Connected

Interdependencies Analysis in Complex Systems

Author: Tom Dolan, UKCRIC Senior Research Fellow, University College London

Interdependencies Analysis in Complex Systems

National infrastructure underpins all supply chains, and provides the foundations for all other social and economic activity. Infrastructure systems also make possible societal and economic outcomes simply not possible in its absence, or when infrastructure is disrupted.

National infrastructure is a complex system enabled by interdependencies, and comprised of physical infrastructure; governance structures; and regulatory frameworks. These interdependencies occur within sectors, between sectors and with the external environment; and include interdependencies with the natural world.

All five economic infrastructure sectors shown in the systems map share at least one absolute and continuous interdependency with at least one other (Figure 1, below).

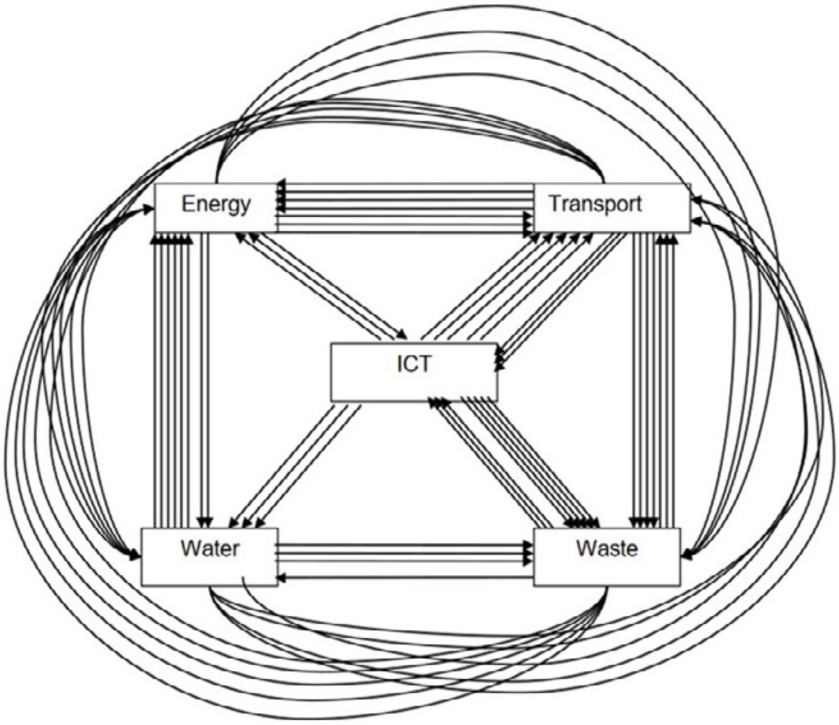

Figure 1: Five sectors systems map (Source: Beckford, 2013).

These interdependencies are fundamental to the normal operation of all national infrastructure systems. They must therefore be included in any characterisation of infrastructure systems [2].

However, a system enabled by interdependencies, is also intrinsically vulnerable to interdependence related disruptions (cascade, common cause, escalating failures) [3]. When one part of an infrastructure system is disrupted, it changes the contingent probability of failure elsewhere in the system, leading to knock-on impacts for all other interdependent parts of the system, notably:

- the flow of infrastructure products and services needed for the system as a whole to operate
- all economic and social activity enabled by the infrastructure system.

Thus, ultimately jeopardising the realisation of all other social, economic and political Priorities and objectives enabled by the system. Therefore, sustainable economic prosperity requires infrastructure systems that are resilient to the disruptive impacts of future resilience challenges [4].

Systemic resilience begins with in-depth understanding of the system of interest. This requires in-depth knowledge of the interdependencies that enable the system and there are a few tools for the identification, analysis, classification, and ultimately improved understanding of interdependencies.

Dependent or Interdependent

We first need to differentiate between the concepts of dependence and interdependence and demonstrate that infrastructure systems are complex interdependent systems. Rinaldi et al (2001) [3] in work linked to the 1998 Presidents Commission illustrated the difference using two system maps. Dependencies are one-way linear relationships between two entities. Figure 2 illustrates this with the system map depicting which critical national infrastructure sectors are dependent upon a flow of electric power from electric power infrastructure.

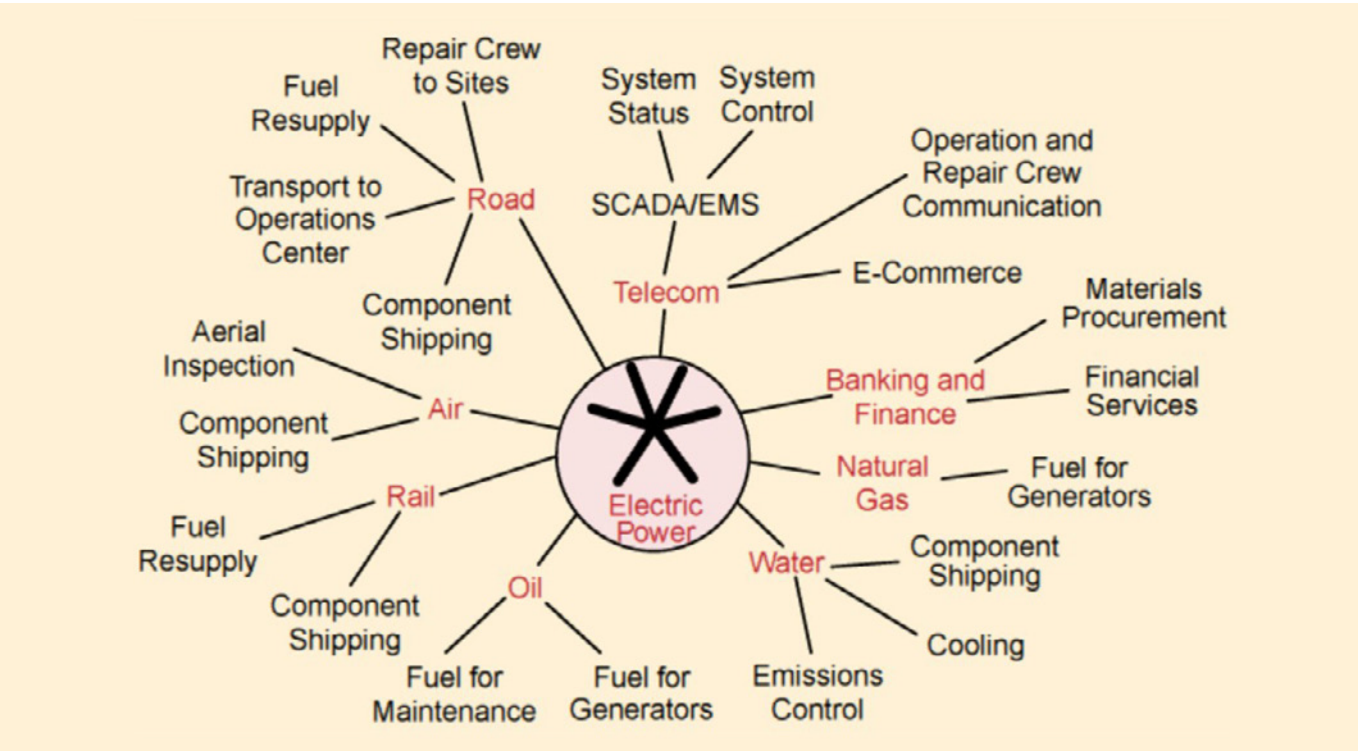

Figure 2: Examples of electric power infrastructure dependencies (Source: Rinaldi, 2001).

Those shown in red depend upon electric power, whilst those shown in black depend upon those shown in red. All depend on electric power. Interdependencies are two-way relationships. They can be a direct (first-order) mutually interdependent relationship between two entities, or an indirect (2nd – nth order) via one or more intermediaries.

Rinaldi et al (2001) illustrate this by mapping both the infrastructure sectors which electric power depends and those which depend upon electric power. In interdependent systems the emergence of feedback loops is inevitable.

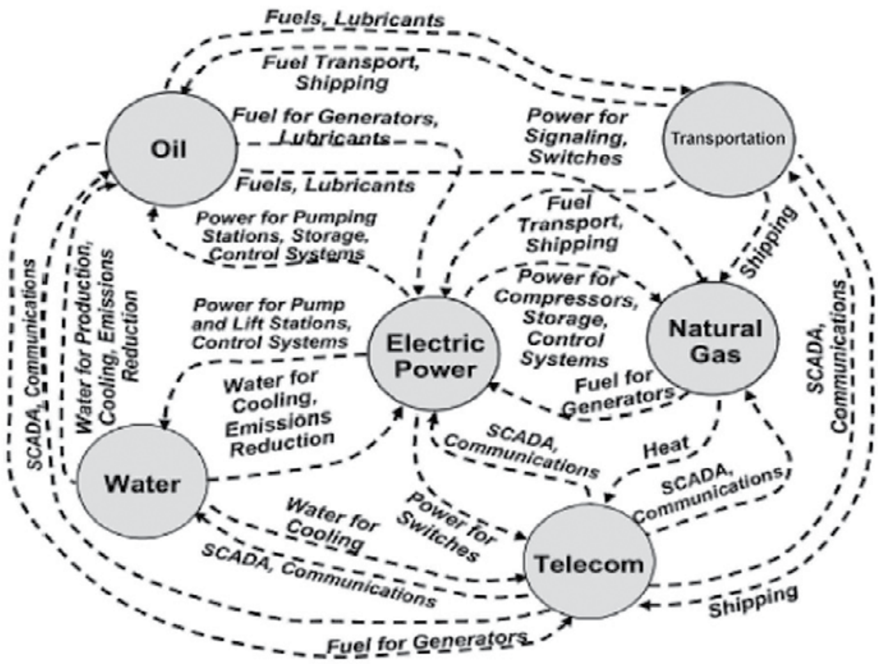

Figure 3: Examples of electric power infrastructure dependencies (Source: Rinaldi, 2001).

Six Dimensions of Interdependence

Recognising that interdependencies are not limited to physical flow between entities Rinaldi et al (2001) [3] identified six dimensions of interdependency.

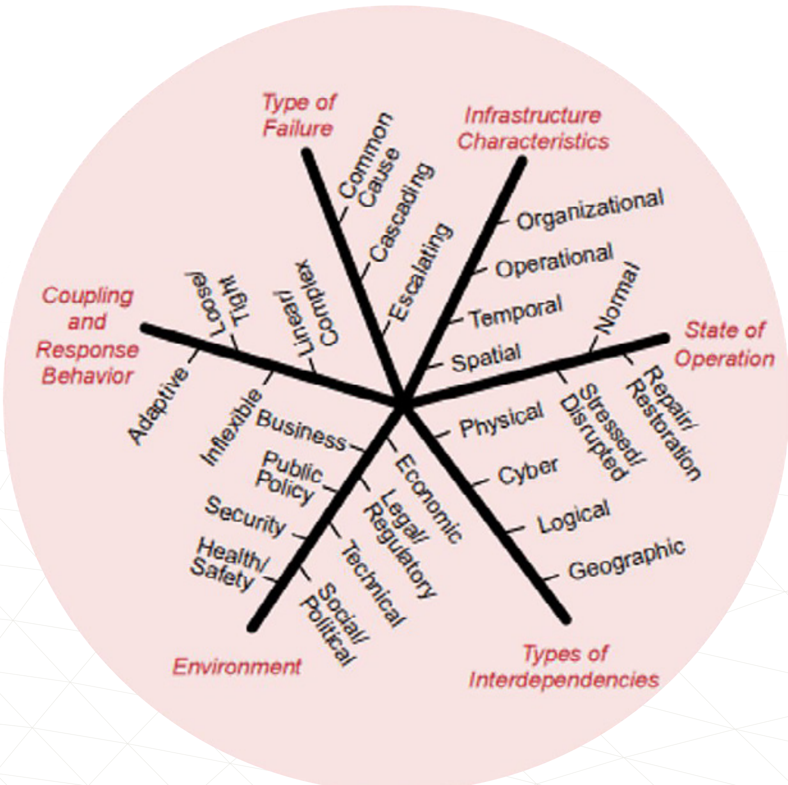

Figure 4: Six dimensions of interdependence (Source: Rinaldi, 2001).

Together these six dimensions provide a systemic framework which can be used as a lens to better understand emergent properties, system performance, systemic vulnerabilities and resilience.

It distinguishes four types of interdependence: Physical; Cyber; Logical; and Geographic. All interdependencies can be classified into one of these four groups. It also identifies three types of failure (or interdependent related disruption – IRD):

- **Cascade Failure:** Initial disruption to a single system component is spread system-wide via interdependencies between system components
- **Common Cause Failure:** Initial disruption to multiple system components initiates multiple initially independent cascade failures
- **Escalating Failure:** Where pre-existing disruptions, stresses and latent vulnerabilities, amplify likelihood, speed, scale and intensity of disruptive impacts.

Dimension: Type of Failure

Type	Description	Relative likelihood
Independent Disruption	Disruptive impacts are isolated to a single (points) of failure.	Low
Cascade Failure:	Initial disruption to a single system component is spread system-wide via interdependencies between system components	Medium
Common Cause Failure:	Initial disruption to multiple system components initiates multiple initially independent cascade failures	Medium
Escalating Failure:	Where pre-existing disruptions, stresses and latent vulnerabilities amplify likelihood, speed, scale and intensity of disruptive impacts.	High

These failure types are all propagated via interdependencies (hence IRD) and are distinct from independent disruptions isolated within a single system component.In a complex interdependent digitally enabled path dependent system, such as infrastructure, escalating failures will be the most prevalent.

It emphasises the importance of Coupling and Response Behaviours (tight or loose), complex interactivity (feedback loops) and the criticality of interdependencies.

It calls for knowledge of all PESTLE factors that comprise the environment in which a system operates and the society and economy it serves and enables.

It acknowledges that the risk of an IRD occurring in a system is contingent, upon the state of operations. Specifically, highlighting that a system operating under stress, and/or yet to fully recover from, or permanently degraded by, a previous disruption, and/or a system that is poorly maintained, are more likely to experience IRD than the same system operating under normal conditions Therefore, questions such as those listed below need to be considered when assessing interdependent risk.

- Are all parts of the system well maintained?
- Are any parts of the system operating under stress? E.g.
  - Outside of original design specification
  - Above design capacity
  - Beyond design life
  - At a higher level of criticality than originally intended
  - At temporarily reduced capacity
  - Operating in prevailing external (environmental, societal, and economic) conditions not envisioned when commissioned
- Have all parts of the system fully recovered from recent disruptive events?
- Have previous disruptions permanently degraded operating capacity?

It highlights four drivers of infrastructure characteristics (organisational, operational, spatial and temporal), that contribute to the unique complexity of every infrastructure system.

Approaches to Interdependence Analysis

Interdependencies can be analysed against criteria related to the six interdependencies dimensions in a number of in a number of ways. For example, the systems mapping techniques used by Rinaldi et al. [3], and by my UKCRIC colleague Prof John Beckford [1].

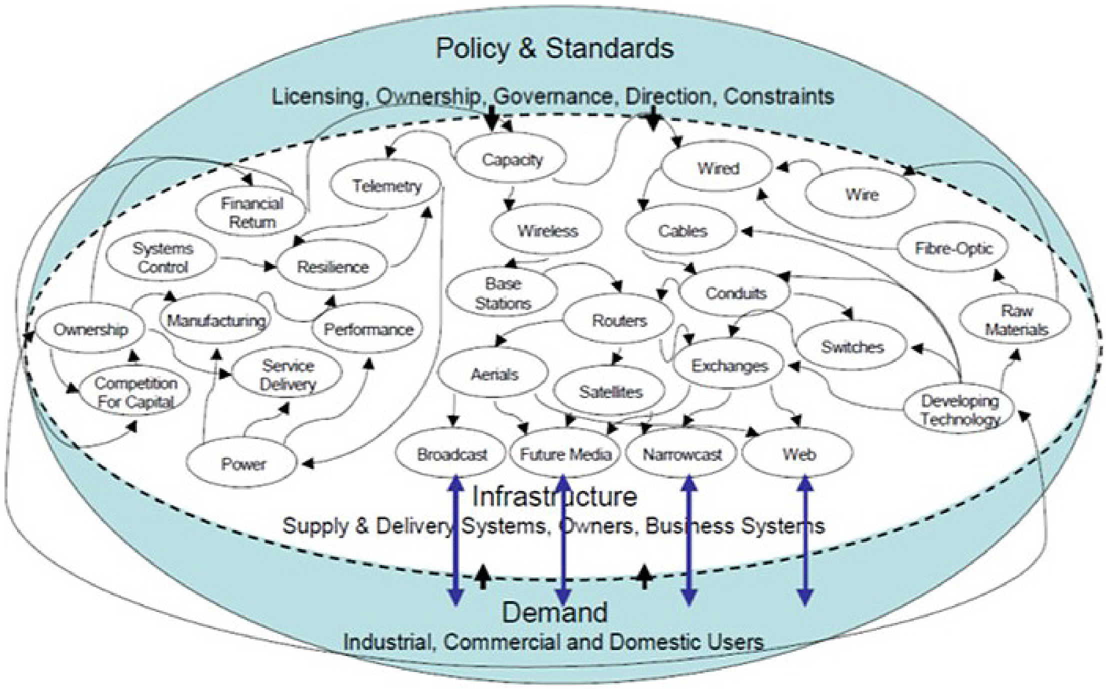

Figure 5: Example of Systemic Interdependency Mapping for ICT Infrastructure

The N-squared matrix was used by my ICIF colleagues when developing an Interdependency Planning and Management Framework for HM Treasury [5] [6] and when partnering with RAEng and ICE on the Engineering the Future Report [7].

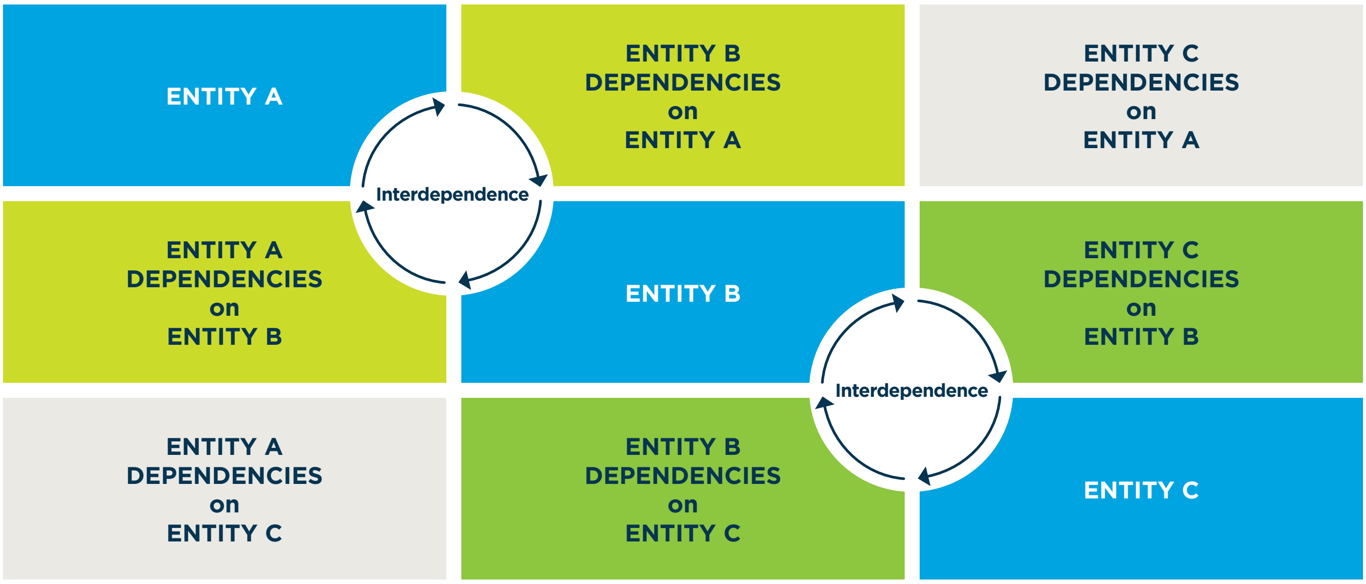

Figure 6: The N-squared matrix (Source: adapted from [5], [7] and [12])

In the N-squared matrix the diagonal specifies the entities between which interdependencies are being analysed.

For each entity the vertical column captures the dependencies an entity has upon other entities; whereas the horizontal row captures the dependencies other entities have upon the entity of interest. The example shown below is adapted from the Engineering the Future Report [7]. It illustrates application of the N-squared matrix to identify interdependencies between five economic infrastructure sectors. A fully populated matrix from 2013 is available in the report [7].

ENERGY	ICT DEPENDENCIES on ENERGY	TRANSPORT DEPENDENCIES on ENERGY	WASTE DEPENDENCIES on ENERGY	WATER DEPENDENCIES on ENERGY
ENERGY DEPENDENCIES on ICT	ICT	TRANSPORT DEPENDENCIES on ICT	WASTE DEPENDENCIES on ICT	WATER DEPENDENCIES on ICT
ENERGY DEPENDENCIES on TRANSPORT	ICT DEPENDENCIES on TRANSPORT	TRANSPORT	WASTE DEPENDENCIES on TRANSPORT	WATER DEPENDENCIES on TRANSPORT
ENERGY DEPENDENCIES on WASTE	ICT DEPENDENCIES on WASTE	TRANSPORT DEPENDENCIES On WASTE	WASTE	WATER DEPENDENCIES on WASTE
ENERGY DEPENDENCIES on WATER	ICT DEPENDENCIES on WATER	TRANSPORT DEPENDENCIES on WATER	WASTE DEPENDENCIES On WATER	WATER

Figure 6: the N-squared matrix applied to interdependencies between 5 economic infrastructure sectors (Source: adapted from [5], [7] and [12])

Moreover, the N-squared matrix can easily be applied to identify the dependencies and interdependencies between any entities of interest (parts, components, assets, sub-systems, systems, networks, processes, organisations, sectors, stakeholder groups, policy options, strategic priorities) that taken together comprise a complex system.

Additionally, to ensure the analysis captures all types of interdependencies, consideration of the four interdependence types: physical, digital, geographic or organisational defined in [3] is recommended when populating the individual cells of the N-squared matrix.

Another approach is the Onion-skin diagram used by the GLA and London Resilience Forum as part of the AnyTown Project [8].

The AnyTown Interdependency Diagram

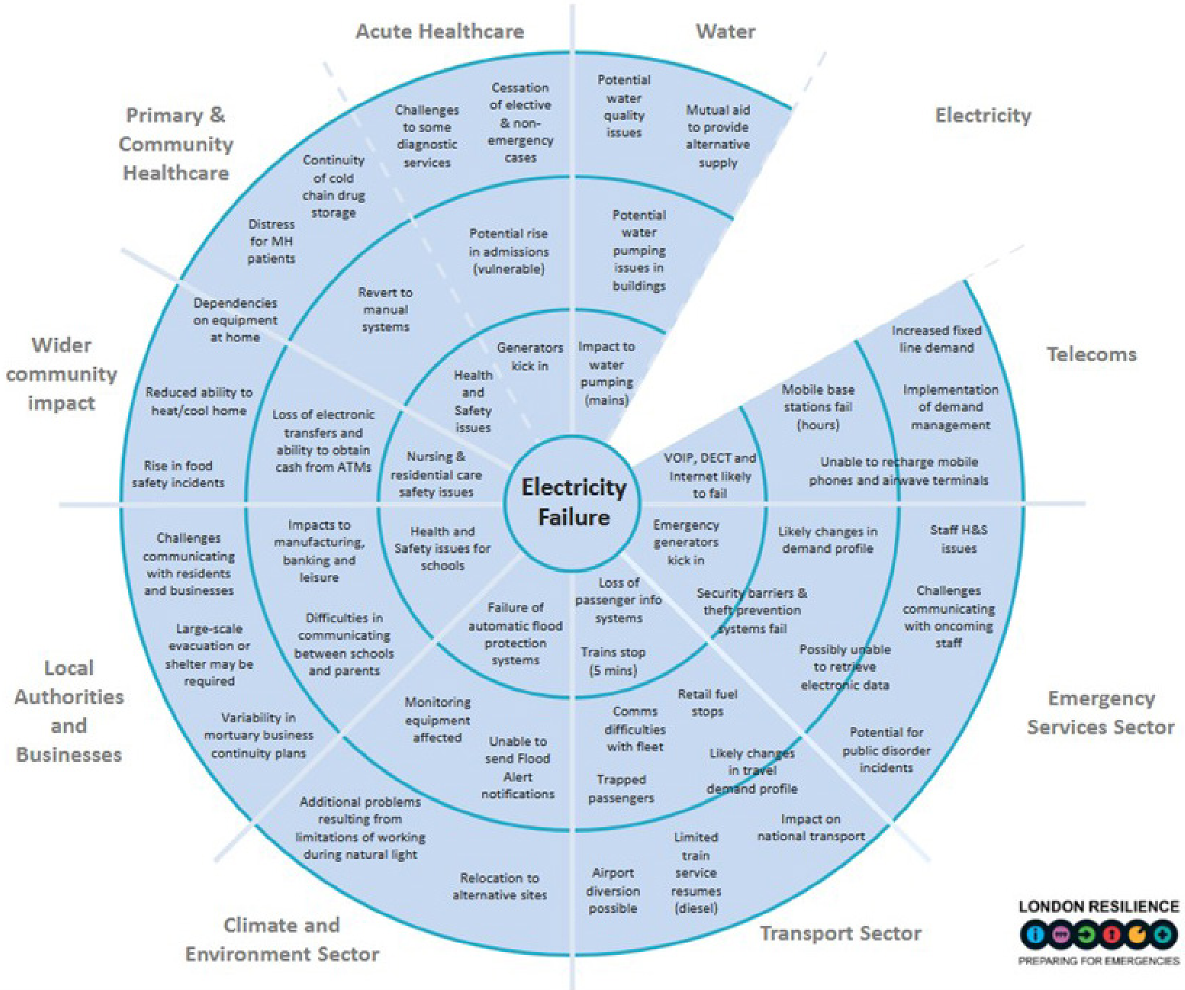

Figure 6: The AnyTown Interdependancy Diagram (Source: Hogan, M. (London Resilience Team, GLA)

This approach enables analysis of the impact of a failure in one sector (centre of diagram) upon the performance of other economic and social infrastructures, supply chain partners, institutions and customers (the segments).

Each concentric layer focuses on the cumulative impacts of longer time duration from the initial disruption. This is a particularly useful approach for identifying cascade failure risk scenarios. In addition to the above, focused on electricity failure, the Anytown project has produced similar diagrams for water, telecoms and gas failures [9].

These three techniques can offer complementary perspectives on the same system. For example, Figure 5 is a system map illustrating interdependencies between economic infrastructure sectors, whilst Figure 7 an n-squared matrix identifying the same thing.

Moreover, they can be applied at different system scales, to give a more holistic understanding of a system. For example, the N-squared matrix has been applied at a sectoral level by the IPMF team, RAEng and ICE in the report Engineering the Future [7]; and at a project level by the IPMF team for case studies on High Speed 2 (HS2) Phase Two [6] and The Lower Thames Crossing (LTC) [14]. It can also be applied at other system scales, for example to analyse interdependencies within and between global supply chains; societal and government priorities; grand challenges.

The HS2 Phase Two case study [6], applies interdependence mapping to enhance understanding of the potential systemic impacts of the project on the established economic infrastructure system into which the project is being added. It does this on a sector by sector basis, dividing each sector (ICT, Electricity, water, waste and transport) into sub-sectors to focus the analysis. Rosenberg and Carhart [12] identified 24 interdependencies between the project and other infrastructure sectors with the potential to enhance the core project proposal. Five of which were selected by participants for further examination. Using the High Speed 2 Phase Two corridor to provide:

- additional electricity distribution capacity into Sheffield and Manchester
- the capability for bulk water transfer between the north and the south
- the capability for inter-regional water transfer
- the capability for additional flood protection:
- additional capacity for the distribution of ICT infrastructure (e.g. fibre optic cables)

Thus, the case study demonstrates that interdependence analysis, at an early stage of the decision making cycle, can identify opportunities to amplify the positive systemic impacts and minimise the adverse systemic impacts, of new infrastructure projects, on an established infrastructure system. Therefore, helping to enhance the value proposition of any investment in a new project, or any other change to an established infrastructure system.

Closing Thoughts

Systems mapping, the n-squared matrix, and the AnyTown onion-skin diagram all involve collaborative workshops. They are inherently cross sectoral and interdisciplinary and are most effective if they draw upon a rich diversity of expert perspectives, experiences, worldviews and priorities, and bring together the multiple communities of interest from which those are drawn.

Relevant communities of interest are likely to include, but unlikely to be limited to: emergency services, government departments, infrastructure sectors, regulators, owners, operators, financiers, planners, policy makers and users. Economists, NGOs, community groups, and citizens.

In my experience, all approaches are as much about the process, experience, shared learning, assumptions challenged and connections created, as they are the production of a formal output. The process of implementation brings communities of interest together, gets them talking, gets them sharing perspectives and priorities. It helps to challenge erroneous assumptions, identify sources of misunderstanding, conflict and mistrust. It can help entrenched parties to climb down the ladder of inference, and replace mistrust and enmity with open dialogue on potential areas of common ground, identify opportunities for mutually beneficial collaborations to tackle shared challenges and build the trust needed to deliver synergistic outcomes.

They can also provide a robust evidence base for policymakers. Moreover, interdependence analysis can be used to: raise citizen awareness; identify cross sectoral research priorities; develop mutually beneficial action plans; identify knowledge exchange priorities; identify regulatory, policy, and government requirements; identify issues that currently fall between the gaps; identify perverse (counter-productive) actions and priorities; identify common desired outcomes, shared purposes and synergistic opportunities (systemic leverage points) for collaborative realisation of common purpose

Tom Dolan, UKCRIC Senior Research Fellow, C-DICE,
Postdoctoral Research Fellow, University College London

Additional Resources

In addition to the sources referenced during my presentation, the following may be of interest.

- **Briefing Note:** Interdependence analysis for systemically resilient infrastructure systems [10]
- **Report section:** Overview of Infrastructure Interdependencies Analysis [p26-40] [11]
- **Journal Paper:** Towards a Common Language of Infrastructure Interdependency [12]
- **Thought Leadership:** Successful Cities Need Resilient Infrastructure [13]

For more information on interdependencies and their identification please contact me or take a look at some of the links included in this document.

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