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Comparative Analysis of Strengths and Limitations of Infrastructure Resilience Measurement Methods

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Abstract: Since the beginning of the 21st century, experts have increasingly used resilience analysis to assess the damages and performance of infrastructures suffering from disturbing events like natural and/or man-made hazards. The resilience of infrastructures is almost always affected by severe calamitous events, even though the damages are not always visible. Researchers have developed several methods, which have been recently adopted by the transportation sector, to define the physical condition and/or performance deviations of affected infrastructures by measuring their resilience. Throughout literature, few studies focus on comparative analysis based on the advantages and disadvantages of these models; therefore, the goal of this paper is to identify and analyze frameworks, based on their applicability and dimensions. To achieve this goal, a thorough review of literature was conducted to define the resilience concept and identify the frameworks. Several of the most recent resilience-measuring models and methods that relate to the technical aspects of the resilience of transportation infrastructures, including the Critical Infrastructure Resilience Decision Support System (CIR-DSS), and Cox's proportional hazards regression model and resilience optimization model, were identified to conduct a comparative analysis. Findings of this study will help researchers explore current gaps in research on resilience of the transportation infrastructure sector, and will guide researchers in developing a resilience measurement model that incorporates all dimensions. This study will also be of great help to researchers and practitioners, as they adopt appropriate methods to measure the severity of damages and identify proactive strategies to reduce unintended consequences of disruptive events.

1 INTRODUCTION

Human civilization is dependent upon critical infrastructures (CI's). Transportation infrastructure is one of the CI's that imposes great economic losses on society if not recovered, as their condition highly determines the recovery pace of residential buildings, water infrastructures, and industrial plants of the affected areas (Bosher and Dainty, 2011). Local businesses are also dependent on network characteristics of transportation (Cox et al. 2011), and destruction of the transport network has the potential to isolate a community from the rest of the world, thus increasing the possibility of damage. Natural disasters have the highest potential for destroying the transportation infrastructure within a very short period of time (Bil et al. 2015, Kermanshachi and Rouhanizadeh, 2018). Over the past few years, such destruction has made researchers realize the necessity of building resilient infrastructures. Local, national, and international governments are also recognizing the need for adopting hands-on actions to make their communities and infrastructures resilient against sudden shocks (Cutter 2016; Kermanshachi et al., 2019).

A range of research works related to resilience can be found throughout the literature. The spectrum of resilience dimensions is vastly diverse, and several resilience-measuring methods, adopting different dimension/dimensions of resilience, have been developed over the years (Cutter 2016). Yet, very few of them implement the dimensions required to quantify the resilience of the transportation sector; even fewer compare the characteristics of these models (Rouhanizadeh and Kermanshachi, 2019a). This lack is a major hindrance to building a single method/tool/technique/solution that comprehensively measures the dimensions of transportation infrastructure resilience. Hence, the aim of this paper is to conduct a comprehensive study of resilience- measuring frameworks, and perform a comparative analysis of the most recent resilience-measuring models of the transportation sector, based on applicability and limitations. The findings of this study will help researchers explore the current gaps in research on the resilience of the transportation infrastructure sector, and will guide researchers in developing a resilience-measurement model that incorporates all dimensions. This study will also help practitioners adopt the appropriate measurement technique in an emergency, and reduce the unintended consequences of disasters to a minimum.

2 RESEARCH METHODOLOGY

A four-step methodology was adopted for this study. The first step was to develop a database. The second step was to read articles on the subject, saving the more appropriate ones for further study. Information essential for grasping the definition of resilience was collected from the pre-selected articles in the third step, as was material pertaining to the various frameworks used to measure the resilience of different systems. Another vital action of this step was to select and set aside, for future reference, the articles that discussed the development of a method that measures the resilience of transportation infrastructures. In the fourth step, methods that measure the technical aspects of transportation infrastructures were listed and further studied, and a comparative analysis, based on their applicability and limitations, was performed. The final step was to present the conclusions.

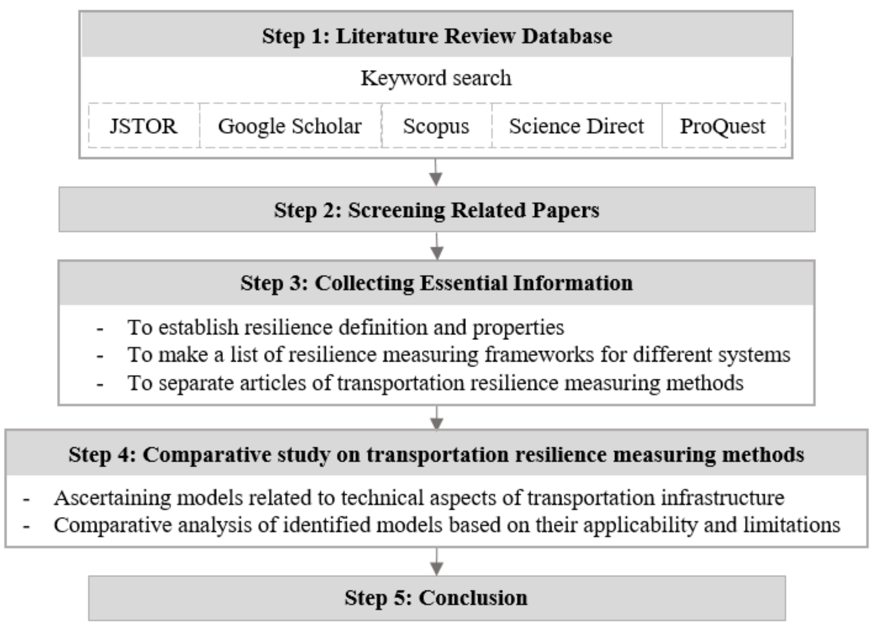

Figure 1: Research Methodology

3 PREPERATION OF DATABASE

The keyword search option in search engines such as JSTOR, Google Scholar, and Science Direct, etc. was used to collect articles which might be useful for this study. Peer-reviewed journal articles were given priority. After careful consideration of main focus of the study, approximately 100 scholarly articles were separated for further study; most of them were related to transportation infrastructure resilience. The journals and the number of articles that were published in them on transportation infrastructure resilience are presented in Table 1.

Table 1: Frequency of Articles by Journals

No.	Journal Title	Frequency	Percentage
1	Reliability engineering and system safety	9	9%
2	Transportation Research Record: Journal of the Transportation Research Board	8	8%
3	Disasters	7	7%
4	International Journal of Disaster Risk Reduction	6	6%
5	International Journal of Disaster Resilience in the Built Environment	6	6%
6	IEEE systems journal	5	5%
7	Natural Hazards	4	4%
8	Journal of Infrastructure Systems	4	4%
9	Global Environmental Change	3	3%
10	Engineering Structures	3	3%
11	Transport Policy	3	3%
12	Transportation Research Part A: Policy and Practice	3	3%
13	Transportation Research Part C: Emerging Technologies	3	3%
14	Transportation Research Part D: Transport and Environment	3	3%
15	Transportation Research Part E: Logistics and transportation review	3	3%
16	Transportation Research Part B: Methodology	2	2%
17	Transportation Research Procedia	2	2%
18	Structures Congress	2	2%
19	Earthquake Spectra	2	2%
20	Other	25	24%
	Total	103	100%

Even though resilience is an age-old concept, resilience-measuring methods for transportation infrastructures is a new concept that has been only recently adopted. As a result, most of the articles that were studied are from recent years. Figure 2 shows the distribution of the papers, based on their year of publication.

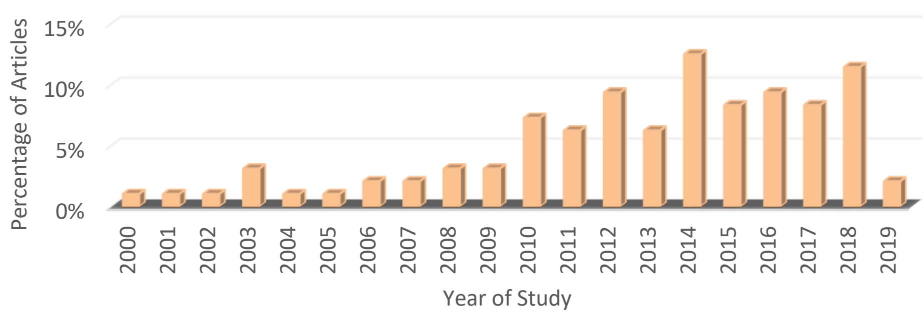

Figure 2: Distribution of Articles based on Year of Study

4 DEFINITION AND DIMENSIONS OF RESILIENCE

Resilience has not been adequately explored in literature, even though it is a rapidly evolving concept (Panteli and Mancarella 2017). As a result, the idea of resilience is still quite fuzzy, and the factors that define it are still a matter of dispute (Bueno 2012). Beginning with the psychology and ecology sectors, the term resilience has made its way through almost all of the systems, including the social, industrial, economic, and infrastructure systems (Gay and Sinha 2013). Researchers from different sectors describe resilience in different ways, yet the main theme of the term is similar. The resilience of a system is its ability, after suffering from disruptive events, to bounce back, in the shortest possible amount of time, to the pre-disaster/predefined satisfactory level of performance (Bruneau et al 2003, Chang and Shinozuka 2004, McDaniels et al 2008, Keogh and Cody 2013). Nan and Sansavini (2017) found that a system maintains this definition through its absorptive, adaptive, and restorative capabilities. Reggiani (2013) divided this definition into two parts, defining the first part as static resilience, which shows the ability of the system to bounce back to the desired level of functionality after a disaster; and the second part as dynamic resilience, which shows how rapid the recovery is. He also presents arguments about the desired degree of resilience for a system, as one resilient system might make another vulnerable. Resilience is a term used in a myriad of ways for different systems; therefore, a variety of terminology is used. Table 2 describes a few of the terminologies that are used throughout the literature.

Table 2: Terminology Necessary for Understanding the Concept of Resilience

SI	Term	Description	Reference
1	Robustness	Ability of the system to face a certain level of damage from a disastrous event without losing its functionality. A robust system has high absorptive capabilities.	Bruneau et al 2003, Reed et al 2009, Blockley et al 2012, Liao et al 2018, McDaniels et al 2008, Reggiani 2013, Panteli and Mancarella 2017
2	Redundancy	Having back-up components with the same functionality to take over the responsibility of damaged components in emergencies. It is an indication of the absorptive capability of the system.	Bruneau et al 2003, Reed et al 2009, Liao et al 2018, Godschalk 2003,
3	Resourcefulness	Ability to utilize material and human resources to achieve recovery goals after a disaster. It is an indication of the adaptive quality of the system.	Bruneau et al 2003, Reed et al 2009,
4	Rapidity	Ability to restore a system in the least amount of time, taking necessary steps to avoid future similar disruptions.	Reed et al 2009, Liao et al 2018, McDaniels et al 2008, Henrey and Ramirez-Marquez 2012
5	Quality	Performance of the system over time, after a disaster.	Reed et al 2009
6	Fragility	The probability of damage due to a given level of disaster.	Reed et al. 2009
7	Vulnerability	Exposure to stress. This term is often used in social resilience and is yet to be defined in regard to infrastructure resilience. It is highly related to lack of robustness.	Blockley et al. 2012, Liao et al 2018, Adger 2000, Reggiani 2013
8	Sustainability	Ability to tolerate. It is related to the robustness of a system.	Blockley et al. 2012
9	Diversity	Having components with different functionality that can withstand a range of threats.	Godschalk 2003, Liao et al 2018,
10	Efficiency	Ability of a dynamic system to have a positive value for the ratio of energy supplied to energy delivered.	Godschalk 2003, Liao et al 2018,
11	Autonomous components	Ability to operate independently.	Godschalk 2003, Liao et al 2018,
12	Strength	Ability to withstand attacks from man-made or natural disasters.	Godschalk 2003, Liao et al 2018,
13	Interdependent	Ability of the interdependent components to support each other under the stress.	Godschalk 2003
14	Adaptability	Ability of the system to learn from the current disaster to better cope with future disasters.	Godschalk 2003, Liao et al 2018, Panteli and Mancarella 2017

15	Collaboration	Ability to share information and resources with components and/or stakeholders.	Godschalk 2003, Liao et al 2018, Murray-Tuite 2006
16	Mobility	Ability to ensure that travelers can travel at an acceptable level.	Liao et al 2018, Murray-Tuite 2006
17	Safety	Ability to prevent users from being exposed to hazards.	Liao et al 2018, Murray-Tuite 2006
18	Resistance	Ability to prevent the damage caused by the primary impact of the disaster.	Panteli and Mancarella 2017
19	Reliability	Indication that the infrastructure was designed to withstand a wide range of unforeseeable events.	Panteli and Mancarella 2017
20	Response and Recovery	A combination of rapidity and resourcefulness to recover an infrastructure after a disaster.	Panteli and Mancarella 2017
21	Flexibility	Ability of the system to cope with unpredictable changes - similar to adaptability of the system.	Faturechi and Miller-Hooks 2014
22	Survivability	Ability to mitigate the vulnerability of a system.	Baroud et al 2014
23	Preparedness	Ability to be prepared for events before they occur.	Jin et al 2014
24	Responsiveness	Ability to recognize changes.	Ivanov et al 2014, Klibi et al 2010, Bertrand 2003
25	Optimization	Ability to have to best in a system.	Blockly et al 2012

Various sectors adopt different dimensions of resilience. Nonetheless, the most frequently used terminologies, irrespective of the type of system, are robustness, redundancy, resourcefulness, and rapidity, collectively known as the 4 Rs. However, while discussing the resilience of the transportation infrastructure, researchers decided to use 10 dimensions instead of 4, namely redundancy, efficiency, diversity, strength, adaptability, autonomous components, collaboration, mobility, safety, and rapidity (Murray-Tuite 2006, Liao et al. 2018). Once a system has acquired the necessary level of these dimensions, it will be technically, organizationally, socially, and economically resilient (Labaka et al. 2016). These four criteria of a system are known as TOSE. The rapidity dimension of resilience indicates that resilience is a time-dependent function (Panteli and Mancarella 2017, Rouhanizadeh et al., 2019b). Hence, a graphical representation with respect to time was used to discuss resilience from the very beginning. Early researchers (Bruneau et al. 2003; Chang and Shinozuka 2004) used graphs somewhat similar to Figure 3 to describe resilience, and over the years, many researchers (Nan and Sansavini 2017; Fang et al. 2016; Francis and Bekera 2014) added relevant components to explain resilience more explicitly.

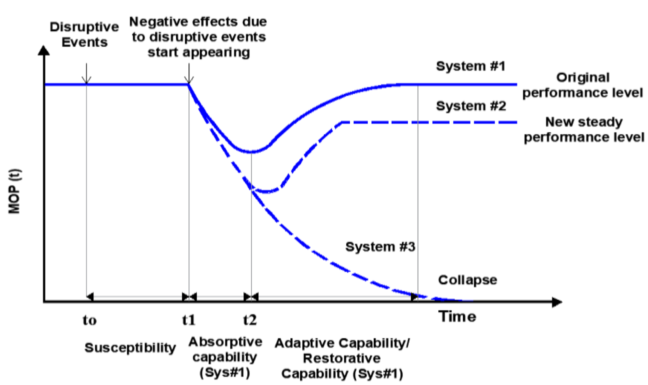

Figure 3. Graphical Representation of Essential Resilience Capabilities adopted form Nan and Sansavini 2017

5 FRAMEWORKS OF RESILIENCE

The Over the years, many frameworks have been developed to measure the resilience of a variety of systems. A list of resilience-measuring models is provided in Table 3. Bruneau et al. (2003) argued that the qualitative conceptualization of resilience was not enough to recover the system to its pre-disaster level right after a disaster. Hence, he provided the first conceptual framework to define and quantitatively measure resilience. He also provided a set of 80 measures in tabular form for five sectors, namely global, power, water, hospital, response and recovery systems. The main focus of this framework was to reduce the likelihood of negative effects, as well as the recovery time of disasters.

Table 3: Resilience Measurement Frameworks

Author	Year	Model
Bruneau et al.	2003	Conceptual framework combining four properties of resilience (4 R's) with four interrelated dimensions of a society (technical, organizational, social, economic).
Chang and Shinozuka	2004	Probabilistic approach builds on conceptual framework of Bruneau et al., 2003 integrating loss estimation methodologies.
Cutter et al.	2008	Disaster Resilience of Place (DROP) model.
Falasca et al.	2008	Simulation-based decision support framework incorporating density, complexity and node criticality of supply chain resilience.
McDaniels et al.	2008	Knowledge-based approach to understanding infrastructure resilience focusing on two dimensions of resilience namely robustness and rapidity.
Cimellaro et al.	2010	Framework using simplified recovery model for hospital building.
Ainuddin and Routray	2012	Framework containing four sequential aspects like potential impacts, vulnerability, risk perception and resilience of a society regarding disaster.
Bueno	2012	Practical approach combining system dynamics and complex network theory to measure degree of resilience.
Abramson et al.	2015	Resilience activation framework combining multidisciplinary systematic perspective
Labaka et al.	2016	Framework consisted of set of resilience policies.
Panteli and Mancarella	2017	Markov approach of analytical techniques incorporating time series simulation model.
Nan and Sansavini	2017	Multilayered hybrid modeling approach.

In 2004, Chang and Shinozuka introduced loss estimation methodologies into Bruneau et al.'s model, and modified it by developing a more concise set of probabilistic resilience measures. However, this model lacked appropriate performance standards for each dimension of TOSE. Focusing on the relationship between resilience and vulnerability, Cutter et al. (2008) designed a model, known as Disaster Resilience of Place (DROP) that only applies to the social resilience of a community. It has not been applied to a real-world case study. Falasca et al. (2008) provided a model that identified the risk of disaster and uncertainty of models in determining the response time of a supply chain following a disaster. McDaniels et al. (2008) developed a knowledge-based, data-driven model to understand resilience. The major limitation of data-driven models is that the authenticity of the collected data shapes the final outcome of the model. Based on the monetary loss for a specific period of time due to disaster, Cimerallo et al. (2010) developed a model that considers technical and organizational issues in the health care system that are due to seismic waves. Ainuddin and Routray (2012) found that most models of resilience were based on indicators that were too broad and cumbersome; consequently, he developed a more refined set of indicators and proposed a framework which would work at the micro level. Labaka et al. (2016) developed a model focusing on internal and external resilience. He defined internal resilience as the resilience of the CI where the disruptive event occurred, and external resilience as the resilience of the rest of the interrelated CI's.

6 TRANSPORTATION INFRASTRUCTURE RESILIENCE FRAMEWORK

The The transportation system is especially vulnerable to the unpredictable and destructive nature of disasters (Liao et al. 2018). As the condition of the transportation infrastructure highly determines the recovery pace of society (Rouhanizadeh and Kermanshachi, 2019b), a great monetary price must be paid if the recovery of this sector is delayed (Mojtahedi et al. 2017). Over the last few decades, resilience has being studied vigorously, yet literature fails to provide a universal model for measuring resilience in the transportation sector (Liao et al. 2018, , Rouhanizadeh et al., 2019a). A few models and techniques that mostly relate to the transportation infrastructure are shown in Table 4, to present a comparison. Murray-Tuite (2006), whose main focus was minimizing travel time, evaluated four dimensions of transportation system resilience, namely adaptability, safety, mobility, and recovery. Medni et al. (2009) proposed a conceptual framework that identified the attributes that a system must have to become a resilient system. Focusing on the recovery and mitigation phase, Croope and McNeil (2011) proposed a framework that measures the resiliency of transportation infrastructures. This system, the Critical Infrastructure Resilience Decision Support System (CIR-DSS), combines GIS, HAZUS, and STELLA with System Dynamics. The framework consists of four components, namely the decision support system, infrastructure management system, resilience management information system, and result presentation system (RPS). The RPS primarily presents reports containing information regarding cost-benefit analysis, the resilience of infrastructures over time, and mitigation measures. However, the major limitation of this framework is that it was developed based on collected data; therefore, the result will have significant misrepresentation if the data is not reliable.

Mojtahedi et al. (2017) proposed a model based on Cox's proportional hazards regression model, and validated it, using the bootstrap resampling technique. The outcome of this model is the recovery rate of infrastructures for a particular area, under different conditions. Covariates used in this model were assumed to be time-independent. However, since the variables were developed by using data from places with similar economic and social configurations, the number of variables was very limited. Hence, before employing this model, much consideration has to be given to the quality of the infrastructure, building standards, and the governmental system of the disaster-affected place. Freckleton et al (2012) expanded a framework that was originally proposed by Heaslip et al (2009). The framework gives four metrics for four areas of resilience, namely individual, community, economic, and recovery. The first two indicate the ability of the transportation system to meet individual and community needs. Economic resiliency indicates the capacity for maintaining a discontinued transportation system in case of disruptive events. Recovery resilience indicates the availability of the resources and qualities necessary to reconstruct the transport network. Liao et al. (2018) proposed a model known as the resilience optimization model. This model focuses on quantifying the ability of an infrastructure to absorb external shocks, and suggests actions that can be taken to restore resilience to its original performance level. The main limitation of this model is that it assumes that the time intervals of the four stages, namely time of occurrence of the disaster, maximum damage propagation, gradual recovery, and full recovery, are equal, which in real cases may not be true.

Table 4. Resilience-measuring Models Related to Transportation Infrastructure

Model (Author)	Modeling technique	Dimension
User equilibrium and System Optimum metrics (Murray-Tuite 2006)	Compares system optimum and user equilibrium	Adaptability, Safety, Mobility, Recovery
Framework to enable design of resilient systems (Madni et al. 2009)	Conceptual Work	System attributes, methods of data collection, metrics, disruption type
CIR-DSS (Croope and McNeil 2011)	System Dynamics	Infrastructure type and condition, Geographical location, likelihood of disaster, Disaster type
Expanded the conceptual framework developed by Heaslip et al (2009) (Freckleton et al. 2012)	Sensitivity Analysis	Level of damage, Redundancy, Rapidity
Conceptual model using Cox's Proportional Hazards Regression (Mojtahedi et al. 2017)	Cox's Proportional Hazard's Regression Model Technique	Region, Type of natural disaster, Cost of Reconstruction, Rapidity.

Resilience Optimization Model (Liao et al. 2018)	DynaTAIWAN simulation-assignment model	Redundancy, efficiency, diversity, strength, adaptability, autonomous components, collaboration, mobility, safety, recovery.

Based on above discussion, it can be said that some models and methods focus on damages due to natural disasters (CIR-DSS), and some models are developed for both natural and man-made disastrous events (resilience optimization model). Major distinguishing characteristics of these models lie in their outcomes. For example, the CIR-DSS model utilizes mitigation strategies, using risk and cost-benefit analyses of different alternative solutions that can be adopted to make a system resilient after a disaster. The conceptual model uses Cox's proportional hazards regression to focus on the pace of recovery in various geographic areas, and the resilience optimization model focuses on the shock absorption capacity and improvement actions that can be taken under the constraints of a fixed budget. Hence, there emerges a need for a model that integrates the three aspects of recovery, namely cost, time, and quality, while providing the resiliency level of the transportation infrastructure.

7 CONCLUSION

The Transportation networks that suffer damage from a disaster are unable to provide emergency commutes, which increases the amount of monetary losses and number of human casualties. Hence researchers, as well as practitioners, are looking for a resilient system. Current literature is hardly able to provide enough material to help researchers build a 'one-for-all' model to measure the resiliency level of the transportation infrastructure. Therefore, this study listed the potential dimensions of resilience measurement of transportation infrastructures, based on literature; explored currently available models that quantify and analyze resiliency in various fields; and discussed a few models that measure transportation infrastructure resilience. The models not only differ in their approach, but also provide outcomes focused on three aspects of recovery: cost, time, and quality. There clearly is a need for a model or framework to measure the resilience of the transportation infrastructure, incorporating all of the dimensions, and resulting in an outcome that integrates the three aspects of recovery, namely cost, time, and quality. This paper will help researchers and practitioners in that regard.

8 ACKNOWLEDGMENT

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