



Infrastructure Interdependency Failures From Extreme Weather Events as a Complex Process

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The loss of infrastructure services under extreme weather events from climate change emerges from complex interactions between the social, environmental, and technological system variables which drive the behavior of infrastructure systems. The complexity of interactions causes failures to cascade in unpredictable ways, often between different infrastructure systems. A common approach to managing this unpredictability is to attempt to characterize the cause-and-effect relationships of infrastructure interdependencies, whether it be related to the resource flows, geographic proximity, logical connections, or the common use of cyber infrastructure. We posit that though a reductive approach toward characterization of interdependencies produces useful insights, it is an insufficient strategy by itself due to the complexity and unpredictability involved in the occurrence and magnitude of cascades of failure across systems. We present historical case studies which demonstrate that cascades from interdependencies display essential tenets of complexity—namely non-linearities, path dependence, and emergence. The Cynefin decision-making framework suggests that management of systems that are in the complex domain include strategies such as Decision Making Under Uncertainty and Safe-to-Fail, which address uncertainty by probing, testing, collecting and analyzing data, and lastly deploying solutions with a commitment to reassessing the systems as conditions change. We therefore recommend that in order to mitigate the surprise from cascades of failure across systems from extreme weather events, infrastructure managers supplement their planning efforts with these types of strategies.

Keywords: interdependencies, complexity, management strategies, historical case studies, climate—impact of

INTRODUCTION

Extreme weather events caused by climate change often exceed infrastructure capacities and design standards and initiate infrastructure hardware and institutional failures which can cascade to service outages (Pederson et al., 2006). Cascades of failures are the result of the many interactions between social, environmental, and technological system variables (Leveson, 2002; Grabowski and Miller, 2017; Markolf et al., 2018; Oughton et al., 2018; Chester and Allenby, 2019). These interactions are part of the *complexity* of infrastructure systems, a domain of systems characterized by unpredictable behaviors when perturbed (Snowden and Boone, 2007). An example of an emergent cascade of failures initiated by a climate event is the 2003 Northeast blackout. An outage

of power to around 50 million people resulted from the confluence of several critical variables including an abnormally hot summer day (environmental), high demand (social/technological), ineffective management of vegetation (environmental/social), limited redundancy (technological), and ineffective operational communication (social) (North American Electric Reliability Council, 2004). During the event, the cascade of failure was surprising to managers and it was only until a task force retrospectively studied the event that causes of failure were identified and understood (North American Electric Reliability Council, 2004).

A significant variable that contributes to failures is the connection between infrastructure systems, or infrastructure interdependencies (Rinaldi et al., 2001; Wilbanks et al., 2015). As described by Rinaldi et al. (2001), interdependencies can exist in many different forms, including the exchange of material outputs (physical), the influence of spatially proximal hardware failures (geographic), the shared dependency on communications systems for operation (cyber), and the influence of institutional decisions (logical). In the 2003 Northeast Blackout example, failures cascaded through physical interdependencies between different power systems and between power and water systems, resulting in a greater extent of power outages and the occurrence of water outages, respectively (Bella et al., 2004). Through the increase in frequency of similar events spurred by climate change, infrastructure managers are recognizing the effect that interdependencies can have on reliability and they are developing strategies to mitigate these effects (Bella et al., 2004). Since the existence of interactions has been recognized and defined for interdependencies, a reductive approach to understanding them is attractive, and many studies suggest characterizing and modeling interdependencies to anticipate how cascades might occur in the future. Though this strategy can provide useful and necessary insights, we posit that it must be accompanied by other strategies which directly address the inherent complexity of modern infrastructure. Through review of historical cases of failures from interdependencies, we find that there is complexity inherent in the dynamics of cascades of failure across systems which is not conducive to purely reductionist approaches. We therefore recommend that managers augment their methods of planning with strategies which are appropriate in the complex domain of the Cynefin framework including decision making under uncertainty, and safe-to-fail (Leavitt et al., 2006; Snowden and Boone, 2007; Ilic, 2014; Derrible, 2017; Kim et al., 2017; Chester and Allenby, 2019). Without including strategies such as these, the surprise from the emergent cascading failures from climate change and other hazards will continue to strain institutions managing infrastructure systems and the customers they serve.

COMPLEX SYSTEMS DIFFER FROM COMPLICATED SYSTEMS

Complex systems share characteristics with complicated systems, but there are important differences which are critical for managers to recognize. Complicated systems contain many parts

and there is uncertainty included in the system, however, cause-and-effect relationships can be understood by characterizing the uncertainty via methods such as statistical distributions (Chester and Allenby, 2019). In contrast, complex systems are characterized by “unpredictability and the presence of unknown unknowns,” or uncharacterizable uncertainty, making it impossible to establish cause and effect relationships (Snowden and Boone, 2007). An example of a complicated system is the process of water treatment. Though there are many interacting parts including sedimentation rate, concentrations of chemicals and organics in the water, and the communities of microbes treating the water, the interactions are well-characterized and the outcomes, the pathogens removed, is predictable (Reynolds and Richards, 1982). Conversely, infrastructure systems which form networks and span across cities have unknown interactions with other aspects of cities, society, and the environment and thus become unpredictable. The essential tenets of complex systems, according to the overview provided by Turner and Baker, are *path dependence* where outcomes are sensitive to initial conditions, *system history* where past events influence future outcomes, *non-linearity* where changes to the system produce disproportionate outcomes, *emergence* where “the interactions from the system components tend to lead to new states, contributing to the system’s unpredictability,” and *irreducibility* where “higher-order states cannot be reduced to their original lower-level states” (Turner and Baker, 2019).

Literature outlining the needs for future design and management of infrastructure systems recommends applying different management approaches for complex systems vs. complicated systems. Knowledge management researchers and consultants, Snowden and Boone, developed the Cynefin framework to help leaders choose strategies which align with their specific context. Through reviewing their experience with consulting they “sorted the issues facing leaders into five contexts defined by the nature of the relationship between cause and effect”—simple, complicated, complex, chaotic, and disorder (Snowden and Boone, 2007). Chester and Allenby adapt the Cynefin framework to infrastructure, and state that “knowing whether you are working in the complicated vs. complex domain when it comes to infrastructure is critical because each domain requires fundamentally different approaches” (Chester and Allenby, 2019). For complicated systems, it is appropriate to primarily use data collection and analysis techniques because experts have the ability to identify the majority of cause-and-effect relationships in the system (Chester and Allenby, 2019). For complex systems, however, analysis techniques are by themselves insufficient (Chester and Allenby, 2019) because hidden or unknown factors contribute significantly to the cause-and-effect dynamics (Park et al., 2013). Therefore, it is recommended that modeling and analysis is only one of a suite of approaches necessary for managing complex systems. Given the unpredictability of complex systems, navigating through their dynamics requires approaches primarily focused on probing and testing, then collecting and analyzing data, and lastly deploying solutions, with a commitment to reassessing the systems as conditions change.

LIMITATIONS OF CHARACTERIZING INTERDEPENDENCIES

In an effort to manage the complexity of interdependent infrastructure systems, the predominant approach has been to employ modeling and analysis to elucidate the interdependencies between systems. Many studies cite modeling as the most appropriate approach (Haimes and Jiang, 2001; Ghorbani and Bagheri, 2008; Lauge et al., 2015), or dive into a modeling approach without justification (Rinaldi et al., 2001; Smith, 2002; Barton et al., 2004; Visarraga, 2005; Pederson et al., 2006). The assumption present in these studies is that though interdependencies are responsible for contributing to complexity in systems, the dynamics of how they impact systems through cascades can reasonably be understood through modeling, and thus are only *complicated* in nature. The basic tenets of complexity are not well-represented in the studies. Many studies have modeled the physical resource flow connections between different infrastructure systems and the exchange of resources across systems (Lall and Mays, 1981; Haimes and Jiang, 2001; Veselka et al., 2001; Barrett et al., 2003; Panzieri et al., 2003; Barton et al., 2004; Eidson and Ehlen, 2005; Zhang et al., 2005; Pederson et al., 2006; Bagheri et al., 2007; Donzelli and Setola, 2007; Pate et al., 2007; Johansson and Hassel, 2010; Pye and Warren, 2011; Rübhelke and Vögele, 2011; Birol and Olerjarnik, 2012; Rheinheimer et al., 2012; Shahid, 2012; Wang et al., 2012, 2013; Bartos and Chester, 2014; Carter, 2014; Lubega and Farid, 2014a; Moini and Asce, 2014; Hwang and Lansey, 2015; Loggins and Wallace, 2015; Berardy and Chester, 2017; Clark et al., 2018). This information can be useful for long-term resource planning, where utilities can plan for the generation of enough resources to support the connected infrastructure system. When interpreting these studies for understanding vulnerability to cascading failures across systems, however, the assumption is often that cascades are linearly related to the amount of resources exchanged between systems. Other studies identify specific places in the infrastructure networks where resources might be exchanged and evaluate how flows of resources might be disrupted if the point of exchange were to be disrupted (Panzieri et al., 2003; Visarraga, 2005; Pederson et al., 2006; Wang et al., 2013; Lubega and Farid, 2014b; Lauge et al., 2015). This information is useful for identifying the impacts of cascades. However, these studies assume that the existence of a potential connection between components determines the occurrence of a cascade. Moreover, while each types of interdependency study contributes particular insights about connected systems, no studies include all of the socio-eco-technical interactions and dynamics between time and space that would be necessary to fully predict the occurrence and magnitude of cascades from interdependencies.

COMPLEXITY OF CASCADES OF FAILURE FROM INTERDEPENDENCIES

Historical events of cascades of failure across infrastructure systems reveal that interdependencies are *complex* in nature instead of complicated—where the occurrence of cascades

emerges from the confluence of many contextual factors in addition to possible connections through interdependencies (Bella et al., 2004; Chang et al., 2007; Rong et al., 2010; Markolf et al., 2018). The following review of select historical events shows that the dynamics of cascading failure from interdependencies display essential tenets of complexity including non-linearity, emergence, and path dependence.

There are *non-linearities* in the outcomes from cascades due to interdependencies. The occurrence and magnitude of cascades are not directly related to only the magnitude of resource flows between systems (in the case of physical interdependencies) or the existence of a connection (for geographic, cyber, and logical types of interdependencies). Other factors contribute significantly to the cascade outcomes. For example, in the 2003 Northeast Blackout, the amount of power resources each of the connected water systems required for their pumping stations did not dictate the number of water outages which occurred. All systems required power and are similar in size, but the water outages seemed to occur more for systems which had less backup water storage or backup power generation (Bella et al., 2004). Clifton, New Jersey was able to avoid having any outages because they had 3 days-worth of water storage (Bella et al., 2004). Thus, the characterization of interdependency connections in terms of the magnitude of resource exchanged, or existence of a connection, provides limited capability for understanding the potential of cascades across systems. The non-linearity of occurrences and magnitudes of cascades is consistent with the vaguely defined “tightness or looseness” aspect of interdependencies described in Rinaldi et al. (2001).

Interactions of social, ecological, and technological systems over time contribute to the *path dependency* of the occurrence of cascades from interdependencies. It is known that these interactions create path dependencies in infrastructure systems operations (Leveson, 2002; Grabowski and Miller, 2017; Markolf et al., 2018; Oughton et al., 2018; Chester and Allenby, 2019), but the occurrence of path dependencies which affects the behavior of cascades across systems is less well-recognized. A historical example is that Clifton, New Jersey evolved to be more prepared for power outages than surrounding cities during the 2003 Northeast Blackout because they prepared for the possible fallout of Y2K ahead of time by installing dual electric feeds and making agreements with their public electric company that they would “run three peaking generators in order to sustain their main treatment plants” (Bella et al., 2004). An additional example presented by Markolf et al. (2018) regards Miami’s approach to managing their “sunny-day floods,” which are initiated by sea level rise and extreme precipitation events, and result in service losses of transportation infrastructure through the transportation system’s interdependency with the deteriorating stormwater infrastructure. They posit that the resulting failures may cause additional interdependency-related failures in the future because the City of Miami may end up encouraging development into the area to raise taxes for the roadway pumps they are installing to mitigate the stormwater vulnerability, which may outpace the pump development and in turn increase the number of people vulnerable to flooding in the future (Markolf et al., 2018). In a general sense, because infrastructure

systems are designed to last decades, the historical design of infrastructure systems will always be a factor in the behavior of current systems, and therefore also in the occurrence of cascades from interdependencies from extreme weather events. Thus, characterizations of interdependencies that omit the effects of historical interactions of social, ecological, and technical systems provide a limited understanding of the potential for cascades across systems.

Interdependent infrastructure systems in different locations vary in characteristics which determine cascades, leading to unpredictability of outcomes, or the *emergence* of outcomes for different cases. For example, two studies which look empirically at the impacts of power outages from similar extreme ice storms in two different cases—in Canada in 1998 (Chang et al., 2007) and China in 2008 (Rong et al., 2010)—show that even though both power systems were connected to the same set of infrastructure, the connected systems that had the greatest extent of cascades and impact from cascades differed. Chang et al. (2007) found that the greatest impact and extent of cascades in Canada from the power sector was to business retail and production, whereas Rong et al. (2010) found that the greatest impact and extent of cascades in China from the power sector was to the mobile telephone sector. This implies that there were contextual aspects in each case that contributed to the occurrence and extent of cascades across specific infrastructure systems. Thus, characterizing generalized rules of cascades from interdependencies provides limited capacity for predicting outcomes of different contexts.

DISCUSSION

Since cascades from interdependencies are complex in nature, managers should not rely on the characterization or modeling of interdependencies alone in their climate change adaptation strategies, but should follow best practices recommended by complex systems science. For example, the Cynefin framework recommends that for complex systems, strategies including probing and testing, collecting and analyzing data, and lastly deploying solutions, with a commitment to reassessing the systems as conditions change should be employed (Snowden and Boone, 2007). Decision-making frameworks which would be appropriate include (but are not limited to) Decision Making Under Deep Uncertainty, and Safe-to-Fail (Leavitt et al., 2006; Ilic, 2014; Derrible, 2017; Kim et al., 2017; Chester and Allenby, 2019). These frameworks tend to establish principles that recognize complexity and call for designing and operating by recognizing uncertainty, testing, and a commitment to long-term reassessment of the asset and its performance under changing conditions.

Decision Making Under Deep Uncertainty is relevant for managing types of uncertainty that are largely unknown and which cannot necessarily be characterized through probability distributions (Helmrich and Chester, 2019). It involves a cyclical process of framing the analysis, performing an exploratory uncertainty analysis, choosing initial actions and contingent actions, and iteration and re-examination (Decision Making Under Deep Uncertainty, 2019). There are multiple approaches

suggested within this framework including Robust Decision-making, and Dynamic Adaptive Planning. Robust Decision-making includes using exploratory modeling to test strategies over possible futures (Decision Making Under Deep Uncertainty, 2019). Dynamic Adaptive Planning focuses on the adaptation of plans overtime when new information is available (Park et al., 2013; Decision Making Under Deep Uncertainty, 2019). Modeling interdependencies could thus be an aspect of exploring future scenarios, but the assumptions and inputs into the model would need to be updated when new information becomes available. Information that might surface overtime regarding interdependencies might include changes in connections between systems, climate hazards, demand profiles, and infrastructure hardware and institutions.

The Safe-to-Fail framework bypasses the need to characterize uncertainty and instead assumes that assets will fail if designed for rigidity in changing conditions. The framework recommends designing with potential failure in mind, and incorporating alternative service delivery approaches to make the system more adaptable (Kim et al., 2017). In the case of managing interdependencies, this might mean that managers would assume that the other infrastructure systems they rely on will fail at some point, and would prioritize providing backup systems (e.g., generators, storage tanks, etc.) to maintain critical services.

Improving the communication and coordination between managers of different infrastructure systems could increase managers' capacity to implement strategies for complex systems (Leavitt et al., 2006; Ilic, 2014; Derrible, 2017; Chester and Allenby, 2019). Though appropriate in the past, literature suggests that separate management of infrastructure systems may limit the capacity to prepare systems for disturbances. Derrible (2017) states that the "dichotomy of responsibility" was developed due to "the global push toward safety, accountability, and higher efficiency." "The mechanistic approach has been shown to be...effective in environments that require routine operation and little change. In these environments high-level management possesses the appropriate amount of knowledge to make decisions and organize work" (Chester and Allenby, 2018). This implies that in environments with high change, one organization might not be in possession of all relevant knowledge. Because infrastructure organizations have evolved without the acute need to coordinate or consider uncertainty, "sharing of knowledge and resources across groups to address interdisciplinary challenges is typically infeasible and solutions to challenges are often prescribed with little opportunity for deviation" (Chester and Allenby, 2019). Without information sharing, flawed expectations about the behavior of the change may lead to undesired consequences (Leveson, 2002; Park et al., 2013). Thus, coordination across organizations would provide the capacity to develop more realistic expectations about the behavior of infrastructure systems and would allow for effective adaptations to be more easily made.

CONCLUSION

A common approach to managing the uncertainty of the failure of infrastructure systems in the face of climate change hazards has been to try to characterize the cause-and-effect behavior

of interdependencies. Historical examples of failures from interdependencies show that the occurrence and extent of cascades of failure from one infrastructure system to another is unpredictable because the systems display essential tenets of complexity—namely non-linearities, path dependence, and emergence. Thus, in order to better prepare for an uncertain future including climate change, managers should consider the complexity of cascades and implement additional strategies which are appropriate for the complex domain of the Cynefin framework. Ultimately, if the complexity of the behavior of cascades of interdependencies is overlooked and additional strategies are not included, the surprise from the emergent cascading failures will continue to strain institutions managing infrastructure systems and the customers they serve.

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DATA AVAILABILITY STATEMENT

All datasets presented in this study are included in the article/supplementary material.

AUTHOR CONTRIBUTIONS

All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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