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Infrastructure Interdependencies: Opportunities from Complexity

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ABSTRACT

Infrastructure networks such as those for energy, transportation and telecommunication perform key functions for society. Although such systems have largely been developed and managed in isolation, infrastructure now functions as a 'system of systems', exhibiting complex interdependencies that can leave critical functions vulnerable to cascade failure. Consequently, research efforts and management strategies have focused on risks and negative aspects of complexity. This paper explores how interdependencies can be seen positively, representing opportunities to increase organisational resilience and sustainability. A typology is presented for classifying positive interdependencies, drawing on fundamental principles in ecology, and validated using case studies. Understanding opportunities from interdependency enables better understanding and management of infrastructure complexity, which in turn allows the use of this complexity to the advantage of society. Integrative thinking is necessary not only for mitigating risk, but for identifying innovations to make systems and organisations more sustainable and resilient.

Keywords: Complexity; infrastructure interdependency; resilience; sustainability; system-of-systems

INTRODUCTION

Infrastructure systems such as those concerned with water, energy and transportation networks perform functions critical to the health and well-being of society by facilitating essential flows of resources, services, and information (Rinaldi et al. 2001). Historically, such systems have largely been developed and managed in isolation from one another, evolving over decades or centuries in many cases as either public or private enterprises. Modern technologies and demands, however, have given rise to an unprecedented degree of complexity and interlinking between previously disparate networks. Infrastructure now functions as a ‘system of systems’, exhibiting complex adaptive behaviour and numerous interdependencies that can leave critical functions highly vulnerable to disturbances, particularly through exacerbating effects of this complexity such as cascade failure (Helbing 2013; Rinaldi et al. 2001; Vespignani 2010).

As a consequence of this, the majority of research efforts and management strategies addressing infrastructure interdependencies have been concerned with risk and vulnerability, placing a primary focus on the negative aspects of system complexity. Interdependency is seen predominantly, or in some cases solely, as a source of risk and uncertainty; Resource Dependence Theory even suggests that the core aim of many organisational decisions is to reduce or eliminate dependencies entirely (Hillman et al. 2009). Conversely, other perspectives argue that sustainability is only achievable when complexity is understood and harnessed rather than eliminated (Ostrom 2009). Understanding interdependency is not a new aim, but it has become increasingly fundamental to infrastructure systems if those systems are to be designed, managed and adapted in ways that will be resilient to future disturbances (Vespignani 2010). Broad challenges emerging from global climate change and population growth are forcing industries, governments and other decision-makers to adapt by reaching across conventional boundaries to share ideas and approaches in order to build resilience in the face of universal concerns (Bissell 2010; Department for Environment Food and Rural Affairs (UK) 2011; Jude et al. 2017; Street and Jude 2019). Further, an evidence gap has been identified around the need for new models and methods to understand the interdependencies present in infrastructure systems (Committee on Climate Change 2016; Guikema et al. 2015; Pederson et al. 2006).

Although risk identification and mitigation make up the majority of research and management efforts on infrastructure interdependencies, the systematic view that is necessary for such efforts can shed light on beneficial elements of these interdependencies as well. Examples exist where interdependencies have been exploited or proposed to enhance the delivery of essential services, or synergised to create entirely new services (Delucchi and Jacobson 2011; Pandit et al. 2015; Roelich et al. 2015), and climate change adaptation efforts frequently state the need for interdisciplinary collaboration (Department for Environment Food and Rural Affairs (UK) 2011; Jude et al. 2017; Street and Jude 2019). Where this has been done in practise, however, there has rarely been an explicit recognition of the positive role played by interdependency; yet in complex natural systems it is generally accepted that interdependency and complexity play key roles in enhancing the sustainability and resilience of the overall system (Capra 1996). Complexity is unavoidable in modern infrastructure systems, but it need not be solely a source of risk and concern. Recognising and adapting to the opportunities generated by this complexity represents a largely untapped potential for designing and building systems that answer the global challenges of sustainability, resilience and efficiency.

The aim of this paper is to illustrate and discuss the ways in which interdependencies in complex infrastructure systems may be viewed as opportunities for enhancing function, resilience and sustainability. To this end, a threefold typology is proposed for considering beneficial interdependencies based on their relative level of integration. Key principles of ecological systems are then discussed, as these represent systems whose complexity builds resilience rather than impedes it, and parallels are explored whereby infrastructure systems might learn from the behaviours and structures of natural systems in order to function more effectively. Finally, this framework is applied to several case studies to explore its use in practise and act as evidence in support of its validity. The perspective and associated typologies described here are presented as a useful tool for managers dealing with complex systems, empowering them to better understand and adapt to the ways in which interdependencies can be harnessed for positive results.

INFRASTRUCTURE INTERDEPENDENCIES

Many infrastructure systems have historically been developed in relative isolation from one another, driven by public interests to provide essential services or by private interests to forward a business case. Technological advancements, societal demand changes and evolving external drivers such as climate change and geopolitics have converged over time to drive adaptations in the purpose and behaviour of critical infrastructures. These systems have now grown interconnected and interdependent, forming a global ‘system of systems’ whose functionality is critical to the smooth functioning of society.

Rinaldi et al. (2001) defined *dependency* as a one-way linkage or flow of causality; whereas *interdependency* was used specifically for bidirectional relationships where two separate systems or nodes both exert influence on the other. The authors further proposed a typology for categorising infrastructure interdependencies according to their nature, which has subsequently been widely adopted by researchers. The framework consists of: physical linkages (where systems share a direct material connection), cyber linkages (where system state depends on information flow), geographic linkages (where systems are connected by spatial proximity) and logical linkages (where systems are interconnected in some other fashion). The existence of this typology has been beneficial in efforts to explore infrastructure interdependencies, as it provides a structured framework by which complex interconnections can be classified, understood and analysed (Chai et al. 2011; Johansson and Hassel 2010; Wu et al. 2016). More recent efforts by Carhart and Rosenberg (2016) have sought to expand upon the Rinaldi framework, proposing subdivisions to the category of logical linkages such as policy/procedural, societal, and economic interdependencies, as well as describing a framework of twelve variables by which interdependencies may be explicitly described and typified.

Given the critical nature of infrastructure systems, coupled with the uncertainties associated with complexity, the focus of most research on infrastructure interdependencies has been on the risks and vulnerabilities they represent. Infrastructure systems have largely been developed from a deterministic, goal-oriented systems engineering approach (Ottino 2004). The unpredictability of complex systems is at odds with this perspective; characteristics of complexity such as nonlinear relationships, threshold effects and emergent behaviours are perceived predominantly as threats to system stability and service delivery (Helbing 2013). Accordingly, most research conducted on infrastructure interdependencies has taken up this stance, viewing interdependency as a threat to be mitigated and protected against.

INTERDEPENDENCY AS OPPORTUNITY

Interdependencies have thus far been explored primarily as a negative force, especially in the context of infrastructure resilience, through the lens of the risks they represent through cascade failures and cross-network vulnerability (Bissell 2010; Chang et al. 2014; Chou and Tseng 2010; Helbing 2013; Santos et al. 2007; Vespignani 2010). Interdependency can, however, be Janusian in nature; representing opportunities as well as risks. In a 2013 workshop bringing together 25 infrastructure stakeholders from the energy, ICT, transportation, waste and water sectors and including representation from industry, academia and governance, a focus was placed on identifying beneficial interdependencies within and across sectors. Of 77 identified interdependencies, 87% intra-sector and 86% inter-sector linkages were categorised as having beneficial outcomes (Carhart and Rosenberg 2016). This result strongly suggests that the prevailing focus on interdependency solely as a risk factor is disproportionate and incomplete.

In order to better identify opportunities from interdependency, these opportunities may be organised into a typology depending on the nature and intensity of the interdependency in question. Previous typologies have been proposed by which infrastructure interdependencies can be broadly categorised and understood (Carhart and Rosenberg 2016; Ouyang 2014; Rinaldi et al. 2001); the aim here is not to replace or challenge these efforts, but rather to complement them by presenting a typology specifically targeted at the identification of beneficial opportunities arising from these interdependencies.

Simple opportunities

A ‘positive interdependency opportunity’ is defined here as an interdependent relationship between two or more elements in a complex system that benefits the resilience, sustainability, and/or efficiency of the system. It is possible that such relationships may also introduce threats to the system, but although these are briefly considered, the primary focus of this paper is to explore the positive opportunities that may emerge from complexity. On a basic level, the sharing of knowledge across network and organisational gaps can inform and improve good practice through exposure to new perspectives and procedures. What might represent standard approaches to ensure secure, efficient or robust design in one system may be novel and applicable to another where such approaches have not previously been explored. Here the opportunity to increase the efficiency and resilience of systems is primarily a matter of establishing lines of effective communication and collaboration between managers, designers and operators that cross traditional departmental or industry boundaries. While a one-time learning event does not itself represent an interdependency, many interdependency-based opportunities begin with the sharing of ideas (even within a single organisation such as to increase productivity or single-plant resilience) and develop from that basis. This knowledge exchange can then become a simple interdependency-based opportunity by establishing a transactional pathway for the recurring transfer of knowledge and information between system operators. These flows can be intermittent and non-critical to system functioning, thus representing comparatively low risk, but also exhibiting a lesser degree of opportunity than more substantial integrations. Simple interdependency-based opportunities are therefore defined as those based primarily on knowledge exchange between practitioners, representing a transactional flow of information that occurs intermittently but repeatedly, that are beneficial but not critical to the operation of the coupled systems.

Geographic/physical opportunities

The physical co-location of multiple infrastructure systems can present opportunities for cost-saving and increasing system efficiency. This represents essentially an expansion of infrastructure sharing concepts to specifically consider sharing across multiple networks and sectors. The placement of mobile phone network antennae on tall buildings or pre-existing telecommunications masts precludes the need to build independent structures. Technologies to store energy at the point of generation, especially in remote examples such as offshore wind farms and wave-based power generation systems, can use combined structures to reduce building costs and the necessary length of new transmission networks (Li and DeCarolis 2015). It should be noted that such geographic co-location, like most interdependencies, can introduce threats as well as opportunities in cases of localised disturbance or damage; however, it is the opportunities that have a greater tendency to be overlooked. Similarly, the establishment of power generation and storage technologies at the point of use, such as with residential solar roof panels and home storage batteries currently under development, can also represent a reduction in the loading demands of the transmission network. Such decentralisation can support a considerable increase in system resilience, freeing end users from sole dependence on a centralised system should a failure occur. Geographic/physical interdependency-based opportunities represent beneficial couplings based on co-location and/or the physical sharing of infrastructure, material or information across systems at a localised scale.

Integrative opportunities

Within the functioning and management of the networks themselves, interdependencies can enable new opportunities for increasing resilience by applying the advantages offered by one network to the management of another. The concepts of ‘smart’ infrastructure and the ‘internet of things’, are fundamental examples of this. Data and information, gathered and distributed by telecommunications infrastructure, are used to actively and efficiently manage decisions and flows in networks of transport, water and power in real time (as opposed to simple opportunities where information flow is used solely to impart knowledge). Integrative interdependency-based opportunities are thus defined by a synergy and extensive functional interconnection between multiple infrastructure systems at multiple points, representing shared risk as well as significant benefits to the effective functioning of all coupled systems, and improving the delivery of existing services and/or making entirely new services possible.

New failure risks emerge if networks become wholly dependent upon the smooth operation of this synergy, so system design should seek to incorporate redundancy and ‘fall-back positions’ to allow individual systems to continue functioning if some breakdown occurs. Such systems should be designed with resilience in mind, and care should be taken to ensure that the transition to smart infrastructure does not occur blindly. An interconnected and interdependent network of networks will not be resilient if many connections are ‘tight’ and allow failures to cascade freely through the system, but designed redundancy and an ability to adapt and compensate for localised failures could greatly increase the resilience of such a complex system. Given future uncertainties around global climate change and population growth, such systems must be resilient and robust as the exact nature and intensity of future risks and pressures remain unknown. With fully integrated complex infrastructure systems, the risks are greater and thus must be recognised and managed effectively, but the potential opportunities are equally more transformative. The ability to design and manage resilient infrastructure systems depends on the ability to identify those cases where the opportunities outweigh the risks.

ECOLOGY AS AN EXEMPLAR OF RESILIENT INTERDEPENDENCY

Why nature is resilient

Natural ecosystems are commonly given as examples of complex, interconnected and resilient systems (Holling 1973; Standish et al. 2014), and as such may offer insight into how such systems can function effectively. Infrastructure systems are analogous to ecological systems in a number of ways: both being highly interconnected, complex and adaptive; both exhibiting characteristic scaling properties; and both relying on flows of material, information and energy (Pandit et al. 2015). In designing and managing infrastructure systems, there may be lessons to be learned and applied from ecosystems, which largely have evolved to be resilient to disturbance and sustainable within their environment. Myriad feedbacks and interdependencies between numerous species of organisms as well as energy and material flow systems act in nature to increase the resilience of the overall system, rather than merely introducing vulnerabilities. Material and energy flows are resilient in part by being fundamentally grounded in physical laws and chemical processes, but also by functioning in cyclical pathways whereby no material is ultimately wasted. At the system level, resilience is achieved through complexity, with the system possessing self-regulating behaviours and feedback relationships that maintain the stability of the system even in the face of disturbances (Capra 1996). At finer scales, organisms and species are resilient in many cases due to overlap and redundancy among ecological niches; rarely is a ‘role’ in the ecosystem filled by only a single species whose loss would destabilise the broader system through cascading effects.

How infrastructure differs from nature

By finding ways in which the relationships and principles found in nature can be applied to infrastructure systems, it may be possible to use complexity and interdependency to the advantage of society by designing in greater resilience and sustainability to global systems. Careful thought and translation will be required, however, as human-built and natural systems share fundamental differences despite their similarities, and are not perfect analogues to one another. Natural ecological systems have largely adapted and evolved to their current stable states through processes of random mutation, high attrition, emergent behaviours and incredibly long time scales in a 'bottom-up' manner. Anthropogenic systems on the other hand, and the societal concerns that drive them, are traditionally designed from a 'top-down' goal-oriented perspective and are generally unable to operate by such methods, being intolerant of such long time scales and resource expenditure. Further, many technological systems have necessarily been developed to operate in a highly controlled and deterministic manner (Pennock and Wade 2015) which is fundamentally at odds with the seemingly haphazard way in which natural systems emerge. Such determinism and reductionist thinking, however, encounters difficulty when considering larger systems, and complexity forces a more integrative and ecological perspective than that which was used to create the system's components and base functionality (Ottino 2004). This forced shift in perspective, from a system's creation based in reductionism and mechanistic design, to a systems approach that recognises and addresses complexity, interdependency and emergent properties, echoes the transition that has been seen in many disciplines over the past half-century. Examples of this include Jane Jacobs' pivotal call for fresh perspectives in urban studies (Jacobs 1961) and the steady rise of complexity science in ecology and biology (Capra 1996). Individual components and sub-systems are necessarily created with a deterministic perspective; however, at the system scale, human-created infrastructures must work to replicate by design and planning the efficiency and resilience that nature has developed by long-term experimentation. With the growing complexity of modern infrastructure systems, the need for building and measuring resilience has become increasingly recognised (Rehak et al. 2019).

How infrastructure can learn from nature

Despite the important differences between human and natural complex systems, commonalities exist where the functioning of nature can be applied as lessons for materials engineering (Fratzl 2007) and infrastructure design and management (Graedel 1996), enabling interdependencies to be viewed as opportunities. In his book 'The Web of Life,' Capra (1996) presents five principles of ecology and system survival and discusses ways in which these lessons can be applied to human society in the pursuit of sustainability. Here, it is considered how these principles can specifically be applied to infrastructure design and management (Table 1).

[INSERT TABLE 1 HERE]

The importance of Capra's first principle, *interdependence*, is already well-known in infrastructure contexts, but with focus usually placed on negative aspects as discussed previously. As in nature, there are also many ways in which these interdependencies can be exploited in a positive sense. This is explored through this paper's typology by which benefits can be realised through the exchange of knowledge and expertise (simple opportunities), infrastructure sharing and co-location (geographic/physical opportunities), and more complete interconnection (integrative opportunities). Smart metering of residential electricity consumption, for example, is growing in interest and uptake in various locations. This ability to provide consumers with detailed and timely feedback has the potential to inform purchasing and lifestyle decision-making toward more energy efficient behaviour, provided the feedback is adequately clear and informative (Fischer 2008).

The second principle, *cyclical flow*, is something that human systems have taken steps to transition toward but more progress is required to ensure sustainability and efficiency. The re-use and recycling of materials, reduction in avoidable waste, and engineering products for long-term use rather than disposability are all actions that will serve to increase sustainability at a society-wide scale. As organisations transition away from a solely competitive perspective and consider circular economies and industrial symbiosis, benefits become apparent for both the industrial community and long-term global sustainability (Chertow and Ehrenfeld 2012). This principle, in an infrastructure context, primarily concerns flows of materials and resources but is closely linked to, and dependent upon, partnership and cooperation between organisations and industries.

Partnership and cooperation are developing in many industries and sectors as interest grows in systemic thinking, conducting interdisciplinary research, and bridging gaps between sectors and networks that have previously operated independently. The realisation of the need for such cooperation has risen in part out of the recognition of the complexity and interdependence that is present in global human-created systems, as understanding such complexity requires information exchange and a coordination of efforts and approaches. At all three levels of interdependent opportunity (simple, geographical/physical and integrative), partnership and cooperation are required and, increasingly, becoming present. The exchange of knowledge and expertise between organisations has become commonplace in industries facing the broad and unifying goal of adapting to climate change, particularly where encouraged to address such long-term considerations by government reporting programmes (Jude et al. 2017; Street and Jude 2019). Infrastructure sharing approaches (variously referred to in terms such as common carriage, unbundling, track sharing, etc. depending upon industry context) represent geographic/physical opportunities already widely exploited by numerous industries to mutual economic benefit (Song et al. 2014). Efforts to develop smart networks and infrastructure for the efficient use of energy and routing of materials and transportation agents again represent a strong integrative opportunity being currently explored, both as a cooperative arrangement and as an interdependency as discussed previously.

Flexibility is a principle whose importance has been highlighted by the need for infrastructures and industries to adapt to the uncertain conditions caused by global climate change. Efforts to build resilience to future disturbances, the exact nature and intensity of which remain unknown, necessarily require a great deal of flexibility and capability to adapt to changing circumstances. Rigid infrastructures and networks that are optimised to remain functional only under a narrow set of external conditions will face a high risk of failure when subjected to circumstances outside of the conditions they were designed for such as extreme weather events. Systems that are able to adapt to these circumstances and focus on maintaining or improving their intended functions, not necessarily or solely by returning to their original state, will prove much more resilient to future disturbances. The possible ways in which driverless vehicles might transform and optimise the use of transportation infrastructure in major cities are an example of this flexibility. When coupled with car sharing and short-term rental business models, the resulting shared autonomous vehicles could cause a shift in personal transport from an owned asset to a shared service, with benefits to urban congestion, emissions-based pollution and manufacturing demand (Fagnant and Kockelman 2014).

Finally, the principle of *diversity* is exemplified clearly in nature by the multitude of species, functional groups and ecosystems that are observed; however its implementation in human systems can be one of the greatest challenges. In large infrastructure networks, it is recognised that redundant linkages play an important role in maintaining functionality should a part of the network fail or saturate. This redundancy thus offers diversity in the sense of multiple flow pathways through the network. However, beyond the mitigation of what is seen as immediate risk, excess redundancy may be viewed as wasteful by decision-makers and stakeholders if the benefit to resilience is not internalised. Conventional economic and industrial practices have also tended to favour mass production, historically providing a financial incentive to populate networks and systems with an overabundance of a single design or approach. In many cases this can be efficient, but in some this low diversity may represent a vulnerability should a failure prove specific to that design or approach. In recent years this has changed with the uptake of 'lean manufacturing' and agile production processes seeking to reduce waste while maximising efficiency and adaptability (Shah and Ward 2003). In the energy industry diversity is more embedded in sources of electrical generation, which provide some resilience to disturbances in the availability of fuel resources. Current research into battery technology and the possibility of distributed, mobile and/or residential electricity storage could also represent a diverse approach, smoothing temporal discrepancies between supply and demand (Yekini Suberu et al. 2014). Such ‘micro-storage’ approaches could provide backup sources of energy to increase resilience across the entire network, especially when coupled with distributed generation (e.g. residential photovoltaic roof panels) and managed using smart grid technology to optimise timing, costs, and social benefits (Kriett and Salani 2012; Vytelingum et al. 2010).

Understanding and analysing integrated infrastructure networks as holistic ‘systems of systems’, as one would an ecosystem, is the first essential step in moving beyond a traditional isolated and sectoral approach and enabling a complete understanding of system dynamics (Pandit et al. 2015; Rehak et al. 2016). When understood in this way, system-level optimisation and management for broad-reaching global interests become realistic possibilities. Further, such a perspective enables the recognition of commonalities that infrastructure networks can share with ecological networks (itself exemplifying a simple, knowledge-based opportunity), and the identification of shared typologies of interdependence. In understanding where and how nature benefits from interdependence, it is possible to adapt this understanding to human engineered systems and appreciate the ways in which they can benefit from complexity. If this understanding can then become incorporated into the business models of organisations and the strategies of managers, and thus directly embedded in the guiding principles of how industries operate and create value (Morris et al. 2005), sustainability and resilience may become much easier and more natural issues to tackle.

Barriers to and enablers of opportunity

Opportunities can be recognised or driven in numerous ways, but several specific areas may be considered from a Janusian perspective as either key barriers to or enablers of interdependency-based opportunity. First, existing *technology* can act as a limiting factor in the realisation of new innovations, but as it develops new opportunities may emerge that were previously unfeasible. This is evidenced in the growth of smart systems, renewable energy generation and increased efficiency in a variety of systems. Second, *design and innovation* play a key role in re-evaluating how systems can function more effectively, such as through the adoption of circular economic principles and the consideration of green and blue infrastructure. If design perspectives are resistant to new ideas and entrenched in conventional approaches this can impede and discourage innovation; however if creative thinking is encouraged and decision-makers are open to new ideas, this can enable opportunity from innovation. Third, how the *maintenance* of built systems is considered influences the efficiency and effectiveness with which they are managed, largely in terms of whether most maintenance activity is only reactive to faults or preventative and thus forward-looking. Fourth, *governance* can act as a considerable barrier to opportunity if regulatory structures rigidly enforce historic approaches and silos, but are equally capable of enabling opportunity through careful and informed consideration of how public policy, regulation and legislation can and should adapt to changing conditions. Finally, societal *behaviour* is fundamental in determining whether innovations will be met with resistance or acceptance, and is thus critical to the recognition and enabling of new opportunities through demand-side responses to service delivery and conscious awareness of the context and implications of consumer decisions.

Pervasive to all of these driving forces, opportunities become easier to recognise and exploit when a holistic, system-based perspective is adopted and perceived boundaries are expanded beyond convention. Opportunities for improving the functioning and resilience of critical infrastructures may even involve linkages with systems outside of critical infrastructure networks, as exhibited in some of the case studies explored below.

CASE STUDIES

The typologies laid out above provide a framework by which system interactions can be explored and understood in ways that can aid in the identification of opportunities. By applying this framework to a series of case studies, the opportunities that have been exploited can be categorised and explained. This helps to show how the framework can be used in future efforts to identify opportunities when multiple infrastructure systems connect. Further, this application to case studies supports the utility and validity of the framework for understanding the positive potential of interdependencies. The studies exhibit diversity not only in the systems they are concerned with, but in the approach they take to harnessing opportunities, the stage at which costs and savings factor in to the process, and whether they represent adaptive changes to or disruptive replacement of existing frameworks (Table 2).

[INSERT TABLE 2 HERE]

Case study: MK:Smart

The MK:Smart project is a collaborative initiative based in the town of Milton Keynes, UK (MK:Smart Consortium 2017). Much of the project centres on the creation and use of a 'Data Hub' where diverse information from a variety of city-wide infrastructure systems is acquired and stored (d'Aquin et al. 2015). The Data Hub presents opportunities for innovation around the ways in which the various datasets can be combined and used, and the project as a whole has enabled previously disparate systems to connect and benefit from one another. Several specific examples out of this project demonstrate the principles present in the framework.

The 'Motion Map' service involves the rollout of sensors across the city to track traffic flows and congestion in car parks and busses (Valdez et al. 2015). This information is intended to be pooled and distributed to local travellers via a mobile app, enabling informed decision-making and intelligent routing. Further, these and similar sensors can be mounted largely on existing lampposts, making use not only of pre-existing structures but the electrical supplies already present. New innovations, like 'BluePillar' systems combining street lamps, electric vehicle (EV) charging points and base transceiver stations provide an example of how such efforts can be integrated from the design stage (BluePillar 2016). In a related sense, the idea of using existing vehicles such as busses or taxis as mounting points for a city-wide sensor network to track traffic, air pollution, and other attributes has been put forward as a potential opportunity for infrastructure sharing and cost reduction (E. Motta, personal communication).

Data on electrical use, EV ownership and the presence of solar photovoltaic (PV) cells by the MK:Smart programme are being gathered and analysed with the intention of exploring potential synergies between electricity and transport systems (Bourgeois et al. 2015; Elbanhawy et al. 2016). The rise in EV ownership has the potential to increase demand on the urban electrical grid; however, an optimised management approach combining EV charging, distributed generation of renewable electrical power through residential PV infrastructure, and distributed electrical storage using residential battery technologies could not only offset these concerns but increase the resilience and sustainability of both the electrical and transport systems. Many home and transport energy demands would be met using renewable systems, and battery storage could correct for discrepancies in the relative timing of electrical supply and demand. The underlying technologies are still in the process of being developed and adopted by residential users, but data collected by MK:Smart are intended to help prepare for the management of such an interconnected system. When completed, this synergy would represent an interdependent opportunity at all three levels of information sharing, physical interlocking, and systemic integration, with many benefits to society.

The entire MK:Smart programme is built on the recognition of opportunities from interdependency that are present in a modern urban system. Simple opportunities underpin many of the interactions that contribute to the project, identifying ways in which historically disparate infrastructure systems can benefit one another through cooperation and idea sharing. The Motion Map service exemplifies this particularly by providing information on real-time transportation infrastructure status to residents to enable more informed decision-making. The use of existing infrastructure to mount and power the sensors also exhibits a clear geographical/physical opportunity through infrastructure sharing.

The integration of electrical use, EV charging and distributed power generation and storage provides a clear example of opportunity at all three levels. Information sharing is present in the rich flow of information between multiple systems and their collective management; geographical/physical opportunity is exploited in the co-location of EV charging points, electrical use and power generation; and the entire system-of-systems represents an integrative opportunity given the depth with which the various infrastructures interact with and benefit from one another. Finally, the Data Hub that underpins the entire MK:Smart programme is itself based on the recognition of previously untapped integrative opportunities that are present across the urban system. Possible weaknesses in the system are most evident in the form of small-scale localised damage taking out multiple network sensors, e.g. vehicle collision with a lamp post, and information security concerns where potentially sensitive data on users and systems across the city are stored in a single unified Data Hub. The combination of different technologies and approaches nevertheless enables the MK:Smart programme to span simple, geographical and integrative types of opportunities, while exhibiting ecological principles of interdependence, partnership, flexibility and diversity.

Case study: Milton Keynes linear floodplain parks

Another example from Milton Keynes, UK, concerns the co-consideration of flood prevention and ecosystem service provision (Varga 2016). The development of natural flood plains into managed linear parks has synergistic benefits. On one hand, the preservation of a natural character of stream channels slows the movement of water during peak flow periods through the use of semi-natural floodplain regions, reducing the risk of hazardous flooding both within the urban area and downstream from it. Concurrently, the presence of green space benefits urban residents through the delivery of ecosystem services such as recreation and well-being, as well as supporting ecological functioning by offering diverse and well-connected wildlife corridors. Such linear connectivity may further act to support city-wide wildlife biodiversity in ways that isolated land parcel-based parks may not (Grafius et al. 2017; Rosenfeld 2012).

While not directly concerning traditional critical infrastructure systems, this example importantly represents a way in which interdependent opportunistic thinking can include natural systems as well as anthropogenic ones. Like examples focused solely on built infrastructure, opportunities of this nature begin with simple knowledge exchange through the recognition of mutually beneficial efforts. Urban planners focused on flood risk mitigation and environmental officers focused on green infrastructure and biodiversity may not have many existing institutional incentives to collaborate with one another; however this example shows how doing so may benefit the goals of both. What begins as a knowledge sharing opportunity can identify geographic opportunities for these shared purposes, and ultimately support an arrangement where urban green infrastructure achieves multiple goals. Further, the use of floodplain lands for parks as opposed to residential development would in fact serve to reduce the threat of damage to personal property, only requiring comparatively inexpensive efforts to clean and repair parklands after flooding events. Here, both simple and geographical opportunities are present, along with ecological principles of partnership and diversity.

Case Study: circular resource model for urban agriculture

A study made use of a rooftop greenhouse in Barcelona, Spain to examine the benefits of a closed-loop hydroponic agricultural production system (Rufí-Salís et al. 2020). Water leaching from substrate bags and nutrients not assimilated by plants were recirculated into the system. The study was evaluated using a life cycle assessment to compare it against a more conventional linear agricultural system with no nutrient or water recovering. Two green bean crop cycles were measured for yield, climatic variables, and water and nutrient balances.

The closed-loop system notably accounted for daily savings of 40% for water, and between 30 and 55% for various nutrients. As some of these nutrients are linked to nonrenewable resources, and urban water security may be an area of growing concern, the importance these findings stands out. As studied in this case, the experimental closed system proved to be less environmentally efficient over its full life cycle due to receiving less radiation input than the linear system and thus requiring a longer time period to reach an equivalent total crop yield. Additionally, the relatively small production volumes coupled with the infrastructure costs associated with leachate recycling resulted in undesirably high environmental impacts. The authors propose that future efforts could mitigate this by using recycled materials in the creation of these systems. Although not presenting an immediately perfect model, the study nevertheless breaks new ground and demonstrates how circular resource flow can be used to make urban agricultural systems more efficient and less wasteful, especially with further research.

Although this example was unable to meet all its desired goals over its full life cycle, it represents a proof of concept that warrants further research and could present multiple benefits through the lowering of direct resource inputs and reduction in waste products. Cyclical flow is at the core of the endeavour, which resonates widely with various infrastructure-based attempts to move toward a more circular economy rather than a ‘take-make-dispose’ model (Bech et al. 2019). More broadly, the pursuit of urban agriculture has benefits in the production of food closer to points of demand, reducing monetary and environmental transport costs and making greater use of local resources that may otherwise be treated as waste, such as rain runoff (Al-Kodmany 2018). Urban agriculture faces many challenges to adoption, and its greatest introduced risks stem from uncertainties around its unexplored economics; however, the importance of its untapped potential is being increasingly recognised (Edmondson et al. 2020; Grafius et al. 2020). The opportunities in this case are geographical and integrative, and the main ecological principle is cyclical flow.

Case study: Olympic Park, London

The Olympic Park area in London was developed primarily to host the 2012 Summer Olympic Games, but with a particular focus on sustainability, responsible development, and the post-Games legacy of the site (LOCOG 2012; Naish and Mason 2014). In contrast to the developments for many past Olympic Games, the Olympic Park in London aimed to be developed as sustainably as possible and create a site that would continue to be used by residents for housing, recreation and events. Examples of specific goals involved the recycling of materials from demolished buildings cleared for site construction (99% of material waste from construction and decommissioning were re-used or recycled, exceeding 90% goal), delivery of new materials to the site primarily by water and rail, and the recycling of wastewater on site to reduce water demand. Permanent structures were engineered with legacy use in mind (e.g. the Olympic Village afterward being used as a residential community of 20-30,000 homes), while other event structures were constructed to be deliberately temporary when it was clear there would not be the demand to support their use after the Games. Visitors were encouraged to travel using rail rather than private vehicles through public transport planning and service upgrades (Fussey et al. 2016). The overarching management approach employed by the programme involved the public Olympic Delivery Authority (ODA) appointing CLM as the delivery partner; a private sector consortium made up of CH2M Hill, Laing O'Rourke, and Mace. These private companies brought experience and expertise in large-scale programme management and construction projects, and were granted the necessary latitude to deliver to targets effectively while ODA retained sufficient assurance and oversight of the broader programme. The importance of forming and retaining an effective relationship between ODA and CLM throughout the programme was known to be essential, so CLM remained integrated into the governance and delivery review meetings throughout the programme's life cycle; a true partner in the process rather than a 'fire and forget' subcontractor (Hone et al. 2011).

The overarching approach encompassing all of the varied goals involves a forward-looking and systematic perspective, recognising opportunities at all three levels from the planning stages. Emphasis was placed on the forming of partnerships, the sourcing of sustainable materials and their use in efficient and intelligent ways, interdisciplinary thinking, an awareness of interdependencies, and the balancing of multiple solutions for multiple objectives. As such, the London Olympic Park's development exemplifies positive interdependency at all levels; from simple opportunities (through interdisciplinary collaboration) to geographical and physical opportunity (through the use of local and recycled materials, circular resource flows and a focus on within-site sustainability) to full integration (through the adoption of a perspective truly focused on designing on-site systems to work together and synergise in as many ways as possible). Unlike many interdependency opportunities, the development also exemplifies a novel approach designed from its beginning to be integrative rather than being a retrofit of existing infrastructure. In so doing, it represents all three types of opportunities (simple, geographical and integrative) as well as ecological principles of interdependence, cyclical flow, partnership, flexibility, and diversity. Widely hailed as a success, the greatest weakness or threat demonstrated by the megaproject is most likely the considerable cost of the approaches it took, which would likely prove prohibitive to most smaller or less-supported developments.

Case study: The sewerless nano-membrane toilet prototype

Conventional sewer systems place heavy impacts on water availability and quality, energy, food and the environment. Poor sanitation resulting from inadequate or insufficient infrastructure can have massive impacts on human health. Modern sewerless sanitation efforts therefore seek to combat these impacts and provide a sustainable alternative to expensive centralised sewerage systems in developing countries, using modern technological advancements (Martin et al. 2015). Such decentralised sanitation systems are primarily concerned with the containment, immobilisation, or destruction of pathogens in human waste. Modern approaches vary by global context, but the Bill & Melinda Gates Foundation's 'Reinvent the toilet challenge' has been instrumental in driving a new generation of research into modular toilets that neutralise pathogens, recover water and nutrients, operate off grid, and are relevant in both low and high income countries. Although many of these systems remain in development, a fully self-contained toilet has the potential to eliminate the dependency on multiple infrastructure systems, greatly reducing risks to the environment and human health.

A major challenge faced by all designs is the separation of solid and liquid wastes, which the nano-membrane prototype accomplishes using silicon tubing and vaporisation of liquid wastes. Energy requirements of the system are then met by the combustion of dried solid residues, while vaporised liquids are condensed and recovered downstream, free of pathogens. CO2, NOx and SOx from the burning solids can be intercepted by a suite of adsorbents. Waste ash from the system will be microbiologically inert and thus can be safely disposed of alongside household waste (Martin et al. 2015).

The main environmental benefit of such a system is its water saving ability, whereas the lack of dependence on critical infrastructure systems would also represent a major economic and social benefit, particularly in rural areas of developing nations. As a prototype it remains difficult to currently assess threats or weaknesses of the system, but a driving principle of the project is reducing user dependency on unreliable or unavailable infrastructure systems, thus removing the potential threat of being denied them. At a broad scale, this prototype system thus appears to represent the elimination of interdependency rather than its exploitation; however at the scale of the individual unit, it is the recognition and deliberate integration of interdependencies between water, energy, health and the environment that drive the system’s design. In this way, the project exhibits an integrative opportunity, while demonstrating interdependence, cyclical flow, flexibility, and diversity as ecological principles.

Case study: Cornwall local energy market

A trial project is currently ongoing in Cornwall by Centrica to test a virtual local energy market that combines renewable distributed electricity generation, home battery storage technology, and a system of smart grid management using supply/demand adaptive pricing structures (Centrica 2017). Under the trial setup, timing discrepancies between the generation of renewable energy and the demand for it are balanced by the presence of home storage batteries, and managed by pricing structures that adapt to encourage participants to use or store power when supply is high, and reduce their use or sell stored power back to the grid when supply is low. The trial is currently ongoing so no final results are currently available at time of writing, but the study is anticipated to prove informative about management and implementation strategies for renewable energy, home power storage and local energy trading.

Like similar examples discussed previously, this locally-focused energy integration combines principles of sustainability and flexibility, reducing load on the national electrical grid and minimising the need for long-distance electrical transmission. The need for accurate real-time usage data in order to manage the system effectively represents a potential weakness in the event of a communications failure, but the distributed nature of the infrastructure introduces a level of geographic resilience not common to more traditional energy grids. The system does this by taking advantage of opportunities at all three levels of integration around the simple sharing of knowledge, the exploitation of geographically co-located resources, and the integrative linking of technologies with system-level optimisation and management. The ecological principles of interdependence, flexibility and diversity are also employed.

Case study: multi-use ocean platforms

Spurred by intergovernmental targets on sustainability and renewable energy production, interest has grown recently in the concept of ocean platforms to support multiple uses, especially combining wind and wave energy generation while in some cases also including aquaculture installations. The advantages of such platforms in shared costs, smoothed power output and combined construction and maintenance efforts make them an attractive proposition; however, their implementation currently faces barriers in the lack of unified governance and support, longer development times, uncertainties around insurance and risk, and the immaturity of important technologies in wave energy capture and local energy storage (Abhinav et al. 2020; Pérez-Collazo et al. 2015; Stuiver et al. 2016). For these reasons such platforms currently remain speculative and theoretical, but prototypes and exploratory case studies to optimise development approaches have been completed (Zanuttigh et al. 2015, 2016).

If constructed, multi-use platforms that combine different offshore infrastructures in a common area or structure would primarily represent the exploitation of a geographic opportunity, taking advantage of co-location to share structures, costs and logistics (Abhinav et al. 2020 (in press)). Co-location remains perhaps the most obvious double-edged sword, as it can represent infrastructure sharing opportunities as well as introducing threats in the event of localised disturbances. Additionally, the offshore nature of such platforms may make them more difficult, costly, or time-consuming to access for maintenance than onshore equivalents. As key energy technologies mature, however, these platforms could grow to represent more integrative opportunities as well through the synergy of different power generation and local storage approaches (Abhinav et al. 2020 (in press)). For now, such projects remain primarily geographical in the nature of their exhibited opportunities, making use of the ecological principles of interdependence, partnership, and flexibility.

Case study: The Kuala Lumpur SMART Tunnel

The Stormwater Management and Road Tunnel (SMART) project in Kuala Lumpur uses a combined approach to mitigate two separate but major problems faced by the city; traffic congestion and storm water management/flooding (Kim-Soon et al. 2016, 2017; Wallis 2004). The tunnel, completed in 2007, consists of a 9.7 km tunnel to divert water during flash flood events, 3 km of which is shared with a two-layer motorway constructed to alleviate traffic problems during peak times throughout the rest of the year. This unique shared use infrastructure is subject to a specially-designed maintenance and management scheme to assure continued fitness for both purposes, and has alleviated numerous potentially damaging flooding events since its completion.

The SMART Tunnel represents a novel case of co-location, recognising a geographic opportunity to alleviate two otherwise unrelated problems facing the city and integrating multiple systems to manage it. Again, this co-location makes the potential risk factors clear; damage to one use case would negatively impact the other, likely requiring repair before either could be fully restored. Nevertheless, under a conventional isolated approach to infrastructure design, such an ambitious and combined project would not have been possible; however, a systematic perspective and consideration of multiple objectives has allowed a shared opportunity to answer multiple needs. This project is thus an exemplar of a geographical opportunity, making use of the ecological principles of both partnership and flexibility.

CONCLUSIONS

Due to the way they have been historically developed, infrastructure systems traditionally tend to be silo-bound; built and managed in ways that discourage systemic thinking and treatment of interdependencies. Future efforts need to capture the 'system of systems' view and work across conventional disciplinary and organisational boundaries in order to plan and manage infrastructure systems in the wider context of one another and with regard to long-term benefits and risks to human well-being.

Where interdependencies are recognised, research, management and policy have largely remained focused on their negative aspects and the risks they represent to resilience; however, further attention is warranted on the opportunities that complexity may represent to society. The risks represented by global climate change (and the interdependencies they highlight) have driven a recognition of the need for organisations to consider these risks and adapt to them together (Dawson 2015; Jude et al. 2017; Street and Jude 2019). By a similar token, infrastructure design and management must recognise the risks and opportunities presented by interdependency and adapt appropriately to these as well. It is advocated here that the focus on interdependency be broadened from solely considering risks and vulnerabilities, and seek to recognise and embrace the myriad opportunities that exist. Numerous projects, either theoretical or in practice, are beginning to recognise and exploit these opportunities as the above case studies illustrate. Such projects can range from adaptations of existing infrastructure systems to novel disruptive business models that seek to replace entire supply chains and conventional approaches (Keely et al. 2016; Moreno et al. 2017), and should be looked to by future efforts for inspiration.

The typologies proposed in this paper represent a way in which the opportunities associated with interdependencies might be more effectively recognised and exploited in future efforts. The case studies seek to exemplify these typologies in action, in both theory and practice. To further recognise and understand opportunities, managers and planners should consider several dimensions: 1. What is the intensity of the opportunity? Is it a true two-way interdependency, and if so how strong are the linkages? If not, is it a one-way dependency or simple co-location, and might it develop into a true interdependency, either deliberately or unintentionally? 2. Has the opportunity been planned in advance, or has it been recognised and exploited based on pre-existing systems? Or is it completely emergent and serendipitous? 3. What specific value does the opportunity offer, i.e. what is its business case? Does it provide increased resilience, an engineering benefit or a cost benefit? Are the benefits represented in the market (i.e. monetary) or not (e.g. societal well-being)? 4. What are the spatial and temporal scales of the benefits? How large a geographic area do they impact, and at what stage in the project's life cycle do they factor in? 5. Finally, how do the benefits weigh against the risks?

All of the above dimensions can and should be used to explore both opportunity and risk, and consider them in the context of one another, in order to weigh the overall value of interdependent efforts. Accurately recognising and understanding opportunities from interdependency can aid managers and decision makers in making informed choices as new innovations are pursued. Most of all, transitioning thinking toward the proactive recognition and pursuit of opportunities from complexity on their own, rather than only in reaction to threats, will have powerful and far-reaching benefits for organisational effectiveness and global well-being.

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Data Availability Statement

No data, models, or code were generated or used during this study.

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TABLE 1. Principles of ecology and system survival (Capra 1996), and examples of how they can be applied to infrastructure to build resilience and sustainability

Principle	Description	Relevance to Infrastructure
Interdependence	All members of an ecological community are connected in a vast and intricate network of relationships via multiple feedback loops that create non-linear response patterns.	• Reliance on outputs as inputs between infrastructures • Information feedback to optimise functioning (smart metering)
Cyclical Flow	Nutrients are recycled so that waste of one species becomes food for another. Organisms are open systems but ecosystems are largely closed with respect to materials. In human society, by contrast, outputs of one market-driven entity may threaten the survival of another, especially as environmental and social costs are 'external' and not considered in market models.	• Recycling of residue from one infrastructure to drive another • Avoidable waste reduction • Circular economy and engineering for re-use • Carbon tax systems etc. to account for environmental and social externalities, thus recognising the closed nature of the system
Partnership and Cooperation	Co-evolution, symbiogenesis and mutually interdependent adaptations	• Infrastructure sharing (asset focus – cost efficiency) • Sharing economy (society focus – enhances well-being and community) • Knowledge exchange
Flexibility	Continual adjustment to feedback in response to constantly changing conditions. Negative feedbacks facilitate stabilisation after disturbance or a shift in conditions.	• Adaptation to uncertainty (e.g. climate change) • Driverless vehicles and responsive traffic routing • Optimising to meet multiple objectives rather than maximisation to one
Diversity	Pluralistic resilience, biodiversity with overlapping ecological functions that can partially replace one another	• Distributed (i.e. pluralistic) energy storage • Multiple energy sources • Multiple network pathways • Replacement of outdated systems

TABLE 2. Comparison of case studies showing types of opportunities exploited, ecological principles exhibited and description of the project

Case Study	Type of Opportunity	Ecological Principles	Description
MK:Smart	Simple, geographical and integrative	Interdependence, partnership, flexibility and diversity	Disparate systems integrated to support efficiency and novel services
Milton Keynes linear parks	Simple and geographical	Partnership and diversity	Urban green infrastructure is preserved and managed for multiple goals
Urban rooftop greenhouse agriculture	Geographical and integrative	Cyclical flow	Water and nutrients recycled in a hydroponic growing system to maximise resource efficiency
London Olympic Park	Simple, geographical and integrative	Interdependence, cyclical flow, partnership, flexibility and diversity	Full life cycle approach identified and exploited opportunities at all stages
Nano-membrane toilet prototype	Integrative	Interdependence, cyclical flow, flexibility and diversity	Prototype to integrate all toilet/sewerage functions into a single unit to eliminate dependency on central infrastructure
Cornwall local energy market	Simple, geographical and integrative	Interdependence, flexibility and diversity	Pilot creation of a novel energy market linking renewable generation, local storage and smart management
Multi-use ocean platforms	Geographical	Interdependence, partnership and flexibility	Theoretical concept for offshore platforms combining energy generation and storage
SMART Tunnel	Geographical	Partnership and flexibility	Combined use urban tunnel managed to mitigate flood risk and traffic congestion