A strategic framework for resilient and sustainable urban infrastructure systems – an overview, modelling, design and assessment

Wael A. Altabey

International Institute for Urban Systems Engineering,
Southeast University,
Nanjing (210096), China
and
Nanjing Zhixing Information Technology Co., Ltd.,
Andemen Street, Nanjing, Jiangsu, China
and
Department of Mechanical Engineering,
Faculty of Engineering,
Alexandria University,
Alexandria (21544), Egypt
Email: wael.altabey@gmail.com

Mohammad Noori*

Department of Mechanical Engineering,
California Polytechnic State University,
San Luis Obispo, California, USA
Fax: +805-903-2411
Email: mnoori@outlook.com
*Corresponding author

Ying Zhao

International Institute for Urban Systems Engineering,
Southeast University,
Nanjing (210096), China
Email: yzhseu@gmail.com

Abstract: In this paper, basic concepts of resilience, ecology and sustainability are introduced first. Then, associated performance metrics and interdependency of critical infrastructure systems are presented and discussed. Moreover, the importance of big data (BD) and data mining (DM), as emerging themes in this field, is discussed. Other relevant issues such as how to foster decision making and accountability to plan for any expansion in resilience services, resources, and the associated performance metrics and interdependency of critical infrastructure systems are presented. It is the recommendation of this study that due to the difficulty and complexity of resilience, and its definitional ambiguity, the ability to assess such a concept helps to bridge the gap between theory and application, and between the academic and the policy circles. A framework for creating resilient, ecological and sustainable infrastructure systems is also proposed, as a recommendation, in a more holistic and comprehensive way.

Keywords: infrastructure systems; resilience metrics; interdependency; resilience capacity; resilient; ecological and sustainable systems; resilience assessment method.

Reference to this paper should be made as follows: Altabey, W.A., Noori, M. and Zhao, Y. (2021) ‘A strategic framework for resilient and sustainable urban infrastructure systems – an overview, modelling, design and assessment’, *Int. J. Sustainable Materials and Structural Systems*, Vol. 5, Nos. 1/2, pp.121–146.

Biographical notes: Wael A. Altabey is an Assistant Professor at Mechanical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt. Currently, he is an Associate Researcher and a Visiting Scholar at Southeast University, Nanjing, China. He was awarded a Postdoctoral Research Certificate in 2018, in Structure Health Monitoring (SHM) and Damage Detection of Composite Structures, from Southeast University, after completing a postdoctoral research fellowship for two years, under the supervision of Professor Noori. He received his PhD in 2015 in the area of fatigue of composite structures and his MSc, 2009, in Dynamic Systems and his BSc with honours, 2004, in Mechanical Engineering, from Mechanical Engineering Department, Faculty of Engineering, Alexandria University.

Mohammad Noori has carried out research on the development of artificial intelligence-based algorithms for damage detection in structural and mechanical systems, probabilistic structural health monitoring, seismic isolation, and nonlinear random vibrations. He served as the Higgins Professor and Head of Mechanical Engineering at WPI, the RJ Reynolds Professor and the Head of Mechanical and Aerospace at NC State and the Dean of Engineering at Cal Poly, where he currently serves as a Professor of Mechanical Engineering. He also has research affiliations with the International Institute for Urban Systems Engineering, Southeast University, China, where he has served in the past as a Distinguished Visiting Professor. He is an ASME fellow, has been the recipient of Japan Society for Promotion of Science Fellowship, and has published over 250 refereed papers, six books and serves as the Executive Editor, Associate Editor and an editorial board member of several journals.

Ying Zhao received his PhD from Southeast University (SEU), in China and currently serves as a Post-doctoral Research Fellow at the International Institute for Urban Systems Engineering at SEU. His research expertise has been in the application of AI tools in structural health monitoring, utilisation of wavelets, genetic algorithms and artificial neural networks for system identification and dynamic analysis of nonlinear systems.

This paper is a revised and expanded version of a paper entitled ‘A strategic framework for resilient and sustainable urban infrastructure systems – an overview, modelling, design and assessment’ presented at 2nd International Workshop on Resilience, Nanjing, Shanghai, China, 31 October to 2 November 2018.

1 Introduction

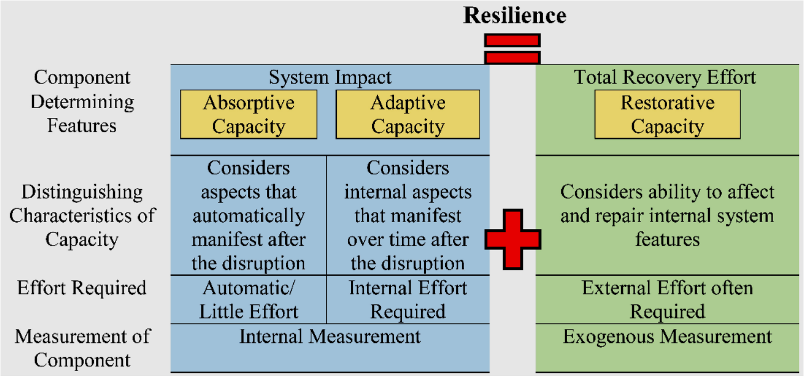
Rapid economic development and extensive globalisation have expanded the scale of infrastructure systems, which need a closer connectivity of subsystems to deal with the ever increasing natural and human triggered disasters. These factors lead to increasing risks, sensitivity and vulnerability of infrastructure systems. A resilient infrastructure system can be viewed as a sophisticated time-varying, multidimensional and interconnected system, and it is a system that is capable of surviving and recovering from the likelihood of damage caused by unexpected disruptions. These changes or disruptions may improve, maintain or lower system performance within a short period of time or a long term. In most cases, disasters or extreme events generally increase system risk, decrease system robustness, and have negative impact on population and their support system (Lounis and McAllister, 2016). Increase in frequency and intensity of man-made and natural hazards, over the past few decades, have posed new challenges in addressing the vulnerability and the protection of infrastructure systems. These systems mainly include buildings, bridges, highways, electric power grids, dams, traffic networks, and pieplines that provide the backbone of the network of society, sustaining the lifeline system. To meet the global challenges of infrastructure provision and the efficient allocation of limited resources, it is increasingly imperative to incorporate resilience, ecology and sustainability as key attributes, and explore and propose a strategy for infrastructure development conceived from a whole life cycle perspective (Lounis and McAllister, 2016).

2 Resilience, ecology and sustainability

2.1 Resilience

Resilience has been used quite differently across a broad variety of social, technical and economic disciplines. For example, the indicators used to assess psychological resilience differ so greatly from those used to assess urban infrastructure resilience, because psychological and critical infrastructure resilience are vastly different. While both are termed resilience, a focus on the indicators used to assess them may show that they have two fundamentally different characteristics. The urban infrastructures resilience is the capacity of urban infrastructure within a city to survive, adapt and thrive, no matter what kinds of chronic stresses and acute shocks they experience. Acute shocks include earthquakes, wildfires, flooding, sandstorms, extreme cold, hazardous materials accidents, severe storms and extreme rainfall, terrorist attacks, infrastructure or building failure, heat waves, to cite a few examples. The flowchart of the suggested framework for the resiliency evaluation of infrastructures is shown in Figure 1.

Figure 1 Resiliency evaluation of infrastructures (see online version for colours)



Resilience

=

	System Impact			Total Recovery Effort
Component Determining Features	Absorptive Capacity	Adaptive Capacity		Restorative Capacity
Distinguishing Characteristics of Capacity	Considers aspects that automatically manifest after the disruption	Considers internal aspects that manifest over time after the disruption	+	Considers ability to affect and repair internal system features
Effort Required	Automatic/ Little Effort	Internal Effort Required		External Effort often Required
Measurement of Component	Internal Measurement			Exogenous Measurement

2.2 *Ecology of infrastructure systems*

Ecology is the relation and the pattern between environment and organisms, sustaining life support system as an organised whole (Pandit et al., 2017; Tao et al., 2013). Ecological systems or networks are composed of interlinked, adaptive and complex components or subsystems which exchange material, energy and information among themselves from and to the environment, exhibiting characteristic scaling properties, ultimately achieving the sustainability of the ecological chain. Infrastructure ecology can be viewed as interlinked and interdependent components and systems constituting a ‘material-water-energy-land use-transportation-socioeconomic nexus’ (McDaniels et al., 2007; Li and Wang, 2014).

Figure 2 Adaptive cycle

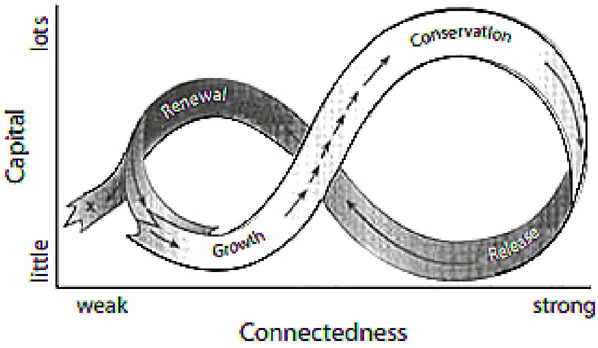
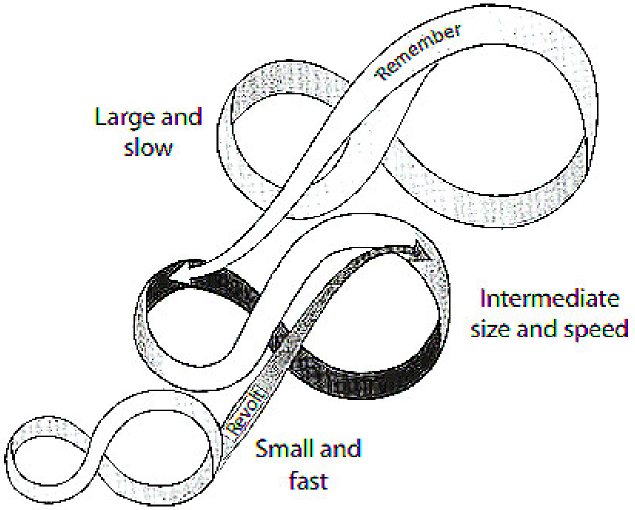


Figure 3 Cross-scale linkages among adaptive cycles (panarchy)



As shown in Figures 2 and 3, most ecological systems are dynamic and vary over time, following four phase patterns: growth, conservation (maintenance), release (collapse), and renewal (reorganisation). The adaptive cycles describe how a human-nature system or social-ecological system is originally established, develops and stabilises, undergoes changes due to disturbances, and then reorganises itself via reallocation of resources to begin a new sequence again, forming a panarchy, characterised by cross-scale, interdisciplinary, and dynamic nature (Holling, 2001).

In an adaptive cycle, a system can be disrupted by disturbance and either regenerate to a similar state or be transformed to some new state. What is happening at multiple scales in a dynamic way requires understanding how the focal system responds to innovation from smaller nested scales and to constraints imposed from larger-scale systems. The property of varying lens of different adaptive cycles suggests that an effective long-term operation, management and policy making for infrastructure and lifeline systems must be highly flexible and adaptive. Different frameworks are further compared to analyse the social-economic system by establishing the corresponding criteria (Binder et al., 2013).

2.3 Sustainability of infrastructure systems

The word ‘sustainability’ is derived from the Latin ‘sustinēre’, meaning to ‘hold up, endure and support’. It is defined by the United Nations Environment Programme (UNEP): the use of the environment and resources to meet the needs of the present without compromising the ability of future generations to meet their own needs (Adams, 2006; Boz and El-Adaway, 2014). The term sustainability can also be described as enduring, resilient, reliable, functional, inclusive, affordable, supportable, permittable, adaptable, implementable, scalable, or pragmatic (Binney, 2010). Sustainability requires a long term strategy to meet a stable and compatible human-nature environment, infrastructure and lifeline systems by using basic material and energy in order to achieve a good life style, freedom and choice, social networks and regional security, economic and culture variation. Sustainability assessment over the life cycle should be considered as a method for integrating decisions throughout the project development cycle (Binney, 2014; Reiner et al., 2014; Gharehbaghi and Raso, 2013; Gopalakrishnan and Peeta, 2010). 'Flow benchmark' is used to demonstrate technological integration and introduce sustainability indicators between macro-level system dynamics modelling, micro-level agent-based simulation, and multi-objective optimisation (El-Adaway, 2013). Four levels of sustainability are given to show the hierarchy including categorisation of key assessment of indicators and criteria (Shen et al., 2010), and three dimensions (economy, ecology and society). Timeline of the development of sustainability and related important events are also presented (Bocchini et al., 2013; Yodo and Wang, 2016). Managing resources to foster resilience to respond to and shape change in ways that both sustain and develop the same fundamental function, structure, identity, and feedbacks is crucial to the future of humanity and the life-support system (Chapin et al., 2009).

3 Critical infrastructure systems and interdependency

3.1 Performance metrics of infrastructure systems

The US Patriot Act defines critical infrastructure as "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems, capitals and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters". Critical infrastructure security and resilience advances a national policy to strengthen and maintain secure, functioning, and resilient critical infrastructure (Directive Presidential Policy, 2013).

The 16 critical infrastructure (Habibian and Minaie, 2017) and key resources (CIKRs) identified by sector-specific agencies and their performance metrics are shown in Table 1, and the corresponding performance measures and tracking parameters are presented as well (Bruneau et al., 2003; Minsker et al., 2015; Vugrin et al., 2010). Topology-based performance metrics, flow-based functional performance metrics, metrics for power-distribution networks, metrics for water distribution networks, metrics for transportation networks are given to measure the performance level of infrastructure networks. Individual component assessment of the performance of structural systems has limited evaluation value, and is gradually being replaced by measures of the reliability of entire interested systems. Comprehensive and revealing performance measures are critical for the assessment of long-term investment plans (Mejia-Giraldo et al., 2012).

Table 1 Critical infrastructure and key resources

CIKR	*Sector-specific agency*	*Performance metric*
Chemical	Department of Homeland Security	Chemical property, health hazard, storage risk
Commercial facilities	Department of Homeland Security	Commercial value of goods, commercial competitiveness
Communications	Department of Homeland Security	Signal stability, communication mode
Critical manufacturing	Department of Homeland Security	Manufacturing raw materials, fabrication process, productivity
Dams	Department of Homeland Security	Storage capacity, discharge quantity, impact on surroundings
Defence industrial base	Department of Defense	Equipment complexity, confidentiality
Emergency services	Department of Homeland Security	Emergency case, supplies, methods and risk
Energy	Department of Energy	Energy production, efficiency, waste and sustainability
Financial services	Department of Treasury	Currency circulation, investment and financing management, stock market
Food and agriculture	Department of Agriculture and Department of Health and Human Services	Food safety, agricultural production, consumption and demand
Government facilities	Department of Homeland Security and General Services Administration	Facility safety, functionality, serviceability, reliability
Healthcare and public health	Department of Health and Human Services	Sources of infection, illness severity and drug safety
Information technology	Department of Homeland Security	Innovativeness of information technology, information security
Nuclear reactors, materials and waste	Department of Homeland Security	Nuclear security, emergency protection
Transportation systems	Department of Homeland Security and Department of Transportation	Intelligent monitoring system and intelligent networking system
Water and wastewater systems	Environmental Protection Agency	Water circulation efficiency and waste water treatment

3.2 Interdependency of networked infrastructure systems

The security and welfare of a region mainly rely on a continuous flow of essential goods (such as energy, food, water, oil, electricity and gas) and services (such as banking, health care, communication and public administration) provided by a set of systems called critical infrastructures. The same type and different types of critical infrastructure are viewed as system components or subsystems. The input and output flow dynamics, and the mutual dependency relationships of each subsystem of the whole are interdependency problem. Intersections and interdependencies between infrastructural components are recognised as a unique feature in that these attributes impact the behaviour of system-of-systems for sparse or dense infrastructure systems subjected to emergencies and disruptions (Reed et al., 2009). The positive impact is that these unforeseen interdependencies may provide the tolerance and redundancy to attacks and failures if well managed. However, the negative effect is that they might also be a source of threat, creating new unknown risks and vulnerability such as cascading failures. The major differences between single system and multiple systems are the interconnection characteristics between systems. Interdependencies of systems manifest in multiple ways:

1. the failure or disruption of partial function in one system may probably propagate to other associated systems in a cascading manner
2. an event exerting on one subsystem may result in adverse or unfavourable influences on several subsystems simultaneously, i.e., 'conjoined symbiosis effect'
3. the effects on one subsystem may build up over time, and then they transfer to other subsystems depending on consecutiveness strength of mutual subsystems, correlation degree and component importance (Fang et al., 2016).

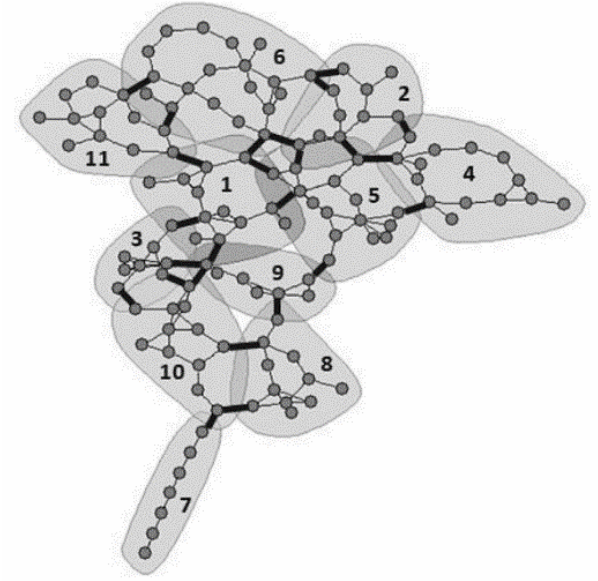
Identifying, understanding, and analysing dependency and interdependency of infrastructure systems are challenging. These interdependencies and resultant infrastructure topologies can create interactions, feedforward and feedback mechanisms (interaction between subsystems and mth orders of effects) that often lead to unintended behaviours and consequences during disruptions (Rinaldi et al., 2001). These linkages showing interdependency include physical, geographic, cyber and logical. Physical interdependency is the physical linkage between the output of one subsystem and input of another. Geographic interdependency describes the spatial proximity between elements of infrastructure systems. Cyber interdependency refers to the interrelated state depending on the information transmitted through information infrastructure systems. Logical interdependency establishes a logical mechanism that is neither physical, cyber nor geographic connections. One property in common of these interdependencies of infrastructures is that they are all complex collections of interactively unidirectional dependent or mutually dependent components changing as a result of adaptively learning processes.

Figure 4 illustrates the key interdependent relationships among several infrastructure subsystems when an unexpected event (e.g., earthquake) occurs.

For 16 critical infrastructure systems, there are theoretically A_{16}^{2} strong and weak interdependencies in total. Generally, they are spatially distributed and have multistep impact effects. Ten important interdependencies of all are listed as follows. The 'links' with a diverse and complex 'network' provide various ways to transmit capitals between 'nodes', which determine the vulnerability and robustness of the network (Anderies et al., 2004). A diagrammatic sketch of delivery importance indicating the strength and weights of subnetwork connections is shown in Figure 5. Three typical topological structures can be constructed, namely the random network model, the core/periphery model and the centre-periphery model. Network connection is used to illustrate the relationship between 'nodes' and 'links' in the spatial dimension (Peng et al., 2017).

Figure 4 Interdependencies between critical infrastructure systems (see online version for colours)

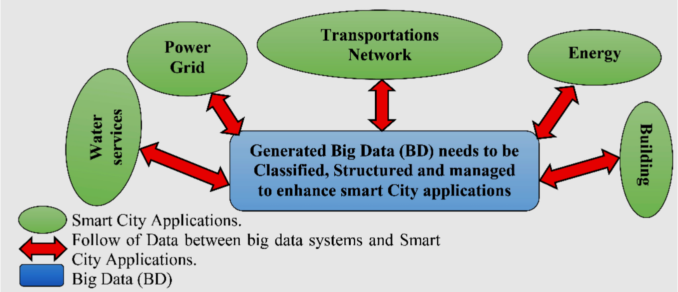
Figure 5 Important delivery of networks



3.3 Big data

Figure 6 shows the function of big data (BD) applications in critical infrastructure. Critical infrastructure applications generate very large amounts of data while BD systems utilise this data to provide information to enhance critical infrastructure applications. Volume refers to the size of data that has been created from all the sources.

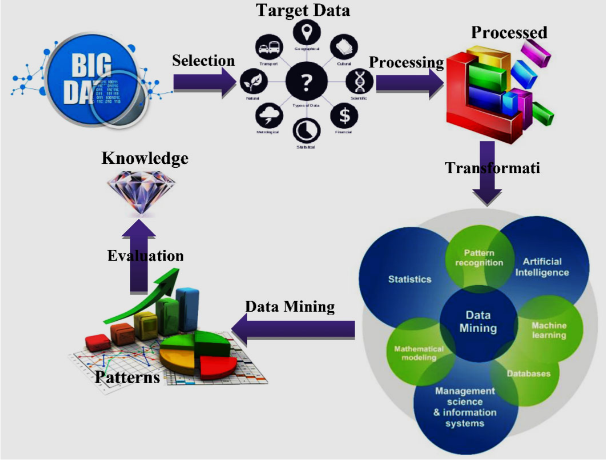
Figure 6 Critical infrastructure and big data relationship (see online version for colours)



3.4 Data mining (DM)

Data mining (DM) can be viewed as a result of the natural evolution of information technology, So DM is a computer-based process requiring new techniques for converting large sets of data (BD) to information and knowledge by finding patterns and opportunities within the data using different techniques of visualisation, reduction of dimensionality, classification, and construction of models. Methods used in DM, as shown in the Figure 7, come from statistical analytics, artificial intelligence (AI) [artificial neural network (ANN), machine learning (ML), deep learning (DL), etc.], and management science and information systems disciplines for pattern recognition, mathematical modelling, databases activities, and data management (including data storage and retrieval, and database transaction processing).

Figure 7 Data mining system (see online version for colours)

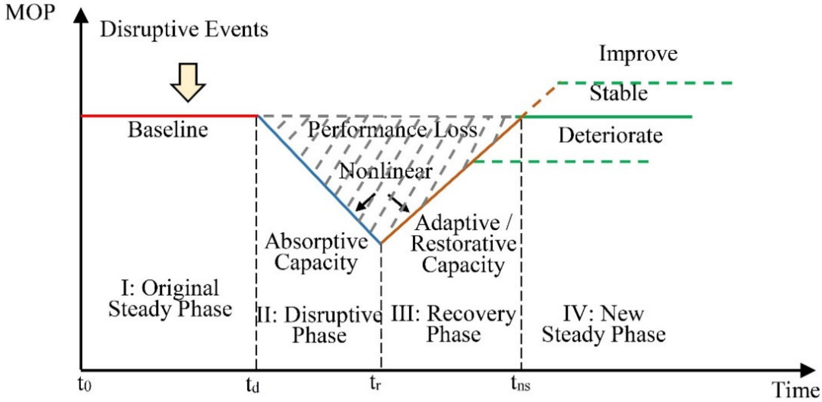


4 Qualitative and quantitative approach for resilience assessment

4.1 Quantification of resilience capabilities

Resilience is a dynamic multi-faceted process and its assessment should cover all the evolutionary phases and essential system features (absorptive, adaptive and restorative capability). Figure 8 shows a general illustration of system resilience. The x-axis is time and y-axis represents the measurement of performance (MOP) of a system. The first phase is the original steady phase ($t_0 < t < t_d$), in which the system performance assumes its target value. The second phase is the disruptive phase ($t_d < t < t_r$), in which system performance begins to drop (in most cases) due to the disruptive event(s) at time t_d until it reaches the lowest level at time t_r. The third phase is the recovery phase ($t_r < t < t_{ns}$), in which the system performance starts increasing until the new steady level. During second phase, the system absorptive capability can be assessed by robustness (R) combined with two complementary measures rapidity ($RAPI_{DP}$) and performance loss (PL_{DP}) to identify the maximum impact caused by disruptive events. The system performance loss can be interpreted and quantified as the region bounded by the graph of the MOP before and after the occurrence of negative effects caused by disruptive events, which can also be referred as the system impact area. Time averaged performance loss (*TAPL*) is introduced to encompass the time of appearance of negative effects due to disruptive events up to full system recovery and provides a time dependent indication of both adaptive and restorative capabilities as responses to the disruptive events.

Figure 8 System resilience transitions and phases



During third phase, the system absorptive capability can be assessed by robustness (R) combined with two complementary measures rapidity ($RAPI_{DP}$) and performance loss (PL_{DP}) to identify the maximum impact caused by disruptive events. The system performance loss can be interpreted and quantified as the region bounded by the graph of the MOP before and after the occurrence of negative effects caused by disruptive events, which can also be referred as the system impact area. Time averaged performance loss (*TAPL*) is introduced to encompass the time of appearance of negative effects due to disruptive events up to full system recovery and provides a time dependent indication of both adaptive and restorative capabilities as responses to the disruptive events.

Rapidity ($RAPI_{RP}$) and performance loss (PL_{RP}) are developed to assess system adaptive and restorative capability. The newly attained steady level may equal to, higher (resilience) or lower than (degradation, collapse) the previous steady state. A resilient system possesses the ability to recover the its normal performance state level from disruptive state, while non-resilient system may gradually decline towards a low performance level with a certain of magnitude due to an unexpected event. Recovery ability (*RA*) is quantitatively developed. Loss function, recovery function model and fragility function were established in comparison with a mechanical analogy (Cimellaro et al., 2010).

4.2 The resilience measures

4.2.1 Fragility

Lifeline resilience may be explored through the use of fragilities. Fragilities are tools commonly employed by structural engineers to characterise the probability of damage given a level of hazard demand such as wind velocity or ground acceleration. Most commonly derived for individual structures, in this investigation, we define fragility depends on a networked lifeline as a whole, i.e., we will connect the fragility equations between each individual index value in network model to get the overall fragility equations of network model.

4.2.2 Quality

Quality is a function derived by the Multidisciplinary Center for Extreme Event Research (MCEER) group and employed by many in the earthquake engineering community to describe structural performance over time following earthquakes. We extend this concept to each damage type in this paper. In addition to earthquakes, we will address flooding, extreme cold, hazardous materials accident, severe storms and extreme rainfall, terrorism, infrastructure or building failure, to cite a few examples. For example when we apply the MCEER function to wind-induced damage in this paper, in equation form, the quality $Q(t)$ is (O'Rourke, 2007; Dorothy et al., 2009):

$$Q(t) = Q_\infty - \left(Q_\infty - Q_0\right)e^{-bt} \tag{1}$$

where Q_∞ is capacity of the fully functioning structural system; Q_0 is post-event capacity; b is parameter derived empirically from restoration data following the event; t is time in days post-event.

In addition, the integration of the area under the curve has been labelled resilience R (Dorothy et al., 2009), in the following equation:

$$R = \frac{\int_{t_1}^{t_2} Q(t)dt}{\left(t_2 - t_1\right)} \tag{2}$$

In this equation, t_1 and t_2 are the endpoints of the time interval under consideration. For the system infrastructure described in Section 2, we may evaluate resilience measures R_1 for subsystem (1) from Q_1, R_2 for system (2), etc., from post-event data. We propose that the system resilience in general for a set a total subsystems is a function of the individual R's as follows:

$$R_S = g\left(R_1, \ldots, R_i, \ldots, R_n\right) \tag{3}$$

where $g()$ is a function to be determined that combines the individual resilience values in a way that reflects their interdependence and connectivity. It should be noted that the system resilience does not appear directly in quality equations, but indirectly incorporates the rapidity and robustness parameters of the individual subsystems.

4.3 Input-output model

Data collection and capturing data from sensors, users, electronic data readers and other sources from the systems of infrastructure, described in earlier sections, pose the most important challenge to handle as the volume rapidly grows to become BD. Storing, organising and processing this data to generate useful results as the outputs of the resilience system is a multi-disciplinary and emerging area of research. To further complicate the challenge, handling interconnected communication infrastructures described in earlier sections, to access contextual information in critical infrastructure applications and physical spaces, to support good decision making processes, requires attention to various aspects of connectivity, security and privacy (UNISDR, 2015). As the data comes from different sources with different formats, there is a need for advanced data management features that will lead to recognising the different formats and sources of data, structuring, managing, classifying, and controlling for all these types and structures. Most available data mining algorithms as shown in Figure 7 can be suitable for big data mining applications, for instance ANN, ML, DL, etc.

4.4 Input-output inoperability

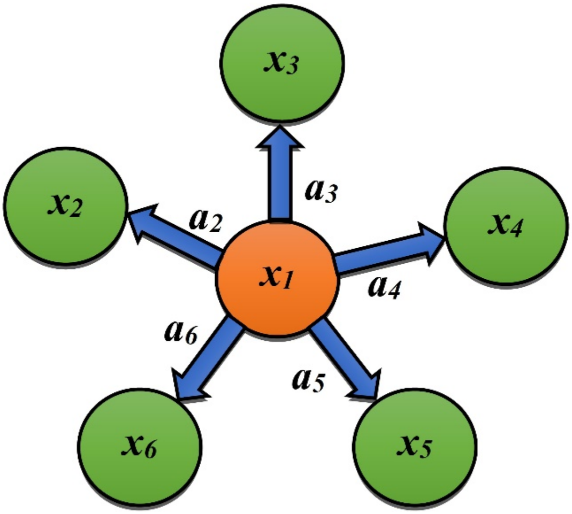
These BD can be combined with proper input-output models to relate resilience to interdependency. A growing body of research has been recently reported in this regard. For instance, Haimes (2004) was able to drive an interdependency model between the various interconnected subsystems of the Critical Infrastructure based upon the following input-output economic model:

$$x = Ax + C \tag{4}$$

where x is a vector of the subsystem inoperability; A matrix is the interdependency between the various subsystems, and C is the disturbance or perturbation vector. This matrix reflects inoperability or reduction of functionality.

In this derivation matrix A takes on values in the range between 0 and 1 and one interpretation is that each element in this matrix, a_{ij}, is related to the probability of inoperability that j^{th} infrastructure contributes to the i^{th} infrastructure. A value of a_{ij} of unity means that a complete failure of the j^{th} infrastructure will lead to a complete failure of the i^{th} infrastructure. A value of zero means that failure of the j^{th} infrastructure has no effect on the i^{th} infrastructure. For a 6-system infrastructure described in Section 2, we use a causal network diagram illustrated in Figure 9 to show the relationship between x_1 infrastructure (such as an electric power delivery) central node and the other systems such as transportation networks, telecommunications, etc. A value of a_{13} of unity means that a complete failure of the x_1 infrastructure system will lead to a complete failure of the x_3 infrastructure system.

Figure 9 Selected *A* matrix coefficients for the 6-system model (see online version for colours)



The values of the *C* vector may be interpreted as the reduction in functionality or level of inoperability induced by extreme events such as hurricanes or earthquakes. Its values are bounded by zero and unity. For example, $c_1 = 0.8$ represents an 80% reduction in subsystem (1) operability or an inoperability of 80%, as denoted by x_1, due to disruption. Also it should be noted that the components of equation (5) are steady state position of interoperability infrastructure when risk happens. A dynamic input-output model means restoration analysis with time scale, i.e., the relation between the recovery of the entire infrastructure and the time of recovery as follows (Haimes, 2004):

$$x = Ax + C + B\dot{x} \tag{5}$$

where *B* matrix represents the relationship between *x* and its derivative with respect to time $\dot{x}$. . Therefore, $\dot{x}$ represents the vector of the subsystem infrastructures inoperability (RS) after part of period of recovery time. The dynamic model gives rise to inoperability versus time curves of the form e^{-bt} during the recovery phase, from which resiliency *R* values may be estimated. Observed values of parameter *b* can be used to validate the dynamic model. Because of the differences in the duration of restorations for each infrastructure data, we compare the restoration using a normalised time scale.

In this paper we found two new important equations for dynamic input-output model needed for the development resilience efficiency of urban infrastructures and development of the subsystems inoperability. These equations are the restoration response (RR), and restoration response indicator (RRI) as follows:

$$x = Ax + C + B\dot{x} + D\ddot{x} \tag{6}$$

$$x = Ax + C + B\dot{x} + D\ddot{x} + E\dddot{x} \tag{7}$$

The RR $\ddot{x}$ vector means the rate of change of subsystem infrastructures RS of a restoration with respect to recovery time, where *D* matrix represents the relationship between $\dot{x}$ and its derivative with respect to time $\ddot{x}$. This equation is very useful for giving rise to RS versus time curves, for example if the *D* matrix is a positive matrix, in which all the elements are greater than zero, that means the subsystem infrastructures RS has increased with the recovery time. If the *D* matrix is a negative matrix in which all the elements are less than zero that means the subsystem infrastructures RS has decreased with the recovery time. The RRI $\dddot{x}$ is very important to evaluate the resilience method that is employed for the measurement of the efficiency of urban infrastructures. RRI means the rate of change of RR $\ddot{x}$ with respect to recovery time, i.e., the RRI represents the exact description of the applicability and effectiveness of the resilience method used with urban infrastructures, where *E* matrix represents the relationship between $\ddot{x}$ and its derivative with respect to time $\dddot{x}$. There are three profiles for RRI matrix *E* defined by the following:

- if *E* matrix is a positive matrix, that means a linear increase of RR at the positive direction of RR to the limit of final restoration
- if *E* matrix is a negative matrix, that implies a linear increase of RR at the negative direction of RR to the limit of final restoration
- if *E* matrix is a zero matrix, that means the RR is regular or zero.

It can be shown that the first profile of RRI is the best one, where the resilience method used in this profile is positive, i.e., the capacity of urban infrastructures within a city to survive and adapt under acute shocks they experience is positive.

5 Discussions

As a means to illustrate the use of the methodology proposed herein, we use the curve of restoration analysis with a normalised time scale (RS) for the power delivery system in the model for post-Hurricane Katrina landfall in Florida, Hanukkah storm 2006 in Mississippi. Graumann et al. (2005) and EOC (2005) used this data for the analysis of RR and RRI curves for resilience method in each case.

Figure 10 represents a comparison of the restoration in three different cities affected with hurricane. As shown in Figure 10, the timescale is the time in days for restoration divided by the total recovery duration. Figure 11 represents a comparison between resilience ability applied in each city by applying equations (6) and (7) for dynamic input-output model that presented the proposed methodology. As shown in Figure 11 the RR of resilience method in Hanukkah and Florida is positive. This means that the RS is increased with the recovery time, although, the slope of RR in Florida is higher than the slope of RR for Hanukkah, which means the increasing rate of RS with the recovery time in Florida resilience system is more than the Hanukkah resilience system.

The RRI curves confirm this point, where the RRI of both cities is positive and constant, but the RRI for Florida resilience system is higher than Hanukkah resilience system.

Figure 10 Restoration analysis with a normalised time scale (see online version for colours)

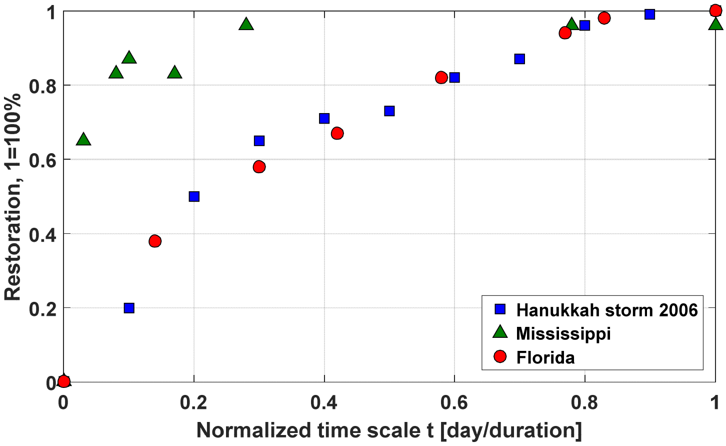
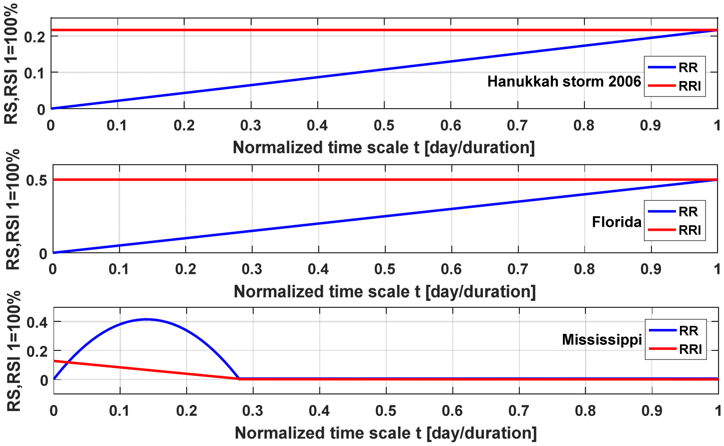


Figure 11 RR and RRI analysis with a normalised time scale (see online version for colours)



This is different with Mississippi resilience system, where the RR curve represents that the RS is increased during the first 17% of total recovery duration, then decreased during the next 11% of total recovery duration and is constant during the remaining of recovery duration. Also as shown in RRI curve of Mississippi resilience system, RRI is has continuously decreased during the first 28% of total recovery duration and has been constant during the remaining of recovery duration.

This is not acceptable in the intelligence and resilience systems in critical infrastructures, where it is required a continuous increase in the RS during recovery duration. In fact, this is the most important characteristic of a good resilience system in critical infrastructure. As stated, the RS curve is not enough to evaluate the resilience system in the case of critical Infrastructure. Unfortunately, due to limitations of this paper, we cannot fully describe the resilient system or dynamic input-output model required for critical infrastructure, however, in the following we will elaborate the RR and RRI equations for a comprehensive evaluation of the resilience systems used.

6 A framework for creating resilient infrastructure systems

6.1 Dimension of Resilience

Given the occurrence of particular disruptive events, system resilience is the ability to efficiently absorb, adapt and restore the existing resources to develop and sustain individuals, groups, organisations and systems and operate coherently and synergistically as a whole performance level. Human behaviour is closely related to natural resources, the integrity of which is a dynamic process of coupled human-nature system or social-ecological system that is interacting, updating and redistributing resources when undergoing unknown changes and disruptions (Liu et al., 2007). Linkages among various elements of the system play an extremely important role since they establish feedback loops or mechanisms by updating and modifying the input and output behaviours of each subsystem. These important linkages not only influence the connectivity of subsystems themselves, but also associate one dimension of system with another.

System resilience can be regarded as the interconnected combination of natural components including environment and ecological systems, and human components including technical, organisational, social and economic systems. The integration of all these multiple domains or components exerts an influence on system resilience, ecology and sustainability. System resilience is also described as an integrative, multi-system model of core resilience (intra-individual factors), internal resilience (inter-personal factors) and external resilience (social-ecological factors) (Liu et al., 2017).

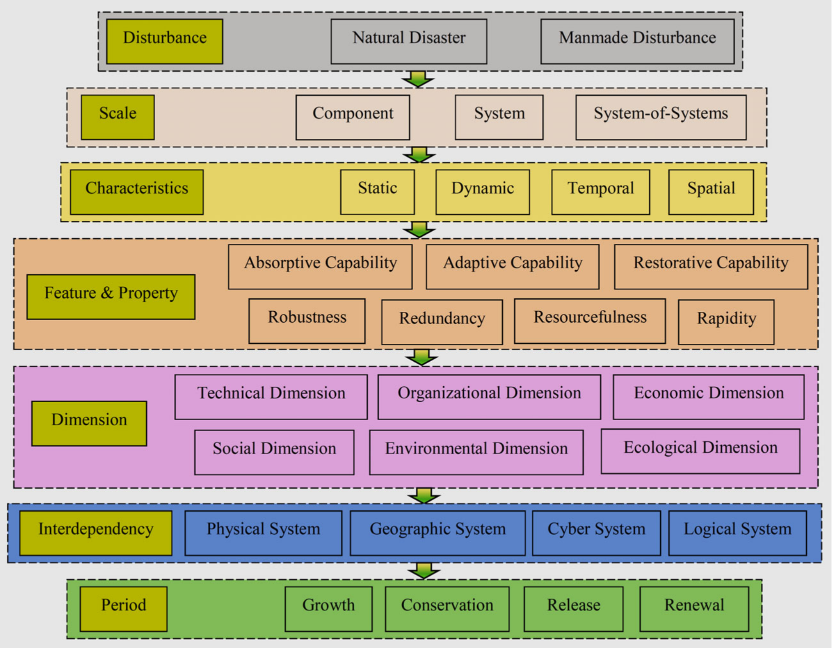
For a natural system, the environmental dimension of resilience refers to the ability of natural systems to recover from disturbances such as natural disasters and to tolerate or adapt to changing climate. The ecological dimension of resilience is the capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and recovering quickly. Such perturbations and disturbances can include stochastic events such as fires, flooding, windstorms, insect population explosions, and human activities such as deforestation, fracking of the ground for oil extraction, pesticide sprayed in soil, and the introduction of exotic plant or animal species.

For a human system, the technical dimension of resilience refers to the ability of physical systems to perform to acceptable or desired safety, serviceability and reliability levels when subjected to hazards. The organisational dimension of resilience refers to the capacity of organisations that coordinate, operate and manage critical facilities and have the responsibility for carrying out critical disaster related functions to make decisions and take actions that contribute to achieving the properties of resilience to help to achieve greater robustness, redundancy, resourcefulness and rapidity. Robustness and rapidity are essentially the ends that are accomplished through resiliency-enhancing measures and are the outcomes that more deeply affect decision makers and stakeholders, while redundancy and resourcefulness are measures employed ready to maintain, improve or enhance the performance of infrastructure systems. The social dimension of resilience consists of measures specifically designed to lessen the impact extent of individuals or communities from which disaster stricken communities and governmental jurisdictions suffer negative consequences due to the loss of critical resources and services as a result of disasters. The economic dimension of resilience refers to the capacity to reduce both direct and indirect, static and dynamic economic losses resulting from disturbances. The six dimensions integrate both human and natural factors that influence system resilience, and they should be well designed, optimised and reorganised to enhance system performance and accommodate likely changes and disturbances.

6.2 A proposed framework

Figure 12 presents a general framework for resilience modelling, design and assessment of critical infrastructures and key resources. It includes seven phases, i.e., phase 1: disturbance, phase 2: scale, phase 3: characteristics, phase 4: features and property, phase 5: dimension, phase 6: interdependency, phase 7: period. Assume that the targeted model to be analysed is a network with various types of 'edges' and 'nodes'.

Figure 12 System resilience assessment framework (see online version for colours)



- *Phase 1:* in this phase, disturbances resulted from natural disasters or man-made disruptions have impact on 'edges' or 'nodes'. The type, numbers, distribution and intensity of disturbances and their randomness are the key variables (Shafieezadeh and Burden, 2014). The infrastructure disruption model is developed to predict the cascading effects that may occur, given the damage to one or more infrastructure systems (Loggins and Wallace, 2015). Disturbance (disaster) impact mechanism is described as a basic cell model with increased direct and indirect impact degrees (Oh et al., 2010, 2012). These disturbances incorporate and may increase higher uncertainties and risks of the system network, and it is generally assessed by probabilistic method (Chang et al., 2014; Ouyang et al., 2012; Franchin and Cavalieri, 2015). Structural health monitoring (Brownjohn and Aktan, 2013) and adaptive governance system (Djalante et al., 2011) can provide a long-term reliable prediction for these uncertain factors by establishing big data platforms and employing the state of the art artificial intelligence analytics technologies (Sun et al., 2017). SHM is a complementary approach for tacking and intelligent management of infrastructure projects (Zhang and Luo, 2017). Proactive maintenance decisions can be enabled through the development of prognostics and health management methods that detect, diagnose, and predict the effects of adverse events (Youn et al., 2011; Mehrpouyan et al., 2014).

- *Phase 2:* in this phase, the scale of a system to be analysed is chosen from: component, system or system-of-systems. For components, safety index, failure probability and reliability are used as measures for a general structure (Frangopol and Saydam, 2011; Ghosn et al., 2016). System-level performance metrics and characteristics such as reliability, redundancy, robustness, resilience, and risk are developed as integral parts of resilient communities and lifeline systems (Ghosn et al., 2016). System-of-systems is used to denote networks that are formed from the integration of independently operating complex systems that interact with one another to provide an overall capability, which cannot be achieved by the individual systems alone. As systems continue to grow in scale and complexity, the 'connectivity effect' plays a more important role. As infrastructure system-of-systems such as buildings, powers, energy networked system, transportation and communication networks, grow in interconnectivity and complexity, measuring and improving the resilience of system-of-systems is vital in terms of safety and reliability, and providing uninterrupted services. Resilience of system-of-systems depends on reliable interconnection of constituent systems (Uday and Marais, 2015; Mostafavi and Abraham, 2014). Higher level of interdependency between subsystems may give rise to increased risks of failures cascading through system-of-systems depending on the increasingly evolutionary topology of the 'network', or can result in collaborative efficiency of the 'network'.
- *Phase 3:* in this phase, resilience is described as a static or dynamic, temporal and spatial system. Static resilience can be regarded as a way to maintain its desired function of a system, while dynamic resilient network is a recovery process of a system after a disruption (Anderies, 2015). The infrastructure network evolves when going through different stages of a period cycle. Spatial scales of the network range from individual parts to the metastructure composed of interdependent infrastructures and the environment. The size, quality and distribution of open spaces may change following the occurrence and the influence of disturbances (Rus et al., 2018).
- *Phase 4:* in this phase, absorptive, adaptive and restorative capabilities are closely related to system interdependency. If one subsystem A is dependent upon subsystem B to operate, the relationship will lower A's absorptive capability in scenarios that negatively affect B. If subsystem A can reorganise and redistribute resources in an automatic way rather than has dependency upon subsystem B, A has a strong adaptive capacity. If subsystem A and B can operate in a collaborative way within a relatively short time when subjected to disturbances, the integral of them will have a strong restorative capability (Bruneau et al., 2003). Robustness and redundancy provide a pre-disaster estimate of the inherent capabilities of the infrastructure systems to absorb perturbations, while resourcefulness and rapidity reflect the post-disaster adaptive activities of the system (Minsker et al., 2015). Responsive,

insurance-related tactics are important to the overall performance of resilient infrastructure systems.

- *Phase 5:* in this phase, six dimensions affect how a system reacts to disturbances. When an unexpected event occurs (e.g., earthquake), the physical infrastructures (e.g., buildings, electrical transmission stations, transportation networks, underground pipelines) are influenced with a 'network effect' due to the change of environmental and ecological system. Business is disrupted and the related emergency services are provided in time, which needs the coordination of both organisational and social communities. Specifications, codes and standards of the construction and design of infrastructures and related technologies (e.g., design of new materials and devices to absorb energy) needs to be improved to resist these unforeseen disruptions, which can be viewed as the technical dimension. Firms, market, demand-supply chain or policy are influenced due to the disruption of the economic system (Mujumdar, 2014). Further, seven dimensions are integrated as a multilayered approach to identify and measure community resilience 'PEOPLES': population and demographics, environmental and ecosystem, organised governmental services, physical infrastructures, lifestyle and community competence, economic development, and social-cultural capital (Cimellaro et al., 2016). Economic and business opportunities, public policy, government investment, legal and regulatory concerns, technical and security issues, and social and political concerns are all determinates that have impacts on the degree of coupling (tightness or looseness), the coupling order, and the linearity or complexity of the interactions (Rinaldi et al., 2001; Rose, 2007).
- *Phase 6:* in this phase, intertwining resources are reorganised to provide continuous interconnections among subsystems. The subsystems can be regarded as 'nodes', and the interconnections are viewed as 'edges'. Important information and control flows are passed between 'nodes' to maintain the necessary functions of the whole infrastructure system. An 'edge' is a physical or virtual entity that represents a direct level of dependence between two 'nodes'. Several key determinants are the growing size of nodes, network evolution or optimisation, connection diversity, dynamical complexity, node diversity. Physical, cyber, geographic and logical dependency are the four types of interdependency. When a system is subjected to a disruptive event, cascading consequence transfer from the 'node' which is the most venerable to the disruption to other 'nodes' (Dudenhoeffer et al., 2006). Interdependency and dependency of 'nodes' are largely related to the recovery time, sequence and trajectory of system 'nodes' (Zimmerman et al., 2017).
- *Phase 7:* in this phase, a resilient system undergoes four stages, i.e., growth, conservation, release and renewal. System state shifts due to risks of disturbances, and it also inherently absorb these disturbances and reorganised to maintain critical functions to reach a new desired and stable state (Sasaki et al., 2015). By appropriately designing event-based constraints, functional dependencies, adjustment of capabilities and strategy, a resilient model was developed with an ultimate goal of self-monitoring (Lundberg and Johansson, 2015). The critical infrastructures and key resources establish a chain of coupling natural-human system. The coupled human-nature system has nested hierarchy structural characteristics. Three 'hands' play important roles in the coupled human-nature system, i.e., the 'invisible hand' of

markets, the 'visible hand' of governments, and the 'third hand' human value contribute the growth, development and well-being of societies. Human interpersonal networks, intelligence, capacity for innovation, and characteristics as a resilient complex system are only a few examples of how humans are not only an integral component of the traditional infrastructures, but also are infrastructures in and of themselves (Barnes and Newbold, 2005). Life-cycle management of infrastructure systems should be established through probabilistic performance assessment and prediction, integration of information from inspection and structural health monitoring, and multi-criteria optimisation for the optimal scheduling of interventions under uncertainties (Frangopol et al., 2014). By building an interaction and feedbacks and between interdependent subsystems, i.e., natural support, economic metabolism, social regulation and complementary relationships, the system can be designed to achieve the integrity of structure, function and dynamic mechanism, as well as system resilience, ecology and sustainability (Fischer and Amekudzi, 2011) in a period cycle.

7 Conclusions

In summary, this paper introduces a systematic framework for measuring resilience of infrastructure systems and both quantitative and quantitative key resources. Resilience research of infrastructure systems covers a wide range of multi-disciplinary domains. Well-designed resilient systems can achieve an optimum system performance by distributing limited resources and exchanging energy in a limited time. With the scale of a system increasing, a good interdependency property determines an optimal network evolutionary path and the performance of typology structure. Establishing consistent criteria for assessing the performance of infrastructure networks or lifeline systems is critical to optimise investment decisions, designing infrastructure structure and managing the coupled human-nature ecological systems (Aktan et al., 2016; Ouyang, 2014). Therefore, some key suggestions and directions are summarised in the following:

1. Environmental and ecological systems establish the material basis for infrastructure or lifeline systems. Socioeconomics is the decision driver rather than a technical or organisational factor. Resilience is a multidisciplinary, trans-disciplinary and multicultural (government, academia and industry) research. Infrastructure owners, regulatory agencies, state and local governments and managers from industry are critical stakeholders who can be brought together for a coordinated and productive discussion of infrastructure issues and options for possible solutions.

2. Infrastructure systems can be regarded as interconnected topology networked structures where material, energy and resources are transmitted through the input or output physical or cyber flows, to reach an optimised, reliable and robust status of the network. The inherent complexity, dynamic property and adaptability are important factors that determine the resilience performance of the network structure.

3. Data accessibility and reliability, comprehensive integrated modelling of system resilience should be further developed. New technologies and innovations, codes and standards, for infrastructures should be transferred to real applications to reduce

lifecycle cost, increase operation and maintenance efficiency and improve risk-based decision-making ability.

4. Resilience of critical infrastructure can be significantly improved y providing a comprehensive methodology of risk and resilience assessment. This assessment is expected to lead to proactive innovations that, eventually, will raise the level of resilience of the Critical Infrastructure. In addition, a number of other factors are expected:
   a. Fostering new product development and solutions, generating new insights for infrastructure and their interdependencies.
   b. Providing novel tools and insights for rapid response planning, improved business continuity and organisational adjustments to become more resilient.
   c. Enhancing resilience of the society as a whole, based on concepts of increased awareness, preparedness and appropriate behaviour during disasters.
5. Critical infrastructure systems are interdependent and integrated so that small failures in one subsystem may spread to other subsystems and lead to catastrophic events, largely affecting the social and economic level. To understand performance response of interdependent infrastructures due to different disturbances, scholars have proposed numerous modelling and simulation approaches, with an emphasis on identifying effective mitigation measures. This paper reviews the conceptual, qualitative and quantitative metrics and discusses a systems thinking strategy (Fiksel, 2003) about resilient infrastructure systems.
6. The ultimate goal of the study on the critical infrastructure and key resources is to coordinate the human-nature relationship with a focus on the structural health monitoring of infrastructure systems, reasonable allocation of resources, optimisation of the human-nature system performance, and enable the implementation of regional and global resilient, ecological and sustainable development.

References

Adams, W.M. (2006) ‘The future of sustainability: re-thinking environment and development in the twenty-first century’, *Report of the IUCN Renowned Thinkers Meeting*, Vol. 29, No. 31.

Aktan, A.E., Moon, F.L., Bartoli, I. and Sjoblom, K. (2016) ‘Identification of infrastructure systems’, *Journal of Infrastructure Systems*, Vol. 22, No. 3, p.02516002.

Anderies, J.M. (2015) ‘Understanding the dynamics of sustainable social-ecological systems: human behavior, institutions, and regulatory feedback networks’, *Bulletin of Mathematical Biology*, Vol. 77, No. 2, pp.259–280.

Anderies, J.M., Janssen, M.A. and Ostrom, E. (2004) ‘A framework to analyze the robustness of social-ecological systems from an institutional perspective’, *Ecology and Society*, Vol. 9, No. 1.

Barnes, J. and Newbold, K. (2005) ‘Humans as a critical infrastructure: public-private partnerships essential to resiliency and response’, *Proceedings, First IEEE International Workshop on Critical Infrastructure Protection*, pp.75–83.

Binder, C.R., Hinkel, J., Bots, P.W. and Pahl-Wostl, C. (2013) ‘Comparison of frameworks for analyzing social-ecological systems’, *Ecology and Society*, Vol. 18, No. 4.

Binney, P.D. (2010) 'Transitional approaches to the development of sustainable civil engineering infrastructure', *Proceedings, World Environmental and Water Resources Congress: Challenges of Change*, pp.504–513.

Binney, P.D. (2014) 'Applying sustainability principles to benefit the overall project delivery cycle of infrastructure systems', *Proceedings, International Conference on Sustainable Infrastructure*, pp.69–78.

Bocchini, P., Frangopol, D.M., Ummenhofer, T. and Zinke, T. (2013) 'Resilience and sustainability of civil infrastructure: toward a unified approach', *Journal of Infrastructure Systems*, Vol. 20, No. 2, p.04014004.

Boz, M.A. and El-adaway, I.H. (2014) 'Creating a holistic systems framework for sustainability assessment of civil infrastructure projects', *Journal of Construction Engineering and Management*, Vol. 141, No. 2, p.04014067.

Brownjohn, J. and Aktan, E. (2013) 'Improving resilience of infrastructure: the case of bridges', *Proceedings, Structures Congress: Bridging Your Passion with Your Profession*, pp.1812–1821.

Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A. and Von Winterfeldt, D. (2003) 'A framework to quantitatively assess and enhance the seismic resilience of communities', *Earthquake Spectra*, Vol. 19, No. 4, pp.733–572.

Chang, S.E., McDaniels, T., Fox, J., Dhariwal, R. and Longstaff, H. (2014) 'Toward disaster-resilient cities: characterizing resilience of infrastructure systems with expert judgments', *Risk Analysis*, Vol. 34, No. 3, pp.416–434.

Chapin, F.S., Folke, C. and Kofinas, G.P. (2009) 'A framework for understanding change', *Principles of Ecosystem Stewardship*, pp.3–28, Springer, New York.

Cimellaro, G.P., Reinhorn, A.M. and Bruneau, M. (2010) 'Framework for analytical quantification of disaster resilience', *Engineering Structures*, Vol. 32, No. 11, pp.3639–3649.

Cimellaro, G.P., Renschler, C., Reinhorn, A.M. and Arendt, L. (2016) 'PEOPLES: a framework for evaluating resilience', *Journal of Structural Engineering*, Vol. 142, No. 10, p.04016063.

Directive Presidential Policy (2013) *Critical Infrastructure Security and Resilience*, PPD-21, Released February 12.

Djalante, R., Holley, C. and Thomalla, F. (2011) 'Adaptive governance and managing resilience to natural hazards', *International Journal of Disaster Risk Science*, Vol. 2, No. 4, pp.1–4.

Dorothy, R., Kailash, C.K. and Richard, D.C. (2009) 'Methodology for assessing the resilience of networked infrastructure', *IEEE Systems Journal*, Vol. 3, No. 2, pp.174–180.

Dudenhoeffer, D.D., Permann, M.R. and Manic, M. (2006) 'CIMS: a framework for infrastructure interdependency modeling and analysis', *Proceedings of the 38th Conference on Winter Simulation*, pp.478–485.

El-Adaway, I. (2013) 'Systems modeling approach for sustainable infrastructure', *Computing in Civil Engineering*, pp.137–144, Conference Information: ASCE International Workshop on Computing in Civil Engineering, 23–25 June, Los Angeles, California, DOI: 10.1061/9780784413029.018.

Emergency Operations Center (EOC) (2005) *Daily Service Outage Reports*, 29 August 2005 through 31 August 2005 (Excel Spreadsheets for Each Day Summarizing Electric, Natural Gas, and Phone Outages), Louisiana Public Service Commission.

Fang, Y.P., Pedroni, N. and Zio, E. (2016) 'Resilience-based component importance measures for critical infrastructure network systems', *IEEE Transactions on Reliability*, Vol. 65, No. 2, pp.502–512.

Fiksel, J. (2003) 'Designing resilient, sustainable systems', *Environmental Science & Technology*, Vol. 37, No. 23, pp.5330–5339.

Fischer, J.M. and Amekudzi, A. (2011) 'Quality of life, sustainable civil infrastructure, and sustainable development: strategically expanding choice', *Journal of Urban Planning and Development*, Vol. 137, No. 1, pp.39–48.

Franchin, P. and Cavalieri, F. (2015) 'Probabilistic assessment of civil infrastructure resilience to earthquakes', *Computer-Aided Civil and Infrastructure Engineering*, Vol. 30, No. 7, pp.583–600.

Frangopol, D.M. and Saydam, D. (2011) 'Performance indicators for structures and infrastructures', *Structures Congress*, pp.1215–1226.

Frangopol, D.M., Soliman, M. and Dong, Y. (2014) 'Practical applications of life-cycle considerations in sustainable development of infrastructure', *Sustainable Development of Critical Infrastructure*, pp.17–36.

Gharehbaghi, K. and Raso, V. (2013) 'Infrastructure sustainability assessment: a systematic approach', *Developing the Frontier of Sustainable Design, Engineering, and Construction, Proceedings of the 2012 International Conference on Sustainable Design and Construction*, pp.319–326.

Ghosn, M., Dueñas-Osorio, L., Frangopol, D.M., McAllister, T.P., Bocchini, P., Manuel, L., Ellingwood, B.R., Arangio, S., Bontempi, F., Shah, M. and Akiyama, M. (2016) 'Performance indicators for structural systems and infrastructure networks', *Journal of Structural Engineering*, Vol. 142, No. 9, p.F4016003.

Gopalakrishnan, K. and Peeta, S. (2010) *Sustainable and Resilient Critical Infrastructure Systems: Simulation, Modeling, and Intelligent Engineering*, Springer-Verlag Berlin Heidelberg, eBook ISBN: 978-3-642-11405-2, DOI:10.1007/978-3-642-11405-2.

Graumann, A., Houston, T., Lawrimore, J., Levinson, D., Lott, N., Mc-Cown, S., Stephens, S. and Wuertz, D. (2005) *Hurricane Katrina: A Climatological Perspective*, NOAA technical report.

Habibian, A. and Minaie, E. (2017) 'Exploring the six dimensions of lifeline infrastructure resiliency', *Pipelines*, pp.431–441, Conference Information: Pipelines 2017, 6–9 August, Phoenix, Arizona, DOI: 10.1061/9780784480878.040.

Haimes, Y.Y. (2004) 'Assessment and management', *Risk Modeling*, pp.837–837, Wiley, New York.

Holling, C.S. (2001) 'Understanding the complexity of economic, ecological, and social systems', *Ecosystems*, Vol. 4, No. 5, pp.390–405.

Li, F. and Wang, R. (2014) 'Urban ecological infrastructure: challenges, construction, and management', *International Conference on Sustainable Infrastructure*, pp.604–608.

Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J. and Ostrom, E. (2007) 'Complexity of coupled human and natural systems', *Science*, Vol. 317, No. 5844, pp.1513–1516.

Liu, J.J., Reed, M. and Girard, T.A. (2017) 'Advancing resilience: an integrative, multi-system model of resilience', *Personality and Individual Differences*, Vol. 111, pp.111–118, DOI: 10.1016/j.paid.2017.02.007.

Loggins, R.A. and Wallace, W.A. (2015) 'Rapid assessment of hurricane damage and disruption to interdependent civil infrastructure systems', *Journal of Infrastructure Systems*, Vol. 21, No. 4, p.04015005.

Lounis, Z. and McAllister, T.P. (2016) 'Risk-based decision making for sustainable and resilient infrastructure systems', *Journal of Structural Engineering*, Vol. 142, No. 9, p.F4016005.

Lundberg, J. and Johansson, B.J. (2015) 'Systemic resilience model', *Reliability Engineering & System Safety*, Vol. 141, pp.22–32, DOI: 10.1016/j.ress.2015.03.013.

McDaniels, T., Chang, S., Peterson, K., Mikawoz, J. and Reed, D. (2007) 'Empirical framework for characterizing infrastructure failure interdependencies', *Journal of Infrastructure Systems*, Vol. 13, No. 3, pp.175–184.

Mehrpouyan, H., Haley, B., Dong, A., Tumer, I.Y. and Hoyle, C. (2014) 'Resiliency analysis for complex engineered system design', *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol. 29, No. 1, pp.93–108.

Mejia-Giraldo, D., Villarreal-Marimon, J., Gu, Y., He, Y., Duan, Z. and Wang, L. (2012) 'Sustainability and resiliency measures for long-term investment planning in integrated energy and transportation infrastructures', *Journal of Energy Engineering*, Vol. 138, No. 2, pp.87–94.

Minsker, B., Baldwin, L., Crittenden, J., Kabbes, K., Karamouz, M., Lansey, K., Malinowski, P., Nzewi, E., Pandit, A., Parker, J. and Rivera, S. (2015) 'Progress and recommendations for advancing performance-based sustainable and resilient infrastructure design', *Journal of Water Resources Planning and Management*, Vol. 141, No. 12, p.A4015006.

Mostafavi, A. and Abraham, D.M. (2014) 'Resilience-based planning in civil infrastructure using system-of-systems analysis', *Construction Research Congress: Construction in a Global Network*, pp.1249–1258.

Mujumdar, V. (2014) 'Developing resiliency measures to reduce seismic hazard impact in the central United States', *Seismic Hazard Design Issues in the Central United States*, pp.143–156, CDRM Seismic Hazard Workshop, April 10, 2012, Memphis, Tennessee, USA,

DOI: 10.1061/9780784413203.ch10.

O'Rourke, T.D. (2007) 'Critical infrastructure interdependencies and resilience', *The Bridge*, Vol. 37, No. 1, pp.22–29.

Oh, E.H., Deshmukh, A. and Hastak, M. (2010) 'Vulnerability assessment of critical infrastructure, associated industries, and communities during extreme events', *Construction Research Congress: Innovation for Reshaping Construction Practice*, pp.449–458.

Oh, E.H., Deshmukh, A. and Hastak, M. (2012) 'Criticality assessment of lifeline infrastructure for enhancing disaster response', *Natural Hazards Review*, Vol. 14, No. 2, pp.98–107.

Ouyang, M. (2014) 'Review on modeling and simulation of interdependent critical infrastructure systems', *Reliability Engineering & System Safety*, Vol. 121, pp.43–60.

Ouyang, M., Dueñas-Osorio, L. and Min, X. (2012) 'A three-stage resilience analysis framework for urban infrastructure systems', *Structural Safety*, Vol. 36, pp.23–31, DOI: 10.1016/j.strusafe.2011.12.004.

Pandit, A., Minné, E.A., Li, F., Brown, H., Jeong, H., James, J.A., Newell, J.P., Weissburg, M., Chang, M.E., Xu, M. and Yang, P. (2017) 'Infrastructure ecology: an evolving paradigm for sustainable urban development', *Journal of Cleaner Production*, Vol. 163, pp.S19–S27, DOI: 10.1016/j.jclepro.2015.09.010.

Peng, C., Yuan, M., Gu, C., Peng, Z. and Ming, T. (2017) 'A review of the theory and practice of regional resilience', *Sustainable Cities and Society*, Vol. 29, pp.86–96, DOI: 10.1016/j.scs.2016.12.003.

Reed, D.A., Kapur, K.C. and Christie, R.D. (2009) 'Methodology for assessing the resilience of networked infrastructure', *IEEE Systems Journal*, Vol. 3, No. 2, pp.174–180.

Reiner, M.B., Fisher, S. and Sperling, J. (2014) 'Evaluation of sustainable infrastructure: Development context matters', *Proceedings of the 2014 International Conference on Sustainable Infrastructure*, pp.420–433.

Rinaldi, S.M., Peerenboom, J.P. and Kelly, T.K. (2001) 'Identifying, understanding, and analyzing critical infrastructure interdependencies', *IEEE Control Systems*, Vol. 21, No. 6, pp.11–25.

Rose, A.Z. (2007) 'Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions', *Environmental Hazard*, Vol. 7, No. 4, pp.383–398.

Rus, K., Kilar, V. and Koren, D. (2018) 'Resilience assessment of complex urban systems to natural disasters: a new literature review', *International Journal of Disaster Risk Reduction*, Vol. 31, pp.311–330, DOI: 10.1016/j.ijdrr.2018.05.015.

Sasaki, T., Furukawa, T., Iwasaki, Y., Seto, M. and Mori, A.S. (2015) 'Perspectives for ecosystem management based on ecosystem resilience and ecological thresholds against multiple and stochastic disturbances', *Ecological Indicators*, Vol. 57, pp.395–408, DOI:10.1016/j.ecolind.2015.05.019.

Shafieezadeh, A. and Burden, L.I. (2014) 'Scenario-based resilience assessment framework for critical infrastructure systems: case study for seismic resilience of seaports', *Reliability Engineering & System Safety*, Vol. 132, pp.207–219.

Shen, L., Wu, Y. and Zhang, X. (2010) 'Key assessment indicators for the sustainability of infrastructure projects', *Journal of Construction Engineering and Management*, Vol. 137, No. 6, pp.441–451.

Sun, P., Zhang, Y. and Cao, Z. (2017) 'Intelligent transportation decision system based on big data mining', *CICTP: Transportation Reform and Change-Equity, Inclusiveness, Sharing, and Innovation*.

Tao, P., Li, Y. and Yan, J. (2013) 'Research on the evaluation of investment benefits in ecological infrastructure project', *ICCREM: Construction and Operation in the Context of Sustainability*, pp.1318–1325.

Uday, P. and Marais, K. (2015) 'Designing resilient systems-of-systems: a survey of metrics, methods, and challenges', *Systems Engineering*, Vol. 18, No. 5, pp.491–510.

UNISDR (2015) *Making Development Sustainable: The Future of Disaster Risk Management*, Global Assessment Report on Disaster Risk Reduction.

Vugrin, E. D, Warren, D. E, Ehlen, M. A, and Camphouse, R.C. (2010) 'A framework for assessing the resilience of infrastructure and economic systems', *Sustainable and Resilient Critical Infrastructure Systems*, pp.77–116.

Yodo, N. and Wang, P. (2016) 'Engineering resilience quantification and system design implications: a literature survey', *Journal of Mechanical Design*, Vol. 138, No. 11, p.111408.

Youn, B.D., Hu, C. and Wang, P. (2011) 'Resilience-driven system design of complex engineered systems', *Journal of Mechanical Design*, Vol. 133, No. 10, p.101011.

Zhang, W. and Luo, X. (2017) 'Framework of life-cycle intellectual management platform for infrastructure projects', *ICCREM: Real Estate and Urbanization*, pp.270–287.

Zimmerman, R., Zhu, Q., De Leon, F. and Guo, Z. (2017) 'Conceptual modeling framework to integrate resilient and interdependent infrastructure in extreme weather', *Journal of Infrastructure Systems*, Vol. 23, No. 4, p.04017034.