The Coherence Problem: Mapping the Theory and Delivery of Infrastructure Resilience Across Concept, Form, Function, and Experienced Value

Paul Jeffrey and Heather Smith
School of Applied Sciences, Cranfield University, UK

ABSTRACT

In this contribution we explore the interface between the functional characteristics of infrastructures as artefacts and social need supplier. Specifically we are concerned with the ways in which infrastructure performance measures are articulated and assessed and whether there are incongruities between the technical and broader, social goals which infrastructure systems are intended to aspire to. Our analysis involves comparing and contrasting system design and performance metrics across the technical — social boundary, generating new insights for those tasked with the design and operation of networked infrastructures. The assessment delivered in the following sections is inherently interdisciplinary and cross-sectoral in nature, bringing thinking from the social and environmental sciences together with contributions from mathematics and engineering to offer a commentary which is relevant to all types of physical infrastructure.

Keywords: Infrastructure, Resilience, Multi-Disciplinary, Concept Coherence

SUBTITLE REQUIRED

Networked infrastructures are “material mediators between nature and the city” [1] and facilitate modern urban life. They channel and modulate flows of information, goods, wastes and people and yet their configurations and the relationships of those configurations to the viability of the services they provide over short and long time scales remain under-studied . Marked spatial differences exist both within and between cities in networked infrastructure characteristics such as network topology, connection intensity, processing capacities, user accessibility and redundancies. These characteristics will underpin the ability of infrastructural services to resist and persist in the face of short term, perhaps sudden shocks. They will also underpin the ease with which infrastructures can be altered to accommodate longer term changes in operating conditions, making some transition pathways more or less feasible, more or less costly, and more or less environmentally damaging.

However, many of the system level relationships between the physical characteristics of networked infrastructures and the socio-economic services which such networks provide are not well understood. This deficiency is particularly acute in the context of being able to ensure commensurability between the metrics we use to portray desirable features of networked infrastructure and those we use to express required service provision performance. The next generation of infrastructures will need to exhibit strong correlation between these two metrics.

1 Kaika, M. & Swyngedouw, E. (2000) Fetishizing the modern city: the phantasmagoria of urban technological networks. International Journal of Urban and Regional Research 24 (1), 120-138 p20.

In this contribution we explore the interface between the functional characteristics of infrastructures as artefacts and social need supplier. Specifically we are concerned with the ways in which infrastructure performance measures are articulated and assessed and whether there are incongruities between the technical and broader, social goals which infrastructure systems are intended to aspire to. Our analysis involves comparing and contrasting system design and performance metrics across the technical – social boundary, generating new insights for those tasked with the design and operation of networked infrastructures. The assessment delivered in the following sections is inherently interdisciplinary and cross-sectoral in nature, bringing thinking from the social and environmental sciences together with contributions from mathematics and engineering to offer a commentary which is relevant to all types of physical infrastructure.

We first turn to a wide (and still growing) body of literature which seeks to describe desirable systemic features of networked utility supply. Although the reader will doubtless be aware of much of the terminology used in these contributions, the detail is worth revisiting in light of the agenda set out above. The meanings we ascribe (see Table 1) are abstracted from a range of literature sources and are intended to communicate a consensual view of each descriptive term rather than offer an orthodox definition. It is worth noting that many of these concepts are synonymous with each other and their definitions are, or have been, contentious.

Table 1 : Standardized definitions of concepts

CONCEPT	GENERALISED DEFINITION
Resilience	The ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance).
Robustness	Strength or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function.
Flexibility	The ability of a system to respond to potential internal or external changes affecting its value delivery, in a timely and cost-effective manner.
Vulnerability	Vulnerability is the antonym to system robustness and resilience taken together, in the same way that risk and safety are opposite.
Reliability	The probability that a component or system will perform a required function for a given period of time under stated operating conditions.
Redundancy	The extent to which substitutable components or other units of analysis exist (active or as standby) and are capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality.

The terms presented in Table 1 pepper debate and dialogue on infrastructure policy and planning, offering a convenient language set with which to illustrate the relationships between form and function. They also proclaim a normative ambition; inferring that each feature needs to be either stimulated (e.g. resilience) or depressed (e.g. vulnerability). Leaving aside for one moment the alarming lack of scrutiny regarding whether these system features can be designed and managed to a level of finesse which secures long term societal benefit, the language of resilience has spawned a new perspective on the relationships between the social and economic security of our communities and the engineered systems which currently underpin their functioning. But a language with which to discuss new concepts is rarely sufficient (of itself) to catalyse change – particularly change in engineered systems. So how are we to analyse the current state of our infrastructure systems and design interventions which might improve their systemic behaviour to make them more robust or less vulnerable ? Turning the rather abstract and ambiguous promise of rhetoric into (confidently) actionable strategies requires the operationalization of the concepts listed in Table 1.

We next turn to a set of analytical approaches which uses the same language as that presented in Table 1 and which attempts to characterise, and oftentimes quantify, the extent or degree of robustness etc. in a networked system. Other methodologies are also adopted (for example simulation modelling) but we focus here on the use of graph theory as a convenient and, we would argue, representative example of attempts to measure desirable systemic infrastructure properties.

Graph theoretic approaches are based on a representation of a network as a series of nodes and vertices. Relatively simple rules can be used to describe the topology of relatively complex networks. The aim here has been to determine universal laws that govern the development and functionality of complex natural and technological networks. In the context of the physical infrastructure networks that underpin energy, transport, water etc. conveyance, it is the relationship between network configuration and service delivery in the face of planned or unplanned change which forms the focus of this work. For such large scale networks both simple and more advanced measures of node and vertex patterning can provide valuable indications of whole system fragility. For example, the identification and characterisation of scale free networks has been influential in understanding the relationships between connectivity and robustness (first reported in Nature by Albert *et. al.*, 2000[2]). Subsequent work[3] has explored the robustness of complex networks in terms of the relative impact of node failure for different network configurations.

Graph theory applications to physical infrastructures propose that an understanding of organized complexity is fundamental to our ability to understand, design, and operate next-generation infrastructure networks and identify potential incongruities in the measures used to characterise network parameters such as vulnerability and robustness. However, graph theoretic (like many complex system) approaches struggle to generate learning outcomes which can be turned in to reliable interventions. They help us understand phase transitions and critical phenomena rather than better predict the future behaviour of all system components (i.e. it supplies general lessons and heuristics rather than laws). The assumption of equivalence between graph and physical infrastructure network becomes eroded the closer the analysis gets to supporting intervention. For example, several of the assumptions needed to ensure the mathematical integrity of graphical analysis (e.g. that the network is located in a single plane) make little sense in terms of real networks. The other major challenge for this family of analytical approaches is that, unlike the rather generic and anonymous nature of nodes and vertices on a graph, engineered infrastructures are (i) often not homogenous in terms of the properties and behaviour of nodes and vertices, and (ii) deliver services and value to communities.

Indeed, there is an assumption in much of the technical literature that structure affects function and that network architecture can be used to analyze network stability, robustness, component failures, demand growth etc.. However, the type of functionality being referred to here is one level away from what we should be interested in. Stability and robustness are merely means to an end in terms of ensuring that out communities have sufficient and equitable access to energy, water etc..

Both abstract discussion of desirable system properties and the application of formal methods to scrutinise system properties have an improvement imperative at their heart. They both seek enhancement of service provision quality which, in the case of infrastructures, infers ‘better’ (more resilient / less vulnerable) energy, telecoms, water, energy etc. services. But what does this mean in terms of a tangible personal or collective experience of an infrastructure ? Do the concepts and metrics discussed above have meaning or significance for the customers of networked services …, and does it matter ?

We primarily experience engineered infrastructure as a service delivery mechanism – a form of conduit through, or by which, we obtain value and amenity in both sensory and economic forms. Consequently, service failures are both qualitative and quantitative and will have impacts beyond an immediate lack of X. It is the social, economic, and in some cases, life support functions which infrastructure provides that shape citizen attitudes towards service quality. These features of the experience of infrastructure create challenges for those charged with its planning and management;

- Secondary and tertiary forms of value are often difficult to identify and therefore difficult to incorporate into plans.
- Any degradation in levels of service (irrespective of cause or time to recovery) is considered as failure by those affected (and also by regulators).
- Those at the end of the pipe or wire are unlikely to value system flexibility, resilience etc. unless they are aware of what might have happened in the absence of such system characteristics.
- The financial, opportunity, and transition costs of instilling system resilience etc. (ultimately borne by citizens) will be critically compared with BAU scenarios, raising questions of (e.g.) how much redundancy or flexibility is needed / desired.

2 Albert, A., Jeong, H., and Barabási, A-L. (2000) Error and attack tolerance of complex networks. *Nature* 406, 378–482

3 Paul, G., Tanizawa, T., Havlin, S., and Stanley, H.E. (2004) Optimization of robustness of complex networks. The European Physical Journal B, 38(2):187:191, 2004.

We note that there is little published work which reports on public conceptions of resilience etc. and provides infrastructure system designers and managers with informed guidance on either suitable system features or acceptable costs. Significant research in this space is sparse although there are signs of recent and well presented engagement [4]. We are also a long way from understanding the extent to which attributes such as flexibility and redundancy might be sourced from the psychological and the social rather than from the engineered and the material. Such an agenda would need to engage with a wider appreciation of what an infrastructure is; one which encompasses both the utility supply medium, the organisations manage and regulate the medium, and the utility beneficiaries. Such agendas are gaining ground in other contexts but are not yet prominent in infrastructure studies.

To summarise, there are three levels of analysis which we argue drive debates around infrastructure provision; (i) abstract frameworks for thinking about the relationships between socio-technical system behaviour and long term societal prosperity, (ii) methodologies which attempt to capture these abstract features in formal descriptive or quantitative measures of the performance of the physical system and (iii) considerations of the relationship between infrastructures and the communities they serve. Although all three perspectives reflect laudable intent and are informed by similar ambitions, it is mistaken to assume that they are necessarily complementary. The disparity being alluded to here concerns a fundamental tension between form and function. To pose this concern as a query - does improving the design and operation of networked infrastructure using the metrics presented in Table 1 reliably deliver the benefits claimed for the related concepts in the abstract sense ? Does 'robustness' in a network configuration or materials properties sense correlate with 'robustness' in the sense of a system which is 'relatively insensitive to change from external pressure and which returns rapidly to some equilibrium state of functioning' ? In order to answer this question we need to be able to relate form (structure, configuration, physical properties) to function (e.g. service delivery).

Infrastructures as artifacts sit at the juncture of ambition and experience – they are a means for fulfilling the promise of universal access and a tool for rendering social value from spatial fragmentation. We argue that the interfaces between the three levels of analysis that we have described above need to be better understood if ambition is to be reliably turned into change on the ground. Specifically, the intellectual and methodological landscapes which shape how resilience, flexibility etc. are mapped between concept, form, function, and experienced value, deserve greater attention. This is not to demand consistency of semantic meaning or interpretation across all four components but rather to ensure that the interventions we adopt to promote resilience are true to the intended benefits of resilience as articulated when we speak of the attribute in more abstract terms. One suspects that simply asking the question (e.g. '*will this intervention bring about the …* ') at appropriate junctures would go some way towards delivering such assurance.

4 Moser, C., Stauffacher, M., Blumer, Y.B., and Scholz, R.W. (2014) From risk to vulnerability: the role of perceived adaptive capacity for the acceptance of contested infrastructure. Journal of Risk Research (in press)