULTS

The following section presents the seven dimensions for assessing the wellbeing and resilience of the transport infrastructure system with their corresponding components and indicators. The seven dimensions are summarized under the acronym PURPOSE and include 1) Physical infrastructure, 2) User behavior, 3) Resources, 4) Preparedness and planning, 5) Organization and management, 6) Socioeconomic, and 7) Environment and Climate.

Due to the word count limit, the full set of the indicators is provided as supplementary material and can be found here.

3.1. Physical infrastructure

The physical characteristics of transport infrastructure play a crucial role in the proper functioning of the system, especially during unexpected events such as earthquakes, floods, hurricanes, landslides, and traffic accidents (Soltani-Sobh et al., 2016). The presence of adequate redundant capacity within these infrastructures can help minimize the impact of adverse events and keep the system relatively stable. For example, suppose a road is blocked due to a car accident. In that case, roads with many lanes or safety elements, such as an emergency lane or with a variable message sign (VMS), can provide drivers with alternative routes, allowing them to avoid the accident and keep the traffic flowing smoothly.

The Physical infrastructure dimension is divided into four components: Links/Edges, Vehicles, Facilities/Structures, Accessories, and Serviceability. The Links/Edges component includes indicators such as accessibility, road density, and road width, while the Vehicles component includes mode of transport, vehicle fuel efficiency, and vehicle age. The Facilities/Structures component comprises facilities, critical components, and traffic load capacity, while the accessories component includes availability of emergency equipment and alternative transport. Lastly, the Serviceability component includes travel time reliability and accessibility of service points.

3.2. User behaviour

The behavior of users is critical in determining the wellbeing and resilience of a transport infrastructure system, as it directly impacts traffic demand and supply. The way users respond to system disruptions is therefore an important factor in modeling traffic demand.

Stochastic and statistical analysis has shown that travelers usually choose their routes or modes of transport based on the minimum expected travel cost, which is typically measured by travel time (Soltani-Sobh et al., 2016). This perceived travel cost is influenced by their knowledge of road capacity and congestion and their past experiences. However, the lack of public knowledge, or what is known as perception error, can significantly impact the wellbeing and resilience of the system. For instance, people often choose the shortest path, assuming it will result in the minimum travel cost. Nevertheless, when traffic flow reaches the route capacity, the reliable performance of the system reduces. Moreover, perception error can also affect the selection of transport mode, as seen after the London underground bombing and Madrid train bombing, where the number of passengers taking the attacked modes fell by 8.3% over four months (Prager et al., 2011) and 4-6% for two months (López-Rousseau, 2005), respectively. Consequently, more individuals switch from statistically safer travel modes to riskier road travel (Cox et al., 2011).

Individual reaction rates and experiences with emergency conditions can also affect the stability of the transport system. Experienced travelers are able to react quickly to unexpected situations and avoid accidents.

The User Behaviour dimension has two components: User Status and Response Under Emergency Conditions. Under User Status, there are five indicators: user's trip making behaviour, driving experience, educational level, user's knowledge, and traveler's perception. Under Response Under Emergency Condition, there are five indicators, including reaction speed, operation under emergency condition (sensitivity to recognize potential risks), availability of emergency kits, emergency plan awareness, and availability of emergency training.

3.3. Resources

Resources are crucial in maintaining normal functions and absorbing disturbances of adverse events. Having adequate resources is fundamental in restoring the damaged system, as a lack of resources can extend the recovery time and even cause further disorder. For example, during Hurricane Rita in 2005, a lack of fuel supply caused significant traffic congestion. Without access to water, food, medical treatment, and public services, panic and civil disorder developed. In addition to having adequate resources, professional technicians and specialists play a crucial role in managing these resources efficiently and effectively. They are responsible for allocating resources based on their experience, manipulating different devices, and checking and maintaining them within a fixed period.

The Resources dimension has three components: Materials and Equipment, Structures, and Supporting Services. The component Materials and Equipment includes the indicators: available fuel, development of high-tech equipment, inventories, availability of alternative energy sources, and availability of communication equipment. The component Structures includes lifeline facilities, temporary facilities, shelters and evacuation routes, and availability of backup infrastructure. The component Supporting Services includes scientific support, checking and renewal of resources, availability of emergency services, availability of public utilities, availability of emergency supplies, and coordination with private sector.

3.4. Preparedness and planning

Effective planning is essential for the wellbeing and resilience of transport systems, especially in the face of disasters or emergencies. Plans should be developed well in advance and cover all stages of an emergency, including preparedness, response, recovery, and restoration. Regular drills and training sessions are also necessary to test and refine these plans, ensuring their effectiveness when put into practice.

It is also crucial to consider the needs of vulnerable populations in emergency planning. People who are disabled, poor, or ill are often more affected by disasters and may require special assistance or accommodations. Failing to account for these populations in emergency planning can lead to ineffective responses and worsen the overall impact of the disaster, as was seen in response to Hurricane Katrina.

In addition to these considerations, emergency plans should also specify the responsibilities of different authorities involved in the response, including government agencies, emergency services, and other relevant organizations. By clearly defining the roles and responsibilities of each organization, the response can be more efficient and effective, leading to a better overall outcome.

The Preparedness and Planning dimension consists of two components: Planning in Different Phases and Execution of Plan. The Plan in Different Phases component has indicators such as pre-disaster preparedness and response skills of citizens, emergency plan, plan for post-disaster recovery and reconstruction, simulations and exercises, funding for emergency management, and public participation. On the other hand, Execution of Plan component includes effective response by responsible authorities, timetable of transport, special treatment for vulnerable groups, plan feasibility, renewal of plan, and integration of private sector.

3.5. Organization and Management

The dimension Organization and Management concerns the way the transport system is managed and coordinated to effectively respond to a disruptive event. It involves the ability of the system to be flexible and adaptive to both internal and external stressors. Information flow is particularly important as it plays a vital role in the entire system's functionality. A free flow of information can make the system respond to disruptive events more quickly. On the other hand, poor communication can lead to the system's failure, reducing people's confidence in the government. For example, during Hurricane Rita, many people were blocked on the road for more than 20 hours due to poor communication (Cox et al., 2011). To enhance the effectiveness of the transport system during crises, organizations need to collaborate with other stakeholders, such as the private sector, communities, and local government. Effective communication is also crucial for coordinating efforts with relevant authorities and stakeholders. This ensures that critical decisions are made in time.

The dimension Organization and Management includes three components: Administrative/Executive, Supporting Measures, and Communication. Administrative/Executive includes indicators such as dissemination of information, effectiveness of decision implementation, effectiveness of management events, and effectiveness of information about road conditions. Supporting Measures includes policies, previous experience dealing with extreme conditions, preparedness and training programs, monitoring of the transport system, mutual trust between citizens and government, and distribution and logistics of resources. Communication includes effectiveness, accessibility, timeliness, language accessibility of communication, and communication redundancy.

3.6. Socioeconomic

The sixth dimension is Socioeconomic. The economy plays an indirect role in the stability and ability to return to the normalcy of the transport system. A diverse economy is generally more resistant to external changes, and infrastructures that are covered by insurance can receive sufficient funding for reconstruction and recovery, reducing the time required to return the damaged system to normalcy. Moreover, population size is an important factor that can significantly impact the performance of a transport system during unexpected events. A notable example is the heavy snow that hit China in the winter of 2008, which destroyed a key railway from Guangzhou to Beijing and resulted in chaos for nearly half a million passengers (Ip & Wang, 2011). A larger population can act as a catalyst, amplifying the effects of any disruption to the transport system. In addition, education and training programs are crucial to simulate real situations and help stakeholders and the public understand what to do in case of an event, enabling them to respond quickly and efficiently. However, it is important to note that transferring principles into actions can be challenging.

The Socioeconomic dimension encompasses three components: Social Composition, Economic Aspects, and Social Education and Awareness. Social Composition includes indicators such as population density, vulnerable user (child and elderly), vulnerable populations, and community cohesion. Economic Aspects includes economic stability, diversity, and vitality, special economic support, allocation of limited budget, car ownership, the price of public transport, investment for new routes, maintenance, and insurance. Social Education and Awareness includes educational programs for local communities, local training programs, emergency preparedness of local communities, and social awareness of evacuation plans. Involvement of Non-profit Organization includes volunteerism of social organizations, educational curriculum and drills for evacuation, funding for non-profit organizations, volunteer training and development, and coordination with the public sector.

3.7. Environment and Climate

The seventh dimension is Environment and Climate. This dimension aims to measure the impact of environmental and climatic factors on the transport infrastructure system. The wellbeing and resilience of a transport infrastructure system are directly impacted by the environment. Different weather conditions can affect the infrastructure's physical performance and people's behavior. For example, heavy rainfall or storms can reduce the friction of road surfaces, including airport runways. As a result, vehicles are more susceptible to accidents due to longer braking distances and decreased visibility. Additionally, heavy rain can cause power outages and telecommunication network collapses. Volcanic eruptions can also cause ash falls that similarly affect transport systems (Wilson et al., 2012).

On the other hand, vegetation on roadsides and isolation strips can protect roads from animals and provide drivers with good driving conditions. Vegetation also helps to absorb pollutants and reduce noise pollution. Green infrastructure such as permeable pavements and rain gardens can reduce the amount of runoff from heavy rainfall, mitigating the risk of flooding and erosion. In this way, natural systems can enhance transport systems' wellbeing and resilience while providing other environmental benefits.

The dimension Environment and Climate includes two components: Weather Conditions and Ecosystem and Environment. Weather Conditions includes indicators such as extreme weather conditions, magnitude and duration of unexpected events, impact on infrastructure, preparedness for extreme weather, and disaster recovery time. Ecosystem and Environment includes living species, roadside plants and vegetation, urban renewal and development, air quality, noise pollution, and natural disaster risk.

4. DISCUSSION AND CONCLUSION

Infrastructure wellbeing and resilience has gained significant attention in recent years due to the increasing frequency and magnitude of natural and man-made disasters. Assessing the wellbeing and resilience of infrastructure systems can be a complex task, requiring the consideration of various factors that impact the ability of infrastructure to withstand, adapt to, and recover from disruptive events. To address this challenge, a comprehensive set of infrastructure wellbeing and resilience (W/R) indicators tailored for the transport infrastructure system was proposed in this paper. The indicators have been classified under a wide range of dimensions and components. Compared to simulation-based approaches, indicator-based approaches are considered more practical and straightforward. They also allow incorporating factors beyond recoverability, such as hardness and adaptive capacity, and can be adapted to communities of different types and sizes.

The proposed (W/R) indicators offer significant potential for advancing research on transport infrastructure systems. These indicators have been developed using a comprehensive approach and can be employed by various methodologies and techniques, including Machine Learning and Bayesian Networks, to provide a comprehensive understanding of the wellbeing and resilience of infrastructure systems.

The proposed W/R indicators provide several potential uses for stakeholders to assess and improve the performance of transport infrastructure systems. Firstly, they provide a common language and framework for communication between different stakeholders, helping to identify and prioritize critical factors that impact the infrastructure’s functionality. Secondly, these indicators can enhance community involvement in assessing and improving transport infrastructure wellbeing and resilience as they recognize the critical role that communities play in building and maintaining resilient infrastructure. Thirdly, by using the proposed indicators to assess the wellbeing and resilience of transport infrastructure before and after an event, stakeholders can evaluate the effectiveness of existing and new resilience-strengthening strategies and identify areas for further improvement.

Nevertheless, the extensive nature of the indicators may make it challenging to use them in practice. Therefore, stakeholders may need to prioritize the most relevant indicators to their specific context, goals, and resources. While the indicators cover a wide range of aspects, assessing the wellbeing and resilience of infrastructure systems remains multifaceted and context-specific. Hence, stakeholders may need to supplement indicators with additional data sources and qualitative information.

Future research should be geared towards developing methods for weighting and aggregating the indicators to provide an overall measure. In addition, research on the cost-effectiveness and feasibility of using the proposed indicators in practice is necessary to ensure that a wide range of stakeholders can use them. Finally, there is a need for research on evaluating the applicability and transferability of the indicators across different types of infrastructure and geographic contexts.

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