Infrastructure Interdependencies: Opportunities from Complexity

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Abstract: Infrastructure networks, such as those for energy, transportation, and telecommunications, 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 organizational resilience and sustainability. A typology is presented for classifying positive interdependencies, drawing on fundamental principles in ecology and validated using case studies. Understanding opportunities that arise from interdependency will enable better understanding and management of infrastructure complexity, which in turn will allow the use of such complexity to the advantage of society. Integrative thinking is necessary not only for mitigating risk but also for identifying innovations to make systems and organizations more sustainable and resilient. **DOI: 10.1061/(ASCE)IS.1943-555X.0000575.** *© 2020 American Society of Civil Engineers.*

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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, in many cases evolving over decades or centuries 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 behavior and numerous interdependencies that can leave critical functions highly vulnerable to disturbances, particularly through the exacerbating effects of complexity, such as cascade failure (Helbing 2013; Rinaldi et al. 2001; Vespignani 2010).

Consequently, 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 has been 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 organizational 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). The need to understand interdependency is not new, but it has become increasingly fundamental to designing, managing, and adapting infrastructure systems in ways that will be resilient to disturbance (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; DEFRA 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 interdependencies as well. In some instances, interdependencies have been exploited or proposed in order to enhance the delivery of essential services or synergized to create entirely new services (Delucchi and Jacobson 2011; Pandit et al. 2015; Roelich et al. 2015); climate change adaptation efforts frequently state the need for interdisciplinary collaboration (DEFRA 2011; Jude et al. 2017; Street and Jude 2019). In cases in which this has been done in practice, 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. Recognizing and adapting to the opportunities generated by complexity represents a largely untapped potential for designing and building systems that answer the global challenges of sustainability, resilience, and efficiency.

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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, because these represent systems whose complexity builds resilience rather than impedes it, and parallels are explored whereby infrastructure systems might learn from the behaviors and structures of natural systems in order to function more effectively. Finally, this framework is applied to several case studies in order to explore its use in practice and act as evidence in support of its validity. The perspective and associated typologies described in this paper 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 business cases. Technological advancements, changes in societal demand, and evolving external drivers such as climate change and geopolitics have converged over time to drive adaptations in the purpose and behavior of critical infrastructures. These systems have now become 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; they used *interdependency* specifically for bidirectional relationships in which two separate systems or nodes both exert influence on the other. The authors further proposed a typology for categorizing infrastructure interdependencies according to their nature, which has subsequently been widely adopted by researchers. The framework consists of physical linkages (in which systems share a direct material connection), cyber linkages (in which system state depends on information flow), geographic linkages (in which systems are connected by spatial proximity), and logical linkages (in which systems are interconnected in some other fashion). The existence of this typology has been beneficial in efforts to explore infrastructure interdependencies, because it provides a structured framework by which complex interconnections can be classified, understood, and analyzed (Chai et al. 2011; Johansson and Hassel 2010; Wu et al. 2016). More recent efforts by Carhart and Rosenberg (2016) sought to expand on 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 and 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 behaviors are perceived predominantly as threats to system stability and service delivery (Helbing 2013). Accordingly, most research conducted on infrastructure interdependencies has taken this stance, viewing interdependency as a threat to be mitigated and protected against.

Interdependency as Opportunity

Interdependencies have so 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, Information and Communications Technology (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% of intrasector and 86% of intersector linkages were categorized 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 organized 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 categorized and understood (Carhart and Rosenberg 2016; Ouyang 2014; Rinaldi et al. 2001); the aim in this paper 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 herein 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 a system, and these are briefly considered; however, 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 organizational gaps can inform and improve good practice through exposure to new perspectives and procedures. Things that may represent standard approaches to ensure secure, efficient, or robust design in one system may be novel and applicable to another system in which such approaches have not previously been explored. In this instance, 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 organization, such as the sharing of ideas 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 noncritical to system functioning, 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; they are beneficial but not critical to the operation of the coupled systems.

Geographic/Physical Opportunities

The physical colocation of multiple infrastructure systems can present opportunities for cost-saving and increasing system efficiency. This represents, essentially, an expansion of infrastructure sharing concepts in order to specifically consider sharing across multiple networks and sectors. The placement of mobile phone network antennae on tall buildings or preexisting 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 colocation, like most interdependencies, can introduce threats as well as opportunities in cases of localized disturbance or damage; however, the opportunities have a greater tendency to be overlooked than the threats. 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 decentralization can support a considerable increase in system resilience, freeing end users from sole dependence on a centralized system should a failure occur. Geographic/physical interdependency-based opportunities represent beneficial couplings based on colocation and/or the physical sharing of infrastructure, material, or information across systems on a localized scale.

Integrative Opportunities

Within the functioning and management of 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 in which information flow is used solely to impart knowledge). Integrative interdependency-based opportunities are, therefore, 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 on the smooth operation of this synergy, so system design should seek to incorporate redundancy and fall-back positions in order to allow individual systems to continue functioning if a 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 localized failures could greatly increase the resilience of such a complex system. Given future uncertainties related to global climate change and population growth, such systems must be resilient and robust, because the exact nature and intensity of future risks and pressures remain unknown. With fully integrated complex infrastructure systems, the risks are greater and must be recognized and managed effectively; however, the potential opportunities are also more transformative. The ability to design and manage resilient infrastructure systems depends on the ability to identify cases in which 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 are highly interconnected, complex, and adaptive; both exhibit characteristic scaling properties; and both rely 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 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; the system possesses self-regulating behaviors and feedback relationships that maintain the stability of the system even in the face of disturbances (Capra 1996). On a finer scale, organisms and species are resilient in many cases due to overlap and redundancy among ecological niches; rarely is a role in an ecosystem filled by a single species whose loss would destabilize 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 greater resilience and sustainability into global systems. Careful thought and translation will be required, however, because human-built and natural systems share fundamental differences despite their similarities and are not perfect analogs to one another. Natural ecological systems have largely adapted and evolved to their current stable states through processes of random mutation, high attrition, emergent behaviors, and incredibly long time scales in a bottom-up manner. Anthropogenic systems and the societal concerns that drive them, however, are traditionally designed from a top-down, goal-oriented perspective and are generally intolerant of long time scales and heavy resource expenditure. Further, many technological systems have necessarily been developed to operate in a highly controlled and deterministic manner (Pennock and Wade 2015) that is fundamentally at odds with the seemingly haphazard way in which natural systems emerge. Such determinism and reductionist thinking, however, encounters difficulty when larger systems are considered, and complexity forces a more integrative and ecological perspective than the perspective used to create a system's components and base functionality

(Ottino 2004). This forced shift in perspective, from the creation of a system based on reductionism and mechanistic design to a systems approach that recognizes 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 subsystems 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 recognized (Rehak et al. 2019).

How Infrastructure Can Learn from Nature

Despite the important differences between human and natural complex systems, there are commonalities to which 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. These principles can be specifically applied to infrastructure design and management (Table 1).

The importance of Capra's first principle, interdependence, is already well-known in infrastructure contexts, but the focus is usually placed on negative aspects of interdependence, as discussed previously. As in nature, there are also many ways in which interdependencies can be positively exploited. This is explored through this paper's typology, by which benefits can be realized through the exchange of knowledge and expertise (simple opportunities), infrastructure sharing and colocation (geographic/physical opportunities), and more complete interconnection (integrative opportunities). Interest in and uptake of smart metering in residential electrical consumption, for example, is growing 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 behavior, 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 reuse and recycling of materials, reduction in avoidable waste, and engineering products for long-term use rather than disposability are all actions that can serve to increase sustainability at a society-wide scale. As organizations 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 organizations and industries.

Partnership and cooperation are developing in many industries and sectors as interest grows in systemic thinking; this is evident in the conducting of interdisciplinary research and the bridging of gaps between sectors and networks that have previously operated independently. The realization of the need for such cooperation has risen in part out of a recognition of the complexity and interdependence that is present in global human-created systems, because 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, are present. The exchange of knowledge and expertise between organizations has become commonplace in industries facing the broad and unifying goal of adapting to climate change, particularly in cases in which industry is encouraged to address such long-term considerations by government reporting programs (Jude et al. 2017; Street and Jude 2019). Infrastructure sharing approaches (variously referred to in terms such as common carriage, unbundling, track sharing, and so forth, depending on the

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 nonlinear response patterns.	• Reliance on outputs as inputs between infrastructures • Information feedback to optimize 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 because 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 reuse • Carbon tax systems, etc., to account for environmental and social externalities, thereby recognizing the closed nature of the system
Partnership and cooperation	Coevolution, 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 stabilization after disturbance or a shift in conditions.	• Adaptation to uncertainty (e.g., climate change) • Driverless vehicles and responsive traffic routing • Optimizing to meet multiple objectives rather than maximization to one objective
Diversity	Pluralistic resilience; biodiversity facilitates overlapping ecological functions that form functional redundancies and can partially replace one another.	• Distributed (i.e., pluralistic) energy storage • Multiple energy sources • Multiple network pathways • Replacement of outdated systems

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 also 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 are unknown, necessarily require a great deal of flexibility and capability to adapt to changing circumstances. Rigid infrastructures and networks that are optimized to remain functional only under a narrow set of external conditions 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 such 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 optimize 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 sharing of autonomous vehicles could cause a shift in personal transport from an owned asset to a shared service, easing 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, the implementation of diversity in human systems is a great challenge. In large infrastructure networks, redundant linkages play an important role in maintaining functionality if a part of the network fails or saturates. This redundancy 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 internalized. Conventional economic and industrial practices have also tended to favor 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 is efficient, but in some cases this low diversity may represent a vulnerability if a failure proves specific to that design or approach. The picture has changed in recent years with the uptake of lean manufacturing and agile production processes, which seek to reduce waste while maximizing 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 may also represent a diverse approach, smoothing temporal discrepancies between supply and demand (Yekini Suberu et al. 2014). Such microstorage approaches could provide backup sources of energy to increase resilience across entire networks, especially when coupled with distributed generation (e.g., residential photovoltaic roof panels) and managed using smart grid technology to optimize timing, costs, and social benefits (Kriett and Salani 2012; Vytelingum et al. 2010).

Understanding and analyzing integrated infrastructure networks as holistic systems of systems as one would view 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 optimization and management for broad-reaching global interests become realistic possibilities. Further, such a perspective enables the recognition of commonalities that infrastructure networks share with ecological networks (which in itself exemplifies a simple, knowledge-based opportunity) and the identification of shared typologies of interdependence. In understanding the ways in which 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 be incorporated into the business models of organizations and the strategies of managers and thereby directly embedded into the guiding principles of industrial operations 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 recognized 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 realization 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 reevaluating how systems can function more effectively, for example, 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, it can impede and discourage innovation; however, if creative thinking is encouraged and decision makers are open to new ideas, it 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 reactive to faults or preventative and, therefore, forward-looking. Fourth, governance can act as a considerable barrier to opportunity if regulatory structures rigidly enforce historic approaches and silos but is equally capable of enabling opportunity through careful and informed consideration of ways in which public policy, regulation, and legislation can and should adapt to changing conditions. Finally, societal behavior is fundamental in determining whether innovations are met with resistance or acceptance and is, therefore, 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.

A pervasive background to all of these driving forces is the fact that opportunities are easier to recognize 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 is exhibited in some of the case studies explored subsequently.

Case Studies

The foregoing typologies 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 categorized 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 also in the approach they take to harnessing opportunities, the stage at which costs and savings factor into the process, and whether they represent adaptive changes to or disruptive replacement of existing frameworks (Table 2).

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 centers on the creation and use of a data hub in which 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 data sets 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 involved the rollout of sensors across the city to track traffic flows and congestion in car parks and buses (Valdez et al. 2015). This information was intended to be pooled and distributed to local travelers via a mobile app, enabling informed decision-making and intelligent routing. These and similar sensors can be mounted on existing lampposts, making use not only of preexisting structures but also of the electrical supply 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 buses or taxis as mounting points for a city-wide sensor network to track traffic, air pollution, and other items has been put forward as a potential opportunity for infrastructure sharing and cost reduction (E. Motta, personal communication).

Data are being gathered and analyzed on electrical use, EV ownership, and the presence of solar photovoltaic (PV) cells by the MK:Smart program 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 optimized 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 also increase the resilience and sustainability of both the electrical and transport systems. Many home and transport energy demands could be met by the use of renewable systems, and battery storage could correct for discrepancies in the 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 completely implemented, 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 program 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 by providing information on real-time transportation infrastructure status to residents in order to enable more informed decision-making. The use of existing infrastructure to mount and power the sensors demonstrates a clear geographical/physical opportunity through infrastructure sharing.

The integration of electrical use, EV charging, and distributed power generation and storage is 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 seen in the colocation 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 each another. Finally, the data hub that underpins the entire MK:Smart program 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 localized damage taking out multiple network sensors—for example, from a vehicle collision with a

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 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 maximize 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 integrates 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
Multiuse 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

lamp post—and information security concerns due to potentially sensitive data on users and systems across the city being stored in a single, unified data hub. The combination of different technologies and approaches nevertheless enables the MK:Smart program to span simple, geographical, and integrative types of opportunities and to exhibit the ecological principles of interdependence, partnership, flexibility, and diversity.

Case Study: Milton Keynes Linear Floodplain Parks

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

While this example does not directly concern traditional critical infrastructure systems, it is important in that it 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 parties. What begins as a knowledge sharing opportunity may result in the identification of geographic opportunities for these shared purposes and ultimately support an arrangement in which urban green infrastructure achieves multiple goals. Furthermore, the use of floodplain lands for parks as opposed to residential development reduces the threat of damage to personal property, requiring comparatively inexpensive efforts to clean and repair parklands after flood events. This case illustrates both simple and geographical opportunities along with the 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 in order to compare it with a more conventional linear agricultural system with no nutrient or water recovery. 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. Because some of these nutrients are linked to nonrenewable resources and because urban water security is an area of growing concern, these findings are striking. As studied in this case, the experimental closed system proved to be less environmentally efficient over its full life cycle because it received less radiation input than the linear system and consequently required a longer period of time to reach an equivalent total crop yield. In addition, the relatively small production volumes coupled with the infrastructure costs associated with leachate recycling resulted in undesirably high environmental impacts. The authors proposed that future efforts could mitigate this drawback by using recycled materials in the creation of the system. Although not presenting an immediately perfect model, the study nevertheless broke new ground and demonstrated how circular resource flow could 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 by lowering direct resource inputs and reducing waste products. Cyclical flow is at the core of the endeavor; this 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 the benefit of producing food closer to the point 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 in its adoption, and its greatest risks stem from uncertainties regarding its unexplored economics; however, the importance of its untapped potential is being increasingly recognized (Edmondson et al. 2020; Grafius et al. 2020). The opportunities in this case are geographical and integrative, and the main ecological principle involved 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 was developed with a particular focus on sustainability, responsible development, and the postgames legacy of the site (LOCOG 2012; Naish and Mason 2014). In contrast to developments for many past Olympic Games, development of the Olympic Park in London aimed toward the highest degree of sustainability possible and the creation of 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 reused or recycled, exceeding a 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 20,000–30,000 homes); other event structures were deliberately constructed to be temporary when it was clear there would not be 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 program involved the public Olympic Delivery Authority (ODA) appointing a private-sector consortium made up of CH2M Hill, Laing O'Rourke, and Mace (abbreviated collectively to CLM) as the delivery partner. These private companies brought experience and expertise in large-scale program management and construction projects and were granted the necessary latitude to deliver to targets effectively; at the same time, ODA retained sufficient assurance and oversight of the broader program. The importance of forming and retaining an effective relationship between ODA and CLM throughout the program was recognized as essential, so CLM remained integrated into the governance and delivery review meetings throughout the program's life cycle as a true partner in the process rather than as a fire-and-forget subcontractor (Hone et al. 2011).

The overarching approach encompassing all of the varied goals involved a forward-looking and systematic perspective, recognizing 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 development of the London Olympic Park exemplifies positive interdependency at all levels from simple opportunities (through interdisciplinary collaboration) to geographical and physical opportunities (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 synergize in as many ways as possible). Unlike many interdependency opportunities, the development also exemplifies a novel approach in that it was designed from the outset to be integrative rather than being a retrofit of existing infrastructure. Therefore, it represents all three types of opportunities (simple, geographical, and integrative) as well as the ecological principles of interdependence, cyclical flow, partnership, flexibility, and diversity. Widely hailed as a success, the greatest weakness or threat demonstrated by the megaproject was most likely the considerable cost of the approaches taken, which would likely have proven prohibitive to most smaller or less-supported developments.

Case Study: 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 centralized sewerage systems in developing countries using modern technological advancements (Martin et al. 2015). Such decentralized sanitation systems are primarily concerned with the containment, immobilization, 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 neutralize pathogens, recover water and nutrients, operate off-grid, and are relevant in both low- and high-income countries. Although many of these systems are still in development, a fully self-contained toilet could eliminate dependency on multiple infrastructure systems, greatly reducing risks to the environment and human health.

A major challenge faced by all self-contained toilet designs is the separation of solid and liquid wastes, which the nano-membrane prototype accomplishes using silicon tubing and the vaporization of liquid wastes. The energy requirements of the system are met by the combustion of dried solid residues; the vaporized liquids are condensed and recovered downstream, free of pathogens. The CO_2, NO_x, and SO_x from the burning solids is intercepted by a suite of adsorbents. Waste ash from the system is microbiologically inert and can, therefore, be safely disposed of alongside household waste (Martin et al. 2015).

The main environmental benefit of such a system is its water-saving ability; the lack of dependence on critical infrastructure systems would represent a major economic and social benefit, particularly in rural areas of developing nations. Because it is a prototype, it is difficult to assess threats or weaknesses of the system, but a driving principle of the project is the reduction of user dependency on unreliable or unavailable infrastructure systems. On a broad scale, this prototype system appears to represent the elimination of interdependency rather than its exploitation; however, on the scale of the individual unit, it represents a recognition and deliberate integration of the interdependencies between water, energy, health, and the environment, which have driven the system's design. In this way, the project exhibits an integrative opportunity and demonstrates the ecological principles of interdependence, cyclical flow, flexibility, and diversity.

Case Study: Cornwall Local Energy Market

An ongoing trial project is being carried out 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 ongoing, so no final results are available at the time of this writing, but it is anticipated that the study will prove informative with regard to management and implementation strategies for renewable energy, home power storage, and local energy trading.

Like similar examples discussed previously, this locally focused energy integration program combines principles of sustainability and flexibility, reducing load on the national electrical grid and minimizing 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 in 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 colocated resources, and the integrative linking of technologies with system-level optimization and management. The ecological principles of interdependence, flexibility, and diversity are also employed.

Case Study: Multiuse Ocean Platforms

Spurred by intergovernmental targets on sustainability and renewable energy production, interest has grown recently in the concept of ocean platforms that support multiple uses, in particular, combining wind and wave energy generation, and in some cases including aquaculture installations. The advantages of such platforms in terms of shared costs, smoothed power output, and combined construction and maintenance efforts make them an attractive proposition; however, their implementation currently faces barriers in the form of a lack of unified governance and support, longer development times, uncertainties with regard to insurance and risk, and the immaturity of important technologies for 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 are still speculative and theoretical; however, prototypes and exploratory case studies to optimize development approaches have been completed (Zanuttigh et al. 2015, 2016).

If constructed, multiuse platforms that combine different offshore infrastructures in a common area or structure would primarily represent the exploitation of a geographic opportunity, taking advantage of colocation to share structures, costs, and logistics (Abhinav et al. 2020). Colocation remains perhaps the most obvious double-edged sword, because it can represent infrastructure sharing opportunities and also introduce threats in the event of localized disturbances. In addition, 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 through the synergy of different power generation and local storage approaches (Abhinav et al. 2020). For now, such projects primarily represent geographical opportunities and make use of the ecological principles of interdependence, partnership, and flexibility.

Case Study: Kuala Lumpur Stormwater Management and Road 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 the tunnel are shared with a two-layer motorway constructed to alleviate traffic problems during peak times throughout the remainder of the year. This unique shared-use infrastructure is subject to a specially designed maintenance and management scheme in order to assure its continued fitness for both purposes and has alleviated numerous potentially damaging flooding events since its completion.

The SMART tunnel represents a novel case of colocation, recognizing a geographic opportunity to alleviate two otherwise unrelated problems facing the city and integrating multiple systems to manage it. Again, this colocation 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; a systematic perspective and consideration of multiple objectives has allowed a shared opportunity to answer multiple needs. This project is, therefore, an exemplar of a geographical opportunity, making use of the ecological principles of 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 organizational boundaries in order to plan and manage infrastructure systems in a wider context and with regard to long-term benefits and risks to human well-being.

When interdependencies have been recognized, research, management, and policy have largely 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 these risks highlight) have driven a recognition of the need for organizations to consider these risks and adapt to them together (Dawson 2015; Jude et al. 2017; Street and Jude 2019). Similarly, infrastructure design and management must recognize the risks and opportunities presented by interdependencies and adapt appropriately to these as well. It is advocated in this paper that the focus on interdependency be broadened from solely considering risks and vulnerabilities to seek to recognize and embrace the myriad opportunities that exist. Numerous projects, either theoretical or practical, are beginning to recognize and exploit these opportunities, as the aforementioned case studies illustrate. Such projects 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 researchers for inspiration.

The typologies proposed in this paper represent a way in which the opportunities associated with interdependencies can be more effectively recognized and exploited in the future. The case studies exemplify these typologies in action, in both theory and practice. To further recognize and understand opportunities, managers and planners should consider several dimensions. First, 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 a simple colocation, and might it develop into a true interdependency, either deliberately or unintentionally? Second, has the opportunity been planned in advance or recognized and exploited based on preexisting systems? Alternatively, is it completely emergent and serendipitous? Third, what specific value does the opportunity offer, that is, 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)? Fourth, 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? Finally, how do the benefits weigh against the risks?

All of the aforementioned 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 recognizing and understanding opportunities that arise from interdependency can aid managers and decision makers in making informed choices as new innovations are pursued. Most of all, the transitioning of thinking about complexity toward proactive recognition and pursuit of opportunities, rather than only reacting to threats, will have powerful and far-reaching benefits for organizational effectiveness and global well-being.

Data Availability Statement

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

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