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Case Study extract from:

'The Intelligent Nation: How to Organise a Country'

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Resilient Infrastructure Systems: Dr. Tom Dolan, UKCRIC

> *Any country that fails to prioritise the systemic resilience of its national system of infrastructure networks (SIN) will regret it: 'Maybe not today, maybe not tomorrow, but soon'. (Casablanca, adapted)*

All aspects of modern societies, including quality of life, social cohesion and economic prosperity and productivity are emergent outcomes enabled either directly or indirectly by National Infrastructure systems. National Infrastructure produces infrastructure products and services (IP&S) to power, heat, cool, hydrate, connect, mobilise and sanitise the society it serves; and to enable the movement of food, people, goods, services and ideas within and between societies. National Infrastructure makes possible the operation of social infrastructure facilities and provision of social infrastructure services. Moreover, National Infrastructure catalyses societal and economic multiplier effects by enabling a range of social and economic activity that simply could not occur in its absence and has the potential to facilitate the long term, sustainable, equitable, affordable realisation of the societally beneficial infrastructure enabled outcomes (IEO). The purpose of National Infrastructure is to enable the outcomes expected by the citizens and society it serves.

National Infrastructure (SIN) cannot effectively fulfil its purpose unless it is systemically resilient. National Infrastructure with a low level of systemic resilience is susceptible to disruption with greater frequency, on a larger scale, with higher intensity and for longer durations (Table 1) than National Infrqastructure with higher levels of Resilience.

National Infrastructure with low resilience jeopardises realisation of all other strategic objectives. In the long term, any Nation enabled by National Infrastructure with low resilience is at risk of initiating a downward spiral in which the cumulative impacts of disruptions to National Infrastructure undermine quality of life, reduce productivity and GDP, damage industry and investor confidence, impairing tax revenues and international competitiveness, channelling national resources into responsive expenditure.

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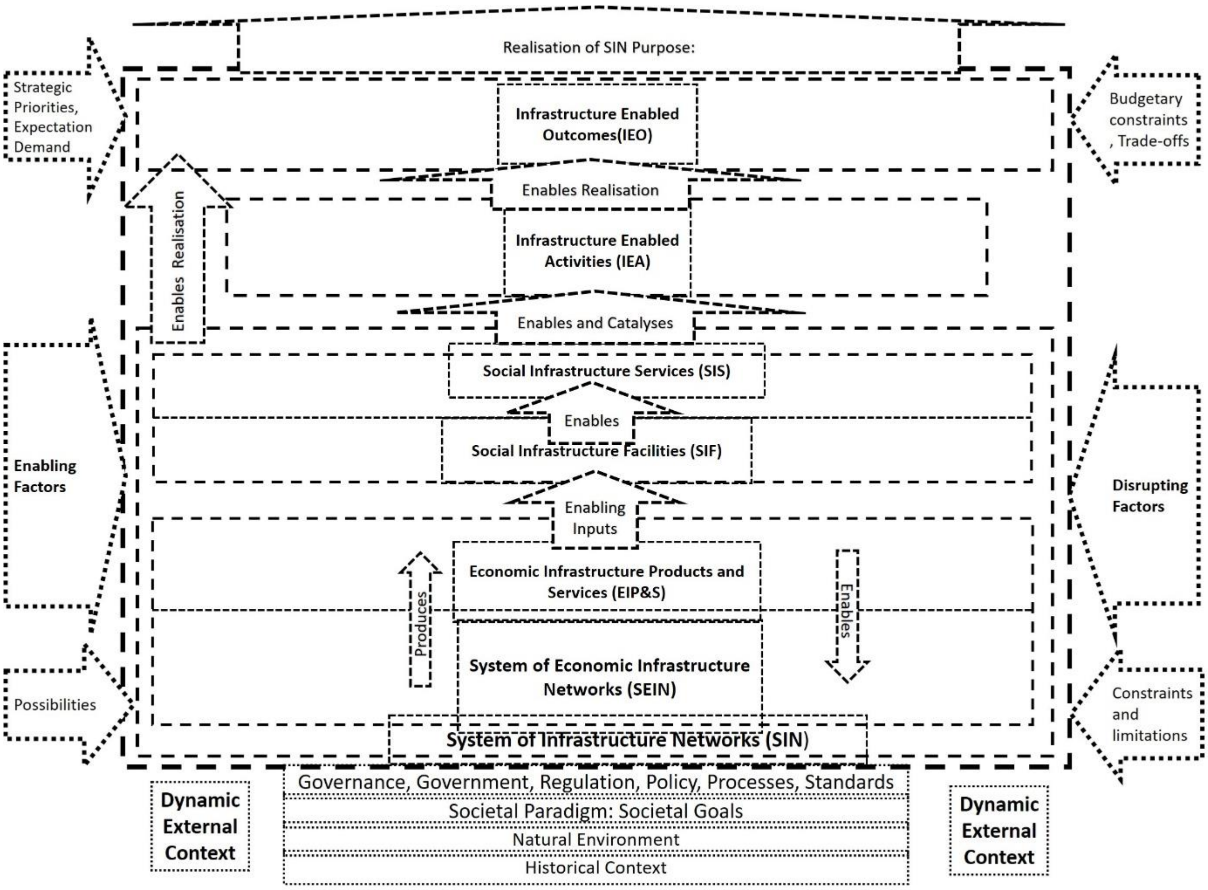

Figure 1. National Infrastructure in Context

Table 1. Overview of Disruption Dimensions

Dimensions	Description
Frequency of disruption	How often disruptive impacts cascade via interdependent related disruption across the SoI
Scale of disruption	The extent to which disruptive impacts cascade via interdependent related disruption across the SoI
Intensity of disruption	The speed at which disruptive impacts cascade via interdependent related disruption across the SoI
Duration of disruption	The length of time which performance of the SoI remains below pre-disruption levels

The Normal operations of National Infrastructure are enabled, constrained and co-evolve in response to the dynamic external context (DEC) within which it is embedded. Any Strategic challenge that disrupts the flow of enabling factors from the DEC, therefore has the potential to disrupt the normal operations of National Infrastructure. The impact of which will affect all levels of Figure 1.

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National Infrastructure is a complex interdependent system of Infrastructure Networks (the SIN). A sub-system of Economic Infrastructure Networks (the EIN) at its core enable it to fulfil its purpose. These EIN is a sub-system, enabled by a predictable flow of Enabling Factors, e.g. supply chain, people, logistics, technology, a stable environment, natural capital and the whole of the enabling eco-system. It is comprised of:

- *Physical infrastructure, Governance structures, management and Regulatory frameworks,*
- *Strategic priorities associated with the Economic Infrastructure Networks (EIN)*
- *Multiple Interdependencies*
    - *Interdependencies within individual Economic Infrastructure Networks (EIN)*
    - *Interdependencies between the elements of the EIN*
    - *Interdependencies between the EIN and the DEC*

The normal operation of the EIN both depends upon and produces a predictable flow of infrastructure products and services. Together, the EIN and the flow of IP&S it produces, enable cascade benefits across all levels of Figure 1, these include:

- *Social Infrastructure Facilities (SIF) and Services (SIS)*
- *Wider economic and societal activity (IEA)*
- *Societally beneficial outcomes (IEO)*

Therefore, any form of disruption to the normal operations of the EIN that reduces production of one or more IP&S has the potential to initiate interdependence related disruption (Table 2) both within and beyond the EIN.

Table 2. Overview of Interdependence Terminology

Concept (source)	Interpretation
Single Point of Failure	A disruption to a single system component
Interdependence Related Disruption (IRD) (Rinaldi, 2001)	A disruption to multiple system components that is propagated between system components through interdependencies present in a system. Three forms of IRD
IRD type 1: Cascade Failure	A form of IRD that is initiated by disruption to a single system component and propagates across the system through interdependencies between system components.
IRD type 2: Common Cause Failure	A form of IRD in which multiple system components are disrupted independently by a common cause, initiating multiple initially independent cascade failures
IRD type 3: Escalating failure	A form of IRD in which a Cascade or common cause failure either occurs, or occurs with greater scale and intensity because the system components disrupted are already operating under stress, or latent vulnerabilities are present in the system
Normal or System Accident (Perrow, 1999)	Terms equivalent to Interdependence related disruption
Ecosystem Accident (Perrow, 1999)	A useful extension to the concept of interdependence related disruption (IRD) that explicitly acknowledges that IRD can be initiated or propagated by interdependencies between system components and the dynamic external context (DEC) in which a system operates
High Risk System (Perrow, 1999)	A system in which IRD/ normal /system accidents are inevitable because components are tightly coupled and interdependent in a complex myriad of way
Incertitude (Stirling, 2010)	A term emphasising that four distinct types of incomplete knowledge (Risk, Uncertainty, Ambiguity and ignorance) can be present in a system and each must be managed different. As system complexity increases ambiguity or ignorance become the more likely forms of incertitude.

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Systemic Resilience Overview

Systemic Resilience is a dynamic, emergent and intrinsic characteristic of a system. It encompasses the degree to which any system is able to reduce the frequency, scale, speed, and duration (Table 1.) of the disruptive impacts (Table 2) initiated by Strategic challenges.

Dolan (2017) gives a brief overview of a number of useful conceptual models of resilience, two of which (Table 3 and Figure 2) are introduced below:

The resilience construct shown in Figure 2 emphasises that resilience is multi-faceted requiring continuous and adaptive strategic management of short-term (people, plans, processes, and procedures) and long-term factors (life cycle asset management, asset design changes, alternative modes of delivery via new technologies).

The intrinsic capabilities of a resilient system (Table 3) are emergent characteristics of a highly resilient system. In any complex system, the less developed these capabilities the lower the systemic resilience to disruptive impacts. To develop, sustain and enhance these capabilities requires long term strategic commitment.

Table 3. Resilient System Capabilities (from Hollnagel, 2014)

Ability	Description
The ability to address the actual (respond)	Knowing what to do. How to respond to regular and irregular disruptions and disturbances either by adopting a prepared set of responses or by adjusting normal functioning.
The ability to address the critical (monitor)	Knowing what to look for. How to monitor what is or can become a threat in the near future. The monitoring must cover both events in the environment and the performance of the system.
The ability to address the factual (learn)	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 (anticipate)	Knowing what to expect. How to anticipate developments, threats, and opportunities further into the future, such as potential changes, disruptions, pressures and their consequences.

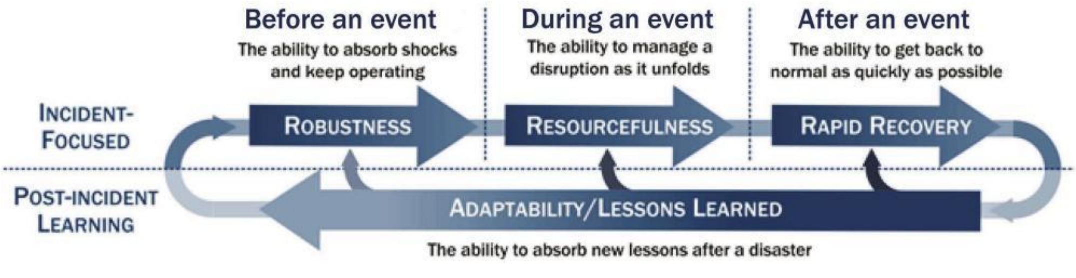

Figure 2. The Resilience Construct (from Berkeley and Wallace, 2010)

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Strategic Challenges and Systemic Resilience

National prosperity is enabled by fit for purpose National Infrastructure. Sustained prosperity requires National Infrastructure that is systemically resilient to the disruptive impacts of strategic challenges (i.e. actions, events, decisions or trends with the potential to disrupt the normal operation of any part of National Infrastructure). Strategic challenges can arise from outside the System (Exogenous disruptors) or from within the system (Endogenous disruptors).

Exogenous disruptors can take effect through one or more of the following mechanisms:

- *adversely affecting the flow of one or more enabling factors*
- *causing direct physical damage or disruption to one or more system components*
- *causing rapid or fluctuating short-term demand change*
- *increasing the frequency of operation beyond design thresholds with increasing likelihood of an individual component failure*

Endogenous disruptors are actions, events, decisions or trends within the EIN that:

- *Change the likelihood of an initial single point, or cascade, failure occurring*
- *Increase the number, frequency and criticality of interdependencies*
- *Alter the relative criticality of individual components*
- *Results in the system operating outside of design specification for increased periods*
- *Removes spare capacity*
- *Optimise the system to inappropriate criteria*

Specific examples of Strategic Challenges include global warming, malicious actions, accidental disruption and numerous other factors inherent in the system itself or the surrounding social, economic, political and physical environment.

Nurturing a Systemically Resilient SIN

To create and sustain the systemic conditions required for the emergence, growth and sustaining of a systemically resilient National system of infrastructure networks (SIN) requires:

- *Policy, Governance, regulatory frameworks, and management/decision making processes for National Infrastructure to be defined for the SIN as a whole and systemically aligned;*
- *The Systemic resilience of National Infrastructure as a whole to be an explicitly stated strategic priority;*
- *In-depth systemic understanding of all levels of Figure 1, and the interdependencies between them.*
- *A set of long-term collaborative commitments at all stages of the resilience cycle to prioritise actions that develop, sustain and enhance the intrinsic characteristics of a resilient system and to avoid actions that reduce systemic resilience*
- *A collaborative, dynamic, multifaceted portfolio of systemically targeted interventions:*

- *Collaborative because systemic resilience cannot be achieved by a single organisation in isolation, and interventions need to be targeted at addressing the root causes of systemic vulnerabilities*
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- *Dynamic because systemic resilience requires continuous action, monitoring review and adaptation to ensure interventions are fit for purpose and sufficient in scope*
- *Multi-faceted to avoid overdependence on any single intervention or intervention type*
- *Systemically targeted to address the root causes of low systemic resilience, intervene at the most effective points in the system, with the most effective intervention types, at the most appropriate time.*