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Infrastructure: opportunities from interdependencies

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Introduction

The recognition and treatment of interdependencies at all scales between infrastructure systems range from ignorance to full substitution under the current paradigm of treating interdependencies as vulnerabilities which might compromise infrastructure resilience[1–3]. Global interconnections have forced many infrastructure networks to function as a 'system of systems', which is at odds to their historical development and management as isolated industries and sectors. Efforts to understand the dynamics of this new complexity have remained predominantly focused on the risks and vulnerabilities presented by interdependencies between separate but functionally linked systems. This paper argues that interdependencies, that is dependencies outside the direct control of a product or service provider that are essential to the provision of the product or service, provide opportunities, from simple to integrative, which have the capacity to aid resilience and sustainable growth.

Methodology

Mixed methods have been used to collect both quantitative and qualitative data. Three approaches were used to collect data: literature review, workshops and expert panels and infrastructure and disaster event data for a region of the UK. Data analysis took a combined economics and environment perspective, identifying interdependency opportunities for which sustainable business models and reduced environmental impact were possible.

We take a complex systems' perspective which recognizes infrastructure systems as dynamical, inter-connected, and co-evolving. Using this perspective we look beyond the role of interdependencies as merely a source of risk and vulnerability to system service delivery, and explore opportunities for positive interdependencies at different levels of intensity and integration. We also consider fundamental principles of ecological systems, where complexity is generally accepted to facilitate rather than impede resilience, and investigate parallels with current and proposed infrastructure developments.

Findings

We propose a threefold typology by which interdependency opportunities can be classified and understood according to the intensity of their interconnection. Knowledge-based opportunities recognise the potential for understanding and expertise to improve standard practices when shared across industry and sectoral boundaries and applied in novel ways through collaborative efforts. Geographical/physical opportunities arise where multiple systems can benefit one another through infrastructure sharing practices, increasing efficiency through the identification and reduction of avoidable costs. Integrative opportunities represent the most tightly-coupled variety, where two systems are interconnected and interdependent through shared functioning.

Infrastructure systems have largely originated from a traditional systems engineering perspective, in which design principles are goal-oriented and deterministic; however, the complex and interdependent nature of modern global systems has forced the adoption of

more systematic perspectives[4]. Ecological systems exemplify ways in which complexity can build resilience rather than vulnerability, and as such their key principles of interdependence, cyclical flows, cooperation, flexibility, and diversity[5] are explored in the context of current and proposed infrastructure developments.

Examples of advantageous use of interdependencies were found to fit most combinations of ecological sustainability principles and type of opportunity. Current efforts to upgrade various infrastructures with smart technologies, enabling real-time feedbacks between information and functionality, represent integrative opportunities that build on interdependency, cooperation and flexibility[6]. By optimising information flows through the system about system functioning, both managers and end users may gain the ability to match supply to demand and maximise efficient behaviours. The ongoing transition toward circular economies to increase efficient and sustainable use of resources exemplifies the principle of cyclical flows[7], while also depending on cooperation between organisations and the exchange of knowledge as well as material flows. Partnership and cooperation are embedded in infrastructure sharing agreements in numerous sectors[8], which are already in wide use through arrangements such as common carriage, track sharing in rail transportation and local loop unbundling in telecommunications. Such cooperation is also practised and essential across multiple industries seeking to adapt to the risks and uncertainties presented by global climate change[9]. Flexibility is strongly linked to resilience and adaptability in the face of uncertain future risks, again with respect to climate change. Additionally, flexibility in infrastructure design, management and use can facilitate the delivery of novel services or the dramatic transformation of existing ones. This is particularly exemplified by the developing advent of autonomous vehicles in dense urban areas and their capability to alter social behaviours, lead to considerable net gains in system efficiency and reduce pollution[10]. Finally, diversity is important in the design of network topologies, as the inclusion of distributed and redundant pathways can prevent the breakdown of service delivery in the event of local node or link failures. Diversity is also exemplified in a different way by the electricity generation industry; both currently with electricity being derived from multiple fuel sources to reduce dependence on individual resources, and in anticipated future developments through the increased uptake of renewable sources and micro-scale generation and storage technologies[11–13]. The ability to generate electricity near its point of use will reduce demand on the overall network infrastructure, and a network of distributed power storage solutions will make the network more resilient to disturbances and aid in smoothing discrepancies in the relative timings of supply and demand.

Many of these examples begin with the sharing of knowledge and build upon their interconnections until highly complex and integrated systems emerge. Such systems must be designed and managed effectively, and risks must be adequately considered and mitigated. Our approach does not advocate that risks and vulnerabilities be ignored; rather, we argue, when a truly system-wide perspective is taken, both risks and opportunities become apparent. Currently a majority of research efforts focus on risk and vulnerability but ignore opportunity. By identifying and recognising the opportunities, however, current human-designed and built systems hold a great deal of potential for more effective functioning.

All of the above examples, either realised or planned for future development, represent economically viable ways in which infrastructure interdependencies can be exploited to produce benefits. These benefits can take a variety of forms; increasing the quality of services delivered, increasing the efficiency with which this is done, creating and delivering entirely new services to respond to shifts in demand, and fundamentally increasing the sustainability and resilience of the overall system of systems. All of these are relevant and

essential to the needs of modern infrastructure systems, when considering the uncertainties and risks associated with growing populations, anticipated and unanticipated changes in stakeholder demands, and global climate change.

Contribution and next steps

This paper raises awareness of the notion of opportunity from interdependency in contrast to most papers in the field of resilience, which treat interdependency as risk that needs controlling at some level, often through creation of back-up and temporary interventions[2,3]. The theoretical contribution is the tabulation and explanatory power of increasing interdependency opportunities, which have been derived from literature, experts, and data. It is a contrasting and complementary perspective to contemporary treatment of interdependency and re-affirms that interdependency has a hidden face of opportunity that has been recognised in some contexts but rarely made explicit[14–16]. It provides a structure by which to determine and assess the level of opportunity and is aligned to basic principles of system survivability. The contribution for practice is that it raises awareness of interdependencies and the possibilities of exploiting them for positive economic and environmental impact.

There is major potential for impact by further development of this contribution since opportunity from interdependency has largely been overlooked in the haste to control it. Applications are possible in all infrastructure systems, through translation of examples in one domain to another. For example, sharing in transport can also be applied to sharing in telecommunications. Future research is required to validate, extend and critique the levels of interdependency opportunity. It is possible that examining such opportunities will identify gaps in legislation and regulation but also opportunities to liberate existing legislation and regulation when opportunities are constrained.

Key words

Infrastructure, resilience, opportunity, complexity, business models

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