INFRASTRUCTURE RESILIENCE; A MULTI-DISCIPLINARY PERSPECTIVE

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Who Should Read This White Paper?

This White Paper is of broad interest to anyone who wants to know more about the concept of resilience, how the concept has been developed and applied by a range of disciplines, and lessons for applying the concept to infrastructure. More specifically, the target audience for this White Paper is the international community of infrastructure practitioner or policy maker who find themselves in a position of needing to more fully understand the concept of resilience as a system property and its potential relevance to the infrastructure decisions they make.

White Paper Key Messages

- Resilience is multi-dimensional concept and as such difficult to define. Common across disciplinary perspectives, are the concept that resilience is a property of a system that emerges from the interaction between (interdependence of) system components. And that a resilient system a certain abilities characteristics.
- All human activity (including construction and operation of infrastructure) takes place in the context of the broader system of which it is a part. It follows any infrastructure asset, sub-sector or sector is only as resilient as the least resilient component of the supply chains or other infrastructure on which it depends. Therefore, it is not possible (or at least very difficult) to be resilient without being systemic.
- In order to be resilient, any action(s) to increase efficiency or optimise a system must be evaluated in the context of potential changes to the system (sudden and gradual) that might affect the ability to preserve existence of function. Explicitly acknowledging and maintaining awareness of broader external factors during problem framing and solution selection, is therefore, an essential element of the resilience approach.
- To increase resilience and reduce recovery time, an organisation must be dynamic in continually planning for, and adapting to, changing external contexts. This requires regular re-evaluation of desired function(s)/outcome(s), and the business model and mode of delivery to enable those. Upgrading/adapting infrastructure assets only after a failure event, or focusing solely on rapid recovery to business-as-usual performance after a failure event, impedes an organisation's ability to be resilient.

Abstract

Resilience is a multi-dimensional concept applicable in numerous contexts and typically the context in which it is applied directly influences the resilience dimensions emphasised. In the absence of a definition which encompasses all resilience dimensions, those involved with infrastructure need to be aware of the full range of contexts in which the term resilience has been used to describe systems properties, and potential lessons, applicable to infrastructure, that can be drawn from those disciplines that have experience of applying resilience as a system property. This white paper provides an overview of how resilience has been applied in ecological systems, socio-ecological-systems (SES), resilience engineering and strategic resilience literature for those with an interest in infrastructure resilience..

Key Words

Resilience, Perspectives, Engineering, Socio-ecological-system, dynamic and intentional systems, context

Connections to Other ICIF White Papers

- Systemic resilience of infrastructure at scale
- Evidence for the Value of a Systems Approach to Infrastructure Planning, Delivery and Operation
- People and infrastructure based services – an opportunity for engagement
- Rethinking 'Sustainable Infrastructure': Natural Processes, Context, Value and Balance
- Learning Journeys and Infrastructure Services: a game changer for effectiveness

Where Can I Find Out More?

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Acknowledgements

This White Paper was produced in response to resilience challenges identified during an industry workshop run by ICIF and iBUILD as part of an event 'Resilience in an Interdependent World' held on 2nd July 2015 and hosted by ICIF, iBUILD, ITRC, ARCC and CIRIA.

ICIF is funded by the Engineering and Physical Sciences Research Council and the Economic and Social Research Council (Grant reference: EP/K012347/1).

This is a draft copy, available online pending publication as a book chapter in the ICIF White Paper Collection, UCL Press [TBC Autumn/Winter 2016]. Prior to publication reference as:

Tom Dolan, T., Jude, S., Varga, L., Quinn, A. and Neil Carhart, N. (2016) Infrastructure Resilience: a multi-disciplinary perspective (advanced copy). In: Dolan, T and Collins, B, (eds.) ICIF White Paper Collection (in Press), UCL Press, London, UK. Available online at: www.icif.ac.uk

Infrastructure Resilience: A multi-disciplinary perspective

1 Introduction

Resilience is a multi-dimensional concept, the definition of which varies both between and within disciplines. Nevertheless, it is a concept applicable in numerous contexts, and knowledge of its application in one context can provide useful learning for application in another. The need to support infrastructure practitioners and policymakers develop a deeper understanding of resilience, its multi-disciplinary nature and potential lessons for application to infrastructure was identified at an industry workshop on 2nd July 2015 run by ICIF and iBUILD as part of an event 'Resilience in an Interdependent World' hosted by ICIF, iBUILD, ITRC, ARCC and CIRIA. This white paper presents insight into resilience from a range of disciplinary perspectives with a view to addressing that need.

The White Paper opens with a brief history of the term resilience (section 1.1). Brief overviews of ecological systems, socio-ecological-systems (SES), dynamic and intentional systems (resilience engineering) and strategic perspectives on resilience are given in sections 2-5. A synopsis of key messages from these perspectives is given at the front of the white paper.

1.1 Resilience: A Brief History
(adapted from (McAslan, 2010a))

In 1818 Tredgold applied the term resilience to describe a property of timber. From this Mallet in 1865 developed a measure, 'the modulus of resilience', to assess the ability of materials to withstand severe conditions. The term resilience has subsequently evolved to describe a property of systems. To date the term resilience has been applied as a property of many systems including: ecological systems (Holling, 1973), social systems (Adger, 2000), socio-ecological systems (Folke, 2006; Walker et al., 2004), psychological systems (Ong et al, 2006), communities (McAslan, 2010b) and dynamic and intentional systems (a category that includes built systems such as infrastructure (Hollnagel, 2014, 2011), and business systems (Hamel and Valikangas, 2003)) .

1.2 Perspectives on Resilience

Resilience lessons applicable to infrastructure can be learnt from other disciplines. Ecological systems, socio-ecological-systems (SES), dynamic and intentional systems and strategic resilience perspectives have been chosen as the focus for this White Paper because:

(i) Resilience has been studied in the environmental disciplines for over 40 years. Ecological insights can be useful an infrastructure context.

(ii) Infrastructure fits the definition of a dynamic and intentional system given by Hollnagel (2014) in his work on resilience engineering

(iii) All dynamic and intentional systems (and therefore infrastructure) exist in the prevailing context of the socio-ecological system (SES) (Folke, 2006; Walker et al., 2004) of which they are a part.

(iv) Resilient infrastructure provision is dependent on strategic management of both short-term (people, plans, processes, and procedures) and long-term (life-cycle asset management, asset design changes, alternative modes of delivery via new technologies) factors (NIAC, 2010)

The quotes in Table 1 introduce these perspectives, further details on each are given in sections 2-5.

Table 1 Four Perspectives on Resilience

Ecological Perspective 'Ecological Resilience' and 'Engineering Resilience' offer different but complementary lenses to examine any situation *"Ecological resilience is concerned with enabling 'existence' of function in a changing*

context, whereas Engineering resilience focuses on the 'efficiency' of function in a stable context." (Holling, 1996)

Socio-ecological-Systems (SES) Perspective

Resilience defined as *"the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks"* is dynamic property of an SES. Resilience is best understood as one of three complementary attributes of a dynamic system, the other two being adaptability and transformability. (Walker et al., 2004)

Resilience Engineering Perspective

Resilience is a characteristic of system performance or behaviour, rather than an inherent quality or feature of a system. Resilience is

"the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions." (Hollnagel (2011) quoted in Hollnagel (2014))

Strategic Resilience Perspective

"Strategic resilience is not about responding to a onetime crisis. It's not about rebounding from a setback. It's about continuously anticipating and adjusting to deep, secular trends that can permanently impair the earning power of a core business. It's about having the capacity to change before the case for change becomes desperately obvious." (Hamel and Valikangas, 2003)

2 An Ecological Perspective

2.1 Ecological and Engineering Resilience

Despite emerging from an environmental context, insights from the Ecological study of resilience are also directly relevant to managing infrastructure in changing political, economic, social, technological and legal context.

Ecological resilience differentiates between two resilience perspectives 'Engineering Resilience' and 'Ecological Resilience'. Ecological resilience is concerned with enabling *'existence'* of function in a changing context, whereas engineering resilience focuses on the *'efficiency'* of function in a stable context.

- Engineering resilience assumes stable external conditions. Under such conditions it is intuitive to optimise for efficient performance within the stable range.
- Ecological Resilience assumes external conditions are subject to gradual change and occasional shocks. Under such conditions maintaining delivery of desired outcomes in the presence of external disruption (often beyond direct control of those affected) becomes of greater significance than achieving efficient delivery.

The two concepts are of course complementary, and the objective of Engineering Resilience must always be framed within the broader context of the need for Ecological Resilience. It follows, therefore, that actions to increase *efficiency* or optimise a system (increase engineering resilience) must be evaluated in the context of potential changes to the system (sudden and gradual) that might affect the ability to preserve *existence* of function (Ecological Resilience). The two perspectives should be used together as they provide different but complementary lenses to examine any situation. Engineering Resilience allows a complex problem to be framed in a way that can be solved, but creates a risk of failure unless the broader factors characterised by Ecological Resilience are explicitly acknowledged in problem framing and solution selection.

2.2 Components of Ecological Resilience

Walker et al. (2004) proposes four components of ecological resilience, latitude, resistance, precariousness, and panarchy. Table 2 defines these and illustrates their potential significance for infrastructure.

Table 2. Components of Ecological Resilience and Significance for Infrastructure

Resilience Component + Definition	Significance to Infrastructure
Latitude: the maximum amount a system can be changed before losing its ability to recover (before crossing a threshold which, if breached, makes recovery difficult or impossible).	Knowledge of the operating conditions for which the infrastructure was designed is important, as is analysis of consequences of operation outside of that range.
Resistance: the ease or difficulty of changing	Knowledge of the factors that make an

the system; how "resistant" it is to being changed.	infrastructure either resistant or vulnerable to change creates an opportunities for pro-active management prior to an infrastructure failure event.
Precariousness: how close the current state of the system is to a limit or "threshold."	Continuous information on how close current operating conditions are to the upper or lower bound of specified operating conditions provides an actionable resistance diagnostic.
Panarchy: because of cross-scale interactions, the resilience of a system at a particular focal scale will depend on the influences from states and dynamics at scales above and below. For example, external oppressive politics, invasions, market shifts, or global climate change can trigger local surprises and regime shifts.	An infrastructure asset is only as resilient as the least resilient component of the supply chains on which it depends. Therefore, it is not possible (or at least very difficult) to be resilient without being systemic. More broadly, knowledge of the extent to which infrastructure is dependent on a stable external context is needed to create strategies which reduce vulnerability to context change.
	Left column from (Walker et al., 2004)

3 Socio-ecological Systems (SES) Perspective

"Socio-ecological systems (SES) are characterised by non-linear dynamics, thresholds, uncertainty, surprise, gradual change, rapid change, and a range of spatial and temporal scales" (Folke, 2006)

The SES perspective has broad applications, because the *socio* component can include all social factors that influence system behaviour and the *ecological* component all natural processes that influence system behaviour.

Consequently, all human activity (including construction and operation of infrastructure) takes place in the context of an SES. Therefore, no infrastructure asset, sub-sector or sector exists in isolation from the SES of which it is a part. It follows, the resilience of any infrastructure component is closely linked to the resilience of the SES in which it is located.

From an SES perspective, resilience is a dynamic property of a system. It is tightly coupled with, and best understood as, one of three complementary attributes of a dynamic system (Table 3), the other two being adaptability and transformability.

Table 3 SES Attributes

Attribute	Significance
Resilience	the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks
Adaptability	the collective capacity of the human actors in the system to manage resilience and is strongly linked to the ability to intentionally manipulate the four components of Resilience
Transformability	the capacity to create a fundamentally new system when the old is untenable
	Adapted from (Walker et al., 2004)

Emphasis on the attributes of system dynamics, illustrates that understanding (i) the current state of these attributes (ii) the potential impacts on infrastructure performance if these attributes were to change, (iii) the underlying causes of change to these attributes, (iv) the factors that inhibit the ability of a system to reorganise (v) how these attributes can be managed to mitigate risk and create opportunities to increase resilience, are all important parts of developing a resilient system.

4 A Resilience Engineering Perspective

4.1 NIAC Resilience Construct

The National Infrastructure Advisory Council (NIAC, 2010) uses a resilience construct (Figure 1) to conceptualise four important abilities of a resilient built system: robustness (prior to the event), resourcefulness (during the event), rapid recovery (after the event) and adaptability/lessons learned (providing feedback throughout). Succinct explanations of each of these abilities are provided in Figure 1.

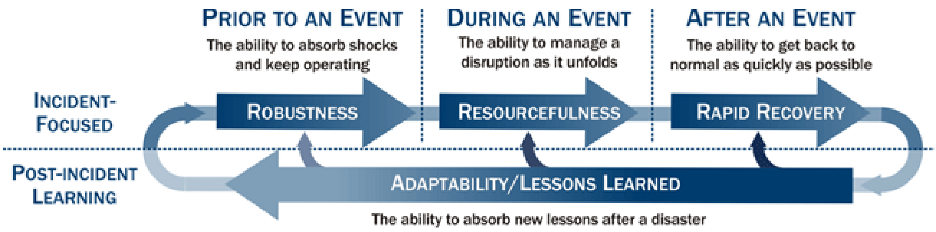

Figure 1. The NIAC Resilience Construct

The NIAC emphasise that at all stages of resilience planning, the ‘resilience construct’ should be applied to two important components of built systems (i) ‘*people, plans, processes and procedure’* and to (ii) ‘*Infrastructure and assets’*. This is because both (i) and (ii) are pivotal to the development of systemic resilience.

4.2 Dynamic and Intentional Systems Resilience

From a resilience engineering perspective, Hollnagel (2014) emphasises that resilience is a characteristic of system performance or behaviour, rather than an inherent quality or feature of a system. With a focus on performance, Hollnagel (2014) proposes four abilities dynamic and intentional systems required to achieve resilient performance (Table 1Table 4). These abilities to address the actual, the critical, the factual and the potential, are also described by Hollnagel as the abilities to respond, monitor, learn and anticipate (see italics in Table 4).

Table 4. Four Abilities of a Resilient Built System

Ability	Description
The ability to address the	Knowing what to do: how to *respond* to regular and irregular disruptions and disturbances either by implementing a prepared set of responses or by

actual.	adjusting normal functioning.
The ability to address the ***critical.***	Knowing what to look for: how to *monitor* that which is or can become a threat in the near term. The monitoring must cover both events in the environment and the performance of the system itself.
The ability to address the ***factual.***	Knowing what has happened: how to *learn* from experience, in particular how to learn the right lessons from the right experience – successes as well as failures.
The ability to address the ***potential.***	Knowing what to expect: how to *anticipate* developments, threats, and opportunities further into the future, such as potential changes, disruptions, pressures and their consequences.
	Source: (Hollnagel, 2014)

These abilities focus on how to make resilient system performance part of 'normal' operations, i.e. how to make resilience a core component of operations.

The value of resilient performance and therefore of these abilities, is in the benefits that arise from being prepared for disruptions, responding to each disruption more effectively than the last and reducing the frequency and impact of system disruption.

5 A Strategic Resilience Perspective

The Hamel and Valikangas (2003) quote on strategic resilience (Table 1) illustrates the many facets of strategic resilience. A strategically resilient organisation recognises the necessary trade-off between increasing efficiency and retaining the ability to dynamically anticipate, adapt to, prepare for, and respond to change in external operating conditions. Hamel and Valikangas (2003) propose that to be strategically resilient, an organisation needs to address four challenges, Table 5 gives our interpretation of these challenges.

Table 5. Strategic Resilience Challenges

Challenge	Explanation
Conquer Denial	Be deeply conscious of external change. Recognise that in a dynamic environment change is more likely than stability. Look to the future and continuously consider how change will affect the organisation. Operate in the world 'as-is', not the world as you would like it to be.
Value Variety	Embrace ideas from all levels of the organisation (not just those in positions of influence). Measure success on a portfolio basis. Encourage experiment on a small scale experiments and do not punish those behind failed experiments. Recognise that variety is insurance against vulnerability and can support continual adaptation of your organisational strategy.
Liberate Resources	Do not overcommit resources to just one strategy. If an existing strategy appears not to be working, recognise that costs already sunk on that strategy are lost. Make resources available to a portfolio of strategies to increase organisational adaptability.
Embrace Paradox	Recognise that the long term value of systematic exploration of strategic options is as valuable or more valuable than maximising short term efficiency. Recognise that you will get the behaviour you reward, therefore structure your organisational values and remuneration strategy with resilience objectives in mind.
	Source: adapted from Hamel and Valikangas (2003)

6 Conclusion

The resilience perspectives presented here share much common ground. The key messages at the front this paper summarise some key points for infrastructure practitioners interested in resilience.

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