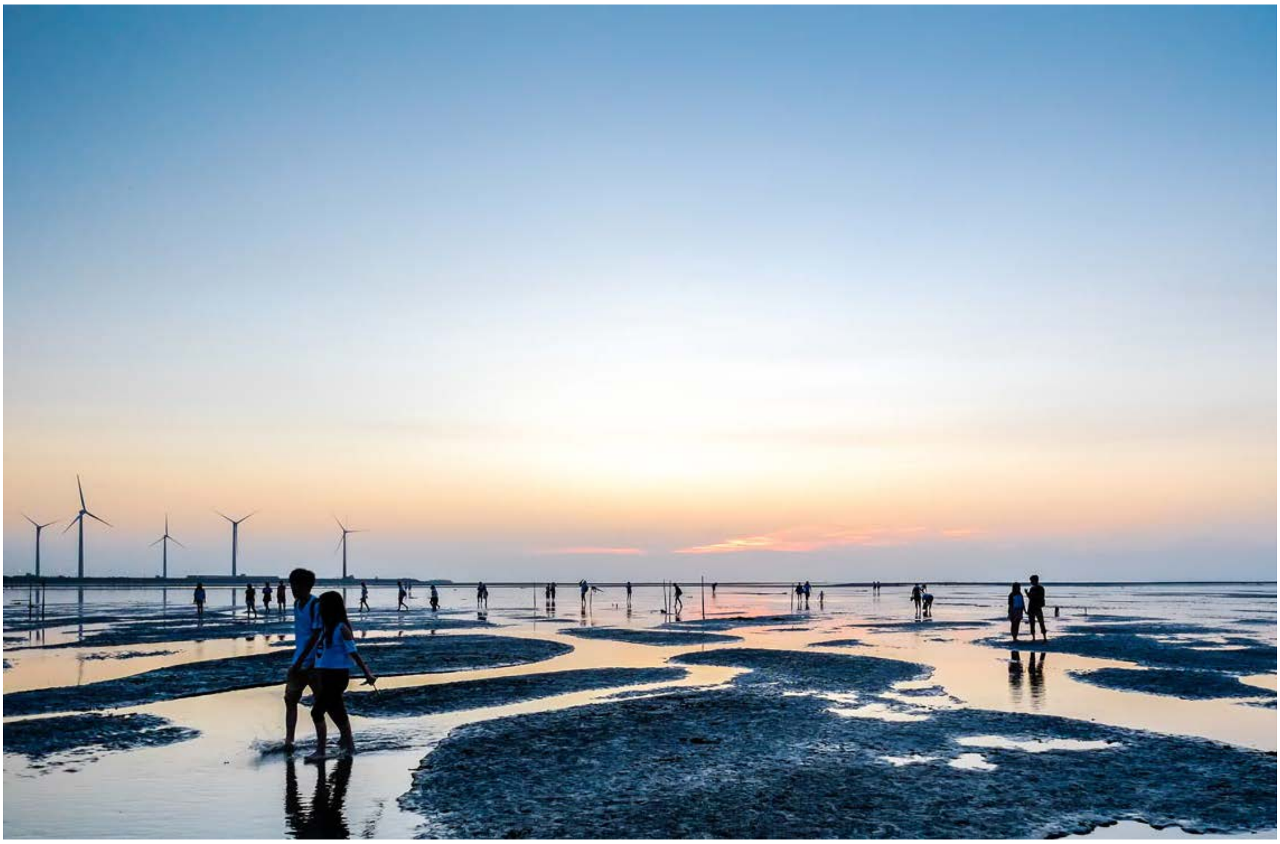
A Review of Resilience in Interdependent Transport, Energy and Water Systems

Agenda Setting Scoping Studies Summary Report



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Introduction

Background

Modern societies depend on critical infrastructure systems to provide essential services that support societal well-being, economic prosperity, governance, and quality of life. The complexity and interdependence of these systems has increased over time due to designers and planners taking advantage of opportunities afforded by new technologies, and responding to increasing pressures to provide more efficient and cost-effective infrastructure services. One unanticipated side-effect has been an increased potential for small failures in one system to cascade, resulting in catastrophic events across the wider network.

Critical infrastructure networks have complex mechanisms in place for planning, financing, funding, design, construction and operation. Resilience, and the emerging concept of resilience engineering within infrastructure, are among the main concerns to those managing such complex systems, alongside stewardship, sustainability, financing and funding mechanisms and project delivery and management [1].

This report forms part of a series of scoping studies carried out as part of the Resilient Shift programme funded by Lloyd's Register Foundation (LRF). The focus of this report is a review of the current practice and future opportunities for resilience engineering in the critical interdependent infrastructure sectors of energy, water and transport.

'Resilience Engineering' was identified as one of four strategic funding priorities for LRF together with the complementary topics of 'Structural Integrity and Systems Performance', 'Human and Social Factors' and 'Emergent Technologies' [2]. The Resilience Shift programme emerged from that strategic standpoint, following a workshop held in April 2015 and subsequent consultation and foresight review [3], which aimed to identify the applications of RE in relevant sectors and to determine any gaps in the understanding, communication and improvement of resilience..

Report scope and structure

This report is based on a review of academic literature and other relevant reports and research programmes based on the topic of resilience engineering and the related topics of performance-based engineering and adaptive capacity, especially at the design and planning stages of the three interdependent infrastructure sectors of energy, water and transport. The focus has been to identify recent examples of the methodologies and implementation of resilience engineering in a range of geographic contexts, particularly where interdependencies between sectors have an impact on the methodologies or practices used.

The structure of the report is as follows: Chapter 2 introduces the key topics, setting out a range of definitions of terms and identifying where commonalities exist. The various methodologies used as part of resilience engineering implementation and monitoring are summarised in Chapter 3, while

Chapter 4 focuses on current practices, identifying existing approaches and metrics. Chapter 5 offers an insight into the barriers and opportunities associated with these methodologies and current practices offering further insight into some of the implications of implementing and embedding resilience engineering in the future of infrastructure planning and design. Concluding remarks are given in Chapter 6.

Definition of terms

Introduction

Before assessing the evolution of resilience engineering (RE), we set out definitions of the terms used throughout this report. A range of definitions have been used over time, as RE has emerged firstly as an academic field and subsequently as a practical measure utilised in infrastructure development and elsewhere in industry. Nevertheless, while there is diversity, there are also commonalities between sectors and between different engineering disciplines.

Resilience and resilience engineering

Resilience

'Resilience' is a term used for many years across a range of different physical, social and ecological disciplines. Many definitions exist, and many reviews have been undertaken to attempt to clarify these definitions [see for example 4, 5-14]. The many distinctions and interpretations are dependent on which aspect of a resilient society is under scrutiny, including security, protection, emergency response, business continuity, environmental issues, and social issues related to human health, safety, and general welfare, as well as integrity of physical infrastructure systems.

Francis and Bekera [12] state that while "resilience is a useful concept, its diversity in usage complicates its interpretation and measurement". To reduce these complications, Woods [9] consolidated the numerous definitions of resilience around four recurring concepts: 1) how a system rebounds from disrupting or traumatic events and returns to previous or normal activities; 2) as a synonym for robustness; 3) as the opposite of brittleness, i.e. how a system extends performance, or brings extra adaptive capacity to bear, when system boundaries are unexpectedly challenged; 4) as the presence of network architectures that can sustain the ability to adapt to future surprises as conditions evolve.

There is a danger that the label 'resilience' only functions in practice as a general pointer to one of the four concepts, so there is a need to be explicit about which of the four senses of resilience is meant when studying or modelling adaptive capacities. In the past there has been more of a focus on the first two of these concepts, 'resilience as rebound', and 'resilience as robustness'. However, concepts 3 and 4 seem likely to be more useful in practice as the field of RE develops in the future [9].

Hollnagel [15] has been instrumental in promulgating the concept of RE, and has developed his definition of resilience since 2006 [16]. Recently, he broadens the scope of resilient performance to suggest that "it is not just to be able to recover from threats and stresses, but rather to be able to perform as needed under a variety of conditions, and to respond appropriately to both disturbances and opportunities" [15]. This focus on adaptability of system performance and response has much in common with the third and fourth concepts discussed by Woods [9].

Key characteristics of numerous definitions of resilience were assessed by Francis and Bekera [12]. Their summary of findings again has much in common with the definitions proposed by Hollnagel and by Woods. They suggest that a resilient system is one which has the ability to (i) anticipate and absorb potential disruptions; (ii) develop adaptive means to accommodate changes within or around the system; and (iii) establish response behaviours aimed at either building the capacity to withstand the disruption or recovering as quickly as possible after an impact.

These factors are common to many of the definitions of resilience: (i) anticipate; (ii) absorb; (iii) adapt; (iv) recover. Indeed, the US National Infrastructure Advisory Council definition of infrastructure resilience [17] frames these factors exactly:

“Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.”

They suggest that critical infrastructure resilience is characterized by three key features:

Robustness: the ability to maintain critical operations and functions in the face of crisis.

Resourcefulness: the ability to prepare for, respond to and manage a crisis or disruption as it unfolds.

Rapid recovery: the ability to return to and/or reconstitute normal operations as quickly and efficiently as possible after a disruption.

Nan and Sansavini [18] propose a similar, simple definition, which describes resilience as “the ability of a system to resist the effects of a disruptive force and to reduce performance deviations”.

These themes that are present in many definitions of resilience are also identified in the LRF foresight review [3]: 1) the occurrence of a disruptive event affecting normal or expected function; 2) a system which has to cope with that event in order to maintain or achieve some desired function; and 3) coping mechanisms which revolve around anticipation and preparation, absorbing and withstanding the effects of the event, adapting to maintain some level of functionality during the event, and recovering to achieve an ultimate, desired level of functionality.

The authors of the LRF review suggest that these common themes provide a starting point for advancing the emerging field of resilience engineering, and that to improve resilience the study and application of RE must be trans-disciplinary, building on expertise across multiple sectors and jurisdictions [3].

Resilience Engineering

In 2006, Woods suggested that RE must build on “advances in modelling and measuring complex adaptive systems”, and that “resilience engineering assesses changes in the adaptive capacity of an organization as it confronts disruptions, change, and pressures” [19].

Hollnagel [15] reinforces these concepts, suggesting that RE must consider how organisations and systems function as a whole. Four basic abilities should be considered which give an overview of how an organisation or system functions: how it responds, how it monitors, how it learns, and how it anticipates. RE comprises the ways in which these four capabilities can be established and managed.

Righi et al. [8] carried out a review of 250 papers on RE, with the aim of answering two research questions: what are the main research areas of RE, and how should a research agenda for RE be structured? While around 15% of these papers were in the field of safety management, over 50% were related to the theoretical aspects of RE. This reflects the reality that unlike other engineering disciplines, which have emerged through ‘hands-on’ experience, trial and error, and iterative learning and development, RE has emerged through a more academic route, with engineers only recently beginning to apply the methods proposed in the literature to real life situations [8]. Of the 150 papers based on empirical data, five domains comprised over 75% of the total: aviation (22%), healthcare (19%), chemical and petrochemical industries (16%), nuclear power plants (10%), and railways (8%).

This has implications for this scoping study, which aims to identify current practice. If much of the literature is on the theory of resilience, safety management or non-infrastructure systems, it severely limits the opportunities to review resilience engineering of interdependent infrastructure systems in practice.

Performance Based Engineering

A related topic to RE is that of ‘performance-based’ engineering (PBE). The topic was initially established in an architectural context [see for example 20, 21], aiming to design buildings and structures to broaden their capabilities in terms of how they are used [22], and to enhance performance, particularly in response to seismic activity [see for example 23, 24, 25].

The more traditional approach in infrastructure system design has been specification-based engineering (SBE), which is more prescriptive and process-oriented. SBE has served the engineering community well for many years, and established techniques and guidelines are easier to implement than a transition towards a performance-based approach [26]. However, the design, construction, evaluation, and preservation of constructed facilities that has been based only on implicit or qualitative descriptions of performance may not meet modern expectations. PBE is a more ‘product-oriented’ approach, such that the desired performance characteristics of the constructed system are described in terms of rational and measurable quantitative indicators, rather than the ‘bricks and mortar’ of the facility. Both PBE and SBE are likely to be needed at the planning and design stage, but while it has been acknowledged to be an important step toward building a resilient and sustainable civil infrastructure, use of performance-based engineering has yet to become a mainstream part of infrastructure planning and design [27-29].

Adaptive capacity

One of the main factors emerging from the discussion of definitions of resilience and resilience engineering is that of adaptability. If we assume that a resilient system is one which can absorb, adapt and recover from unexpected events, then the resilience capacity can be considered as the combination of these three capacities, as shown in the 'resilience triangle' in Figure 1 [adapted from 12].

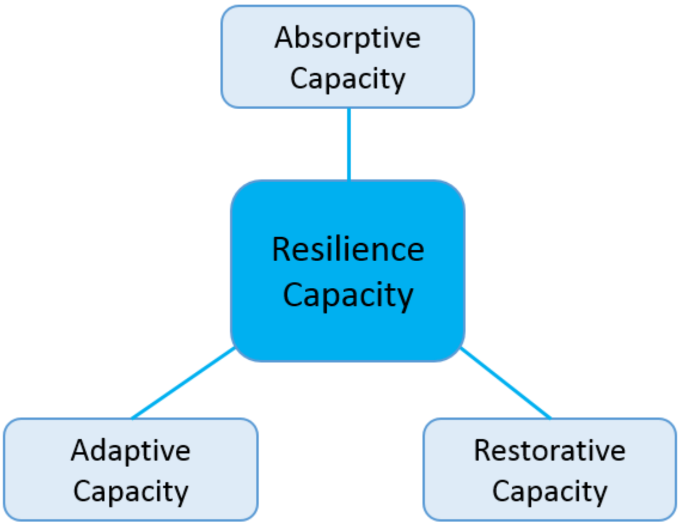

Figure 1: Resilience triangle, adapted from Francis and Bekera [12]

Absorptive capacity is a measure of how much stress the system can withstand before an event impacts on its performance level, while restorative capacity is a measure of how quickly a system can return to some functional level after the event. Central to the idea of resilience, however, is adaptive capacity [5, 30]. Francis and Bekera [12] define adaptive capacity as "the ability of a system to adjust to undesirable situations by undergoing some changes". Adaptive capacity is distinct from absorptive capacity, in that adaptive systems change in response to adverse impacts in order to allow them to continue to function, especially if absorptive capacity has been exceeded. This capacity is enhanced by the system's ability to anticipate any disruption prior to the event, to recognise unanticipated events, and to reorganise after the occurrence of an adverse event.

Methodologies

One of the limitations of this study is that many papers and studies focus on the theory of resilience engineering (RE) rather than the practice. However, that theoretical work provides a good background to the potential future options for RE in infrastructure. This chapter summarises the various methods in use, existing and proposed approaches to apply RE in the three critical infrastructure sectors of energy, water and transport, as well as studies focusing on cross-sector interdependence. While many of the examples below are sector-specific, these methodologies could be applicable across other sectors.

Interdependent infrastructure systems

Much work has been done to develop models and methods capable of analysing interdependent infrastructure systems [for a more detailed overview, see for example 31, 32-34]. Johansson and Hassel [35] suggest these methods can be divided into two categories: empirical and predictive approaches. Empirical approaches examine past events in order to increase understanding of infrastructure dependencies. Predictive approaches mainly focus on modelling or simulation, examining how interconnected infrastructures interact, for example, to assess how disturbances cascade through the systems.

Ouyang [34] groups modelling and simulation approaches into six types: empirical approaches, agent based approaches, system dynamics based approaches, economic theory based approaches, network based approaches, and ‘others’.

Various modelling and framework-based approaches are used in the literature to assess the impact of change on infrastructure systems, and hence the resilience of those systems. These approaches are discussed briefly below, but are set out in more detail in the accompanying Working Paper.

Quantifying system resilience is an important step towards assessing system change and various approaches have been used, including probabilistic, graph theory, fuzzy inference, and analytical methods [see, for example 14, 18, 31, 36-40]. However, most quantification methods are incomplete and present a very narrow field of applications, possibly due to the diverse range of definitions and contexts for resilience which vary among researchers and discipline fields, and the dominance of traditional mathematical approaches, such as the probabilistic or the graph theory in systems engineering, which may not be entirely appropriate for RE, and thus require better insight. Other techniques, such as entropy theory may yield better, more complete assessments of resilience [33].

Energy infrastructure systems

Resilience in energy transmission, distribution and generation networks generally implies a continuation of energy supply to meet demand at peak times and provide energy security, especially where there is a reliance on non-domestic generation and supply. Some of this resilience is built into modern energy supply systems by planning to be able to supply with a certain percentage capacity margin beyond the expected peak. How this planning is achieved is the focus of this section, which discusses the methodologies which help planners and designers to provide reliable and resilient energy distribution in practice.

The ability to model the energy supply and distributions system gives planners an opportunity to observe how the system would respond to unexpected shocks and changes given certain levels of demand, and allows modellers to observe impacts of new technologies such as smart grids.

Different modelling approaches are appropriate in different contexts. For instance, a scenario-based linear optimisation model assesses cost minimisation given electricity generation requirements and location constraints in the UK [41]. The Planner-Attacker-Defender model determines how robust electricity transmission networks are against failure events [42]. An interdependent modelling suite includes a layer of risk and vulnerability modelling capability [43], assessing different national strategies for infrastructure provision based on their risk-footprint under climate change across a range of socio-economic futures. Multi-agent system design principles are used for the coordination and control of ‘smart’ power systems [44], or to determine control strategies for active distribution networks [45].

Resilient energy systems involving ‘smart grid’ technologies should in theory have characteristics of increased reliability, self-healing, self-sufficiency and interactivity [46, 47]. ‘Self-healing’ relies on outputs from algorithms to enable the system to take preventative actions or to handle problems after they occur, and together with adaptive materials and automated energy-self-sufficient sensor networks are important technologies for resilience engineering [48].

Modelling studies often sit within a framework which helps define the scale of the problem and potential solution space. Such frameworks can be useful at a planning stage, as well as offering a methodology for monitoring outcomes, and some examples are given below.

Policies within a ‘holistic resilience framework for Critical Infrastructures’, consisting of ‘technical’, ‘organisational’ and ‘economic’ resilience factors, with an additional fourth external ‘social’ dimension, defines how actors should respond in emergency situations. A case study application is given for a Southern European nuclear power station [49]. An early example of an analytical planning framework assesses vulnerability in critical infrastructures and the potentially systemic and disruptive nature of technological change [50]. Multidisciplinary design optimization (MDO) is used to develop a framework of ‘Evolutionary Energy Performance Feedback for Design’ to support early stage design decision-making by providing rapid iteration with performance feedback, in other words ‘designing in performance’ [51]. The FRAME concept (Flexibility, Reliability, Availability, Maintainability and Economics) [52] is another method of incorporating performance indicators at the design stage of energy infrastructure. ‘Flexibility’ equates to adaptability, ‘Reliability’ implies a continuation of function despite internal changes, while ‘Maintainability’ refers to the system being restored to a previous state. ‘Availability’ refers to amount of time the system functions given exogenous uncertainties of the surrounding environment.

Water infrastructure systems

Similar assessment approaches to those used for energy systems can be applied for water infrastructure systems, but the different nature of the infrastructure assets means it is appropriate to give alternative examples of modelling and framework studies applied to the water sector.

Key aspects of resilience in underground water systems are: redundancy (to ensure continuation of supply when one pipeline fails); storage capacity (to prevent wastewater treatment plant overload and flooding) structural integrity (to enable systems to function under abnormal conditions); and backup power and structural stability [53].

Literature relating to design, planning and use of water infrastructure tends to focus on developing countries, where water quality and distribution systems are likely to be relatively poor, although there is also a focus on the resilience of large-scale assets such as dams [54], such as a U.S. review exploring methods already implemented by other engineering communities. One of their main recommendations was to explore greater use of numerical models to analyse past extremes and record their effectiveness in assessing current and future drivers of climate events for use in hydrologic design.

Cost effectiveness is a common objective in water distribution system design. An example ‘reliability index’ combines cost minimisation with a focus on water quality, as part of multi-objective optimisation to assess water distribution systems, applying a scenario-based case study in the town of Jahrom, Iran [55]. A water distribution system ‘resilience index’, based on demand, capacity and water quality has been used to assess the functionality and the restoration process following an extreme event. Scenario events were applied in a case study in the small town of Calascibetta, Sicily, to determine how different stresses impact the local distribution network [37]. Engaging stakeholders in decision-making can help develop a future vision for infrastructure development, such as the strategy development aiming to improve the commitment to water resources in Latin America and the Caribbean [56].

Transport infrastructure systems

The importance of a robust and reliable transport system from an economic and welfare perspective has led to considerable research in order to understand the mechanisms and interrelationships that create its vulnerability, to find ways to make it more robust and resilient, and to mitigate consequences of disturbances and disruptions [57]. Design principles are already in place to help increase safety on the various networks (e.g. [58] presents guidelines for performance-based highway design processes). A selection of papers are reviewed below, to give examples of some of the methodologies used to assess resilience and vulnerability in transport networks.

Public transport systems, where large numbers of people are often confined in low-security areas, are vulnerable to the threat of terrorism. To determine a system's resilience to such a threat, operational metrics are used which help inform decision-makers when assessing resource allocation and how to design a portfolio of security and recovery strategies [39], and applied to a case study example of London's transportation system.

Network and interdependency modelling was used to devise a vulnerability assessment framework, representing critical infrastructures as complex interdependent social-technological systems [59]. This framework was applied to the rail network in Great Britain to examine the impact on rail travel of infrastructure failure and flooding.

A decision support system for the resilience of critical infrastructure to extreme weather events has been developed as part of the INTACT project [60], which aims to develop and demonstrate best practices in engineering, materials, construction, planning and designing protective measures as well as crisis response and recovery capabilities.

An alternative process for the evaluation of the system's resilience involves the use of entropy theory [61]. As a system's entropy equals the sum of the entropies of the system's components, it is inferred that the transportation system's resilience can be assessed on the basis of the components' resilience.

A case study to estimate the resilience of train, tram and street networks in Melbourne, Australia applies network analysis using data extracted from GPS-mapping [62]. The interdependency and interaction of these networks is then used to risk assess Melbourne's transportation system.

In the relatively poverty-stricken regions of Latin America and the Caribbean, the impacts of climate change and El Nino on infrastructure design are considered in a series of reports and workshops by the Corporación Andina de Fomento [56, 63-65], the Latin American development bank. Including adaptation criteria within the infrastructure design process can be beneficial, although increasingly difficult given scarce resources. Sharing knowledge and experience is found to be an effective way to increase involvement with stakeholders, although there needs to be more cooperation between sectors, especially as the effects of climate change and El Nino are likely to increase inequality across the region.

Initiatives in Research and Practice

As stated earlier, much of the literature is on the theory of resilience, safety management or non-infrastructure systems. The brief example studies above give an insight into some of the potential future directions of research and practice. Additionally, there are research programmes and national strategies which aim to place resilience engineering and related practices at the centre of infrastructure planning and design and increase the resilience of critical national infrastructure. A selection of these cross-sector and sector-specific programmes and studies are summarised below.

INTACT Project – Europe

The INTACT project[1] is an EU-funded programme of knowledge and experience sharing aiming to develop and demonstrate best practices in engineering, materials construction, planning and designing protective measures as well as crisis response and recovery capabilities, including a methodological framework for critical infrastructure vulnerability assessment and an analysis of protection measures.

Envision infrastructure rating system – USA

Envision[2] is an infrastructure rating system which helps professionals plan and execute more sustainable infrastructure projects through the assessment of 60 sustainability criteria covering a range of environmental, social, and economic impacts to sustainability in project design, construction, and operation [29]. An enhanced version of the framework, Envision 2.0 has subsequently been developed, aiming to incorporate more guidelines and performance benchmarks from the American Society of Civil Engineers' (ASCE) Sustainable Sites Initiative programme.

Resilient Interdependent Infrastructure Processes and Systems – RIPS – USA

In 2014, the National Science Foundation (NSF) in USA awarded grants totalling nearly $17 million through cross-disciplinary funding by its Directorates for Engineering and Computer and Information Science and Engineering to 16 institutions to carry out transformative research in the area of Resilient Interdependent Infrastructure Processes and Systems[3] (RIPS), across a range of topics. The research also aims to investigate questions related to vulnerability, risk and resilience in the face of various hazards as well as everyday degradation.

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[1] INTACT – further details available from www.intact-project.eu

[2] Envision – further details available from https://sustainableinfrastructure.org/envision

[3] RIPS – further details available from http://bit.ly/2rUV2Xr

Critical Resilient Interdependent Infrastructure Systems and Processes – CRISP – USA

The RIPS investment set the foundation for NSF's cross-directorate activity Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP)[4], which aims to foster an interdisciplinary research community to create new approaches and engineering solutions for infrastructure design and operation, enhance the understanding, design, innovation, efficiency and resilience of interdependent critical infrastructure systems. Funding will be made available during 2017 for 2 to 4 year projects which fulfil these aims.

ARCC Network – UK

The EPSRC-funded ARCC Network[5] (Adaptation and Resilience in the Context of Change) supports the creation and in-depth understanding of robust built environment and infrastructure sectors within the UK, providing and integrating knowledge with enhanced accessibility and uptake of research outputs to help ensure policy and practice have the best available evidence. The programme is associated with a number of projects focusing on infrastructure, including ARIES and ITRC (see below).

Infrastructure Transitions Research Consortium (ITRC) – UK

ITRC[6] is an EPSRC-funded collaborative programme, providing concepts, models and evidence to inform the analysis, long-term planning and design of critical national infrastructures of energy, transport, water, waste and digital communications, using NISMOD, an infrastructure system-of-systems model. NISMOD-RV is an assessment tool of risk and vulnerability in critical infrastructures. The second phase of the ITRC programme, MISTRAL (Multi-Scale Infrastructure Systems Analytics) aims to build NISMOD version 2 which will comprise an integrated analytics capability to inform infrastructure decision-making across scales, from local to global.

National Infrastructure Commission – UK

Outcomes from the ITRC research programme are part of the evidence base utilised by the UK’s National Infrastructure Commission (NIC)[7], an independent organization providing the UK government with impartial, expert advice on major long-term infrastructure challenges. One of their recent reports assesses infrastructure planning for energy and transport systems internationally [66]. One of their ‘policy insights’ is that cross-sector planning can help policymakers recognise the resilience implications for the entire infrastructure network.

National Resilience initiative – Japan

[4] CRISP – further details available from http://bit.ly/2sb5dLc

[5] ARCC – further details available from www.arcc-network.org.uk

[6] ITRC – further details available from www.itrc.org.uk

[7] NIC – further details available from www.nic.org.uk

In response to Japan's natural and nuclear disasters of 2011, a series of programmes has been set up, including the 'Fundamental Plan for National Resilience'[8] aimed at building resilience in critical energy, water, transport and other lifeline infrastructures [67]. Disaster-resilient renewable energy systems have been among the largest markets in Japan's private-sector spending since 2011. Other core markets include earthquake-proofing of infrastructure, reinforcement of transport systems, disaster-relief robotics, communications resilience, and training of specialist leadership.

Critical Infrastructure Resilience Strategy – Australia

The aim of the Australian Government's Critical Infrastructure Resilience Strategy is the continued operation of critical infrastructure in the face of all hazards [68]. Four outcomes will help deliver more resilient infrastructure: 1): Business-government partnerships, ensuring information sharing and collaboration on risk and resilience initiatives; 2) Risk management of the operating environment, aiming to increase sectoral cross-sectoral understanding of critical infrastructure assets or networks; 3) Rick-based strategic understanding and management, and 4) An understanding of organisational resilience, building capacity within organisations for unexpected events.

Action Plan for Critical Infrastructure – Canada

This Action Plan and associated National Strategy [69] recognise that responsibilities for critical infrastructure in Canada are shared by federal, provincial and territorial governments, local authorities, and critical infrastructure owners and operators. One of the key aspects of the strategy is knowledge sharing via the National Cross Sector Forum, linking critical infrastructure operators, who can inform the development of comprehensive emergency management plans and, government bodies who have information on risks and threats relevant to operators.

International Risk Governance Council – IRGC

The International Risk Governance Council[9] (IRGC) is an independent non-profit foundation which provides insight into systemic risks that have impacts on society. IRGC has developed a web-based Resource Guide on Resilience for researchers and practitioners. The guide is a collection of authored pieces reviewing existing concepts, approaches and illustrations or case-studies for comparing, contrasting and integrating risk and resilience, and for developing resilience.

ARIES (Adaptation and Resilience in Energy Systems) – UK

ARIES[10] aims to provide a risk framework to assess the resilience of the UK energy systems to ensure a balance between changing patterns of demand and supply, and to model the physical and economic impacts of climate change on current and new energy generation technologies. In order to deliver this, an enhanced set of future energy systems and climate scenarios has been developed, alongside modelling capabilities provided by programmes such as ITRC (see above).

[8] Fundamental Plan on National Resilience – see http://bit.ly/2r7v8Qv

[9] IGRC – further details available from www.irgc.org

[10] ARIES – further details available from www.arcc-network.org.uk/aries

FRACTAL (Future Resilience for African Cities and Lands) – South Africa

FRACTAL[11] aims to advance scientific knowledge about regional climate responses to human activities and work with decision makers to integrate this scientific knowledge into climate-sensitive decisions at the city-regional scale (particularly decisions relating to water, energy and food with a lifetime of 5 to 40 years). FRACTAL is designed to work across disciplines within the scientific community and foster strong collaboration between researchers, city government officials and other key decision makers in southern Africa.

FRS (Future Resilient Cities) – Switzerland and Singapore

FRS[12] is an ETH Zurich initiative in Singapore that addresses the challenges of increasing interconnectedness and complexity of infrastructure systems. It aims to develop a framework, concepts, and tools to make interconnected infrastructure systems more robust and resilient.

[11] FRACTAL – further details available from www.fractal.org.za

[12] FRS – further details available from www.frs.ethz.ch

Barriers and opportunities

Very few organisations or infrastructure providers are explicitly using RE as part of their safety or business management philosophy, nor are they systematically integrating principles of RE into management routines. This can become a bottleneck for the evolution of RE, as theory building would benefit from the observation of experiences of large-scale 'building in' of resilience engineering by an infrastructure provider [8]. Tamvakis and Xenidis [33] note that "current methods [of resilience quantification] are mostly incomplete and largely dependent on concepts and approaches which emanate from other well-established and well-elaborated methodological frameworks, thus failing to provide solutions in the context of resilience engineering".

Further to this lack of evidence of current practice, there are issues around the wide diversity of definitions and frameworks (discussed in Chapter 2) which add potential confusion during infrastructure planning and design. The Resilience Shift programme, together with the examples of other related programmes set out in Chapter 4 suggest that there is a movement towards a more standardised approach which will help put RE at the centre of the future of infrastructure planning and design.

This report has highlighted the numerous approaches to modelling of infrastructure and related systems, but the accuracy and relevance of such models is dependent on good quality data. This may not be too problematic for developed countries, but infrastructure planning is also crucial in the developing world and in post-disaster and post-conflict situations, and reliable data can be much harder to acquire in such contexts. One example is the recent work carried out as part of ITRC's MISTRAL programme with the UN Office of Project Services (UNOPS) developing NISMOD-International, a model which has relatively simple data requirements (i.e. population, economy, infrastructure asset location and service delivery), but is still capable of assessing relatively short-term future changes.

Another potential barrier is the lack of coordination in governance, planning and delivery ('silo-based' thinking), especially for decisions about assets with long build times and asset lives. In the rural environment in particular, this can cause problems [70]. Greater collaboration between government, industry, not-for-profits and communities would help alleviate these problems, as would acknowledgement of interdependencies and cross-sector approaches to planning, design and implementation. However these may still be difficult to enable in practice.

One of the original aims of this review was to gain insight from experts in industry about their experiences with embedding resilience engineering in the planning and design processes, but the lack of such processes made this aspect of the review untenable. One potential future study for the Resilience Shift programme could focus on why such processes are currently only theoretical in nature, by carrying out a systematic large-scale survey of institutions and infrastructure providers to investigate the extent to which resilience engineering principles have been implicitly used by industry, as well as to identify the perceptions of industry experts regarding the future direction of resilience engineering.

That said, there are some outcomes from this review which already offer such insight for future opportunities. For instance, Aktan et al. [71] suggest that future civil engineers involved in the planning and design of critical infrastructures will need access to various classes of operating infrastructure to study and experiment with in the context of coordinated, multi-discipline, problem-focused field research. They suggest that these engineers will need access to actual infrastructures through ‘living infrastructure laboratories’, part of an academe-industry-government partnership that include infrastructure stewards as champions for innovation. Such laboratories would provide best-practice demonstrations for performance-based engineering and lifecycle asset-management of infrastructures.

Another interesting concept yet to be fully explored is contained in the ongoing research of Tamvakis and Xenidis (2012, 2013). They assert that a methodological framework based on entropy theory better captures the underlying interrelations of systems modules and, therefore, constitutes a more appropriate and effective framework for quantifying resilience of infrastructure systems than other resilience quantification methods, such as probabilistic, graph theory, fuzzy inference, and analytical methods.

Unlike other engineering disciplines, resilience engineering has emerged through academia rather than through experience and knowledge of engineers and planners. This is a potential barrier, and this review has identified that currently very few organisations or infrastructure providers are explicitly using RE as part of their safety or business management philosophy. In order for such change to be enacted, further research into the implicit methods and practices in place throughout infrastructure planning should be undertaken.

Conclusions

‘Resilience Engineering’ (RE) was identified as one of four strategic funding priorities for LRF together with the complementary topics of ‘Structural Integrity and Systems Performance’, ‘Human and Social Factors’ and ‘Emergent Technologies’, and this forms the basis for the Resilience Shift programme.

This report has reviewed a large quantity of literature which describes studies of resilience engineering in a range of contexts, and has also discussed a number of national and international programmes to help increase awareness, cooperation and knowledge sharing of resilience of critical infrastructure systems. It is unfortunate (although perhaps unsurprising) that at this stage much of the literature is focused on the theory of resilience, safety management or non-infrastructure systems, which has limited the opportunities to review RE of interdependent infrastructure systems in practice. However, such theoretical work can still provide a good background to the potential future options for RE in infrastructure, and numerous papers and studies have been considered here to this end. These papers illustrate the range of existing and proposed approaches to the application of RE in the three critical infrastructure sectors of energy, water and transport, and thereby highlight the lack of consistency in RE at present.

A number of key barriers have been identified during this work which may pose difficulties in achieving a consistent and widespread application of RE across infrastructure sectors. In addition to a lack of consistency in the definitions and approaches used, these include the absence of large scale implementations to allow benchmarking and practice-based learning, difficulties in obtaining the required data (particularly in developing contexts), a lack of coordination in infrastructure governance, planning and delivery, and difficulties in transferring theoretical knowledge from academia to practitioners.

However, the fact that the field of practical RE is still in its infancy presents very significant opportunities to get things right, particularly in a context where coordinated planning and decision-making for infrastructure systems is becoming more common (for example through bodies such as the UK National Infrastructure Commission). Later stages of the Resilience Shift programme should aim to take advantage of these opportunities and assist in transferring potentially transformative ideas around resilience and performance-based engineering from theory into practice.

References

1. Aktan, A.E., Innovating infrastructure planning, financing, engineering and management, in Second Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures2013: Istanbul, Turkey.

2. LRF, Lloyd's Register Foundation: Strategy 2014-2020, 2014: London, UK.

3. LRF, Foresight review of resilience engineering: designing for the expected and unexpected, in Lloyd's Register Foundation Report Series: No. 2015.22015: London, UK.

4. Aven, T., On some recent definitions and analysis frameworks for risk, vulnerability and resilience. Risk Analysis, 2011. 31: p. 515-522.

5. Bergström, J., R. van Winsen, and E. Henriqson, On the rationale of resilience in the domain of safety: a literature review. Reliability Engineering & System Safety, 2015. 141: p. 131-141.

6. Haimes, Y.Y., On the definition of resilience in systems. Risk Analysis, 2009. 29: p. 498-501.

7. Hosseini, S., K. Barker, and J.E. Ramirez-Marquez, A review of definitions and measures of system resilience. Reliability Engineering & System Safety, 2016. 145: p. 47-61.

8. Righi, A.W., T.A. Saurin, and P. Wachs, A systematic literature review of resilience engineering: research areas and a research agenda proposal. Reliability Engineering & System Safety, 2015. 141: p. 142-152.

9. Woods, D.D., Four concepts for resilience and the implications for the future of resilience engineering. Reliability Engineering & System Safety, 2015. 141: p. 5-9.

10. Alexander, D.E., Resilience and disaster risk reduction: an etymological journey. National Hazards and Earth System Sciences, 2013. 13(11): p. 2707-2716.

11. Zhou, H., et al., Resilience to natural hazards: a geographic perspective. Natural Hazards, 2008. 53: p. 21-41.

12. Francis, R. and B. Bekera, A metric and frameworks for resilience analysis of engineered and infrastructure systems. Reliability Engineering & System Safety, 2014. 121: p. 90-103.

13. Rose, A., Economic resilience to disasters, Community and Regional Resilience Institute Report No 8, Editor 2009.

14. Ibanez, E., et al., Resilience and robustness in long-term planning of the national energy and transportation system. International Journal of Critical Infrastructures, 2016. 12(1-2): p. 82-103.

15. Hollnagel, E. Resilience engineering. 2017]; Available from: http://erikhollnagel.com/ideas/resilience-engineering.html.

16. Hollnagel, E., D.D. Woods, and N.C. Leveson, Resilience engineering: concepts and precepts. 2006, Aldershot, UK: Ashgate.

17. NIAC, Critical infrastructure resilience - final report and recommendations, National Infrastructure Advisory Council, Editor 2009: Washington, DC, US.

18. Nan, C. and G. Sansavini, A quantitative method for assessing resilience of interdependent infrastructures. Reliability Engineering & System Safety, 2017. 157: p. 35-53.

19. Woods, D.D., Resilience engineering: redefining the culture of safety and risk management. Human Factors and Ergonomics Society Bulletin, 2006. 49(12).

20. Kolarevic, B. and A.M. Malkawi, Performative Architecture: beyond instrumentality. 2005, New York, US and London, UK: Spon Press.

21. Oxman, R., Performance-based design: current practices and research issues. International Journal of Architectural Computing, 2008. 6(1): p. 1-17.

22. Whalley, A., Product and process: performance-based architecture, in Performative Architecture: beyond instrumentality, B. Kolarevic and A.M. Malkawi, Editors. 2005, Spon Press: New York, US and London, UK.

23. Priestley, M., Performance based seismic design. Bulletin of the New Zealand society for earthquake engineering, 2000. 33(3): p. 325-346.

24. PEER, Guidelines for performance-based seismic design of tall buildings, in Report No. 2010/05, Pacific Earthquake Engineering Research Center, Editor 2010: University of California, USA.

25. Ghobarah, A., Performance-based design in earthquake engineering: state of development. Engineering Structures, 2001. 23(8): p. 878-884.

26. Aktan, A.E., B.R. Ellingwood, and B. Kehoe, Performance-based engineering of constructed systems. Journal of Structural Engineering, 2007. 133(3): p. 311-323.

27. Ghosn, M., et al., Performance indicators for structural systems and infrastructure networks. Journal of Structural Engineering, 2016. 142(9).

28. Li, Y., A. Ahuja, and J.E. Padgett, Review of methods to assess, design for, and mitigate multiple hazards. Journal of Performance of Constructed Facilities, 2011. 26(1): p. 104-117.

29. Minsker, B., et al., Progress and recommendations for advancing performance-based sustainable and resilient infrastructure design. Journal of Water Resources Planning and Management, 2015. 141(12).

30. Lundberg, J. and B.J.E. Johansson, Systemic resilience model. Reliability Engineering & System Safety, 2015. 141: p. 22-32.

31. Huang, C.-N., J.J.H. Liou, and Y.-C. Chuang, A method for exploring the interdependencies and importance of critical infrastructures. Knowledge-Based Systems, 2014. 55: p. 66-74.

32. Yusta, J.M., G.J. Correa, and R. Lacal-Arántegui, Methodologies and applications for critical infrastructure protection: State-of-the-art. Energy Policy, 2011. 39(10): p. 6100-6119.

33. Tamvakis, P. and Y. Xenidis, Comparative evaluation of resilience quantification methods for infrastructure systems. Procedia - Social and Behavioral Sciences, 2013. 74: p. 339-348.

34. Ouyang, M., Review on modeling and simulation of interdependent critical infrastructure systems. Reliability Engineering & System Safety, 2014. 121: p. 43-60.

35. Johansson, J. and H. Hassel, A model for vulnerability analysis of interdependent infrastructure networks, in European Safety and Reliability Conference / 17th Annual Meeting of the Society for Risk Analysis Europe2008: Valencia, Spain.

36. Zimmerman, R., Q. Zhu, and C. Dimitri, Promoting resilience for food, energy and water interdependencies. Journal of Environmental Studies and Sciences, 2016. 6(1): p. 50-61.

37. Cimellaro, G.P., et al., New resilience index for urban water distribution networks. Journal of Structural Engineering, 2015. 142(8).

38. D'Lima, M. and F. Medda, A new measure of resilience: an application to the London Underground. Transportation Research Part A, 2015. 81: p. 35-46.

39. Cox, A., F. Prager, and A. Rose, Transportation security and the role of resilience: a foundation for operational metrics. Transport Policy, 2011. 18: p. 307-317.

40. Ouyang, M., A mathematical framework to optimize resilience of interdependent critical infrastructure systems under spatially localized attacks. European Journal of Operational Research, 2017. In Press.

41. Chaudry, M., et al., Building a resilient UK energy system, UKERC, UK Energy Research Centre, Editor 2011.

42. Fang, Y. and G. Sansavini, Optimizing power system investments and resilience against attacks. Reliability Engineering & System Safety, 2017. 159: p. 161-173.

43. Hall, J.W., et al., The future of national infrastructure: a system-of-systems approach. 2016, Cambridge, UK: Cambridge University Press.

44. Farid, A.M., Multi-agent system design principles for resilient coordination & control of future power systems. Intelligent Industrial Systems, 2015. 1(3): p. 255-269.

45. Degefa, M.Z., et al., MAS-based modeling of active distribution network: the simulation of emerging behaviors. IEEE Transactions on Smart Grid, 2016. 7(6): p. 2615-2623.

46. Amin, M., Toward self-healing energy infrastructure systems. IEEE Computer Applications in Power, 2001. 14(1): p. 20-28.

47. Arefifar, S.A., Y.A.R.I. Mohamed, and T.H.M. El-Fouly, Comprehensive operational planning framework for self-healing control actions in smart distribution grids. IEEE Transactions on Power Systems, 2013. 28(4): p. 4192-4200.

48. Linkov, I., et al., Changing the resilience paradigm. Nature Climate Change, 2014. 4(6): p. 407-409.

49. Labaka, L., J. Hernantes, and J.M. Sarriegi, Resilience framework for critical infrastructures: an empirical study in a nuclear plant. Reliability Engineering & System Safety, 2015. 141: p. 92-105.

50. Hellström, T., Critical infrastructure and systemic vulnerability: towards a planning framework. Safety Science, 2007. 45(3): p. 415-430.

51. Lin, S.-H.E. and D.J. Gerber, Designing-in performance: a framework for evolutionary energy performance feedback in early stage design. Automation in Construction, 2014. 38: p. 59-73.

52. Ajah, A.N., On the conceptual design of large-scale process & energy infrastructure systems integrating flexibility, reliability, availability, maintainability and economics (FRAME) performance metrics, in Faculty of Technology, Policy and Management2009, Delft University of Technology: Delft, Netherlands.

53. Matthews, J.C., Disaster resilience of critical water infrastructure systems. Journal of Structural Engineering, 2015. 142(8).

54. Hossain, F., et al., Review of approaches and recommendations for improving resilience of water management infrastructure: the case for large dams. Journal of Infrastructure Systems, 2017.

55. Shokoohi, M., et al., Water quality based multi-objective optimal design of water distribution systems. Water Resources Management, 2017. 31(1): p. 93-108.

56. Miralles, F., Adaptación al cambio climático y gestión de riesgos, Corporación Andina de Fomento, Editor 2014.

57. Mattsson, L.-G. and E. Jenelius, Vulnerability and resilience of transport systems - a discussion of recent research. Transportation Research Part A: Policy and Practice, 2015. 81: p. 16-34.

58. Neuman, T.R., et al., A performance-based highway geometric design process, National Cooperative Highway Research Program, Research Report 839, Editor 2016: Washignton, D.C., USA.

59. Pant, R., J.W. Hall, and S.P. Blainey, Vulnerability assessment framework for interdependent critical infrastructures: case-study for Great Britain's rail network. European Journal of Transport & Infrastructure Research, 2016. 16(1).

60. Kiel, J., et al., A decision support system for the resilience of critical transport infrastructure to extreme weather events. Transportation Research Procedia, 2016. 14: p. 68-77.

61. Tamvakis, P. and Y. Xenidis, Resilience in transportation systems. Procedia - Social and Behavioral Sciences, 2012. 48: p. 3441-3450.

62. Leu, L., H. Abbass, and N. Curtis, Resilience of ground transportation networks: a case study on Melbourne, in 33rd Australasian Transport Research Forum Conference2010: Canberra, Australia.

63. CAF, Programa de adaptacion al cambio climatico, Corporación Andina de Fomento, Editor 2013.

64. CAF, Infraestructura en el desarrollo de America Latina. Infraestructura y cambio climático, Corporación Andina de Fomento, Editor 2014.

65. CAF, El Nino en America Latina. ¿Cómo mitigar sus efectos en el sector eléctrico?, Corporación Andina de Fomento, Editor 2016.

66. International Transport Forum, Strategic infrastructure planning - international best practice, OECD and National Infrastructure Commission, Editor 2017.

67. DeWit, A., Japan's 'National Resilience' and the legacy of 3-11. The Asia-Pacific Journal, 2016. 14(6).

68. Australian Government, Critical infrastructure resilience strategy: plan, Commonwealth of Australia, Editor 2015: Canberra, Australia.

69. Public Safety Canada, Action Plan for Critical Infrastructure, 2013.

70. Freeman, J. and L. Hancock, Energy and communication infrastructure for disaster resilience in rural and regional Australia. Regional Studies, 2016: p. 1-12.

71. Aktan, A.E., F. Moon, L., and D.S. Lowdermilk, Engineering and management of infrastructure systems, in 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure2013: Hong Kong.