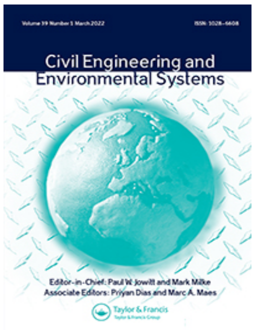

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RESEARCH ARTICLE

Managing disaster risk associated with critical infrastructure systems: a system-level conceptual framework for research and policy guidance

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ABSTRACT
This paper presents a new conceptual framework of the disaster risk of critical infrastructure systems in terms of societal impacts. Much research on infrastructure reliability focuses on specific issues related to the technical system or human coping. Focusing on the end goal of infrastructure services – societal functioning – this framework offers a new way to understand how those more focused research areas connect and the current thinking in each. Following an overview of the framework, each component is discussed in turn, including the initial buildout of physical systems; event occurrence; service interruptions; service provider response; user adaptations to preserve or create needed services; and the ending deficit in societal function. Possible uses of the framework include catalysing and guiding a systematic research agenda that could ultimately lead to a computational framework and stimulating discussion on resilience within utility and emergency management organisations and the larger community.

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Infrastructure systems; electric power; water; societal impact; adaptations

1. Introduction

Critical infrastructure systems, such as electric power, water supply and telecommunications, are essential to community functioning and minimising disruptions in the services they provide is an important part of resilience. A great deal of engineering-focused research has been conducted in recent decades to characterise the hazards to which infrastructure systems are exposed, the vulnerability of their physical components to damage and the resulting interruptions in the services they provide (e.g. Chang et al. 2007; Dong et al. 2020). At the same time, more recently, there has been growing recognition of the importance of connecting the concepts of *system functioning*, which has been the main focus of those engineering efforts, and *societal functioning*, which is the concept of ultimate interest (e.g. Links et al. 2018; NEHRP 2014; ATC 2016; NIST 2016; Hasan and Foliente 2015;

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Davis 2019, 2021; Rojahn et al. 2019; Bruneau et al. 2003). The former refers to the provision of the service through a network, for example, the percentage of customers receiving water and the latter refers more generally to the ability of industries and businesses to operate; emergency services to perform their duties; households to participate in or get to work, school and leisure activities; and individuals to drink, bathe and live their daily lives.

There remains a need to better understand the specific ways infrastructure system services meet societal needs, how disruptions of those services impair societal functioning and how interventions can best be designed to minimise societal impact. That knowledge will enable the development of a clear basis for infrastructure system performance goals expressed in terms of societal functions, a method to assess the current performance of the nation's infrastructure systems in societal terms and a pathway to achieve the expressed societal performance goals.

In this paper, we advance knowledge in this direction by presenting a new interdisciplinary system-level conceptual framework of the disaster risk of critical infrastructure systems in terms of societal impacts. In particular, we contribute to the literature by offering a framework for understanding how the disparate, more focused research areas centred in different disciplines connect and the current thinking in each of those contributing areas. We do not present a traditional literature review nor a single method for assessing the societal impacts of infrastructure system service interruptions. Rather, we provide an encompassing frame for the problem and describe key concepts, challenges and methods proposed for each topic (e.g. modelling of disruptive events, user adaptations) with the aim of catalysing research and thinking across this complex challenge in a way that moves those topics together. The conceptual framework represents a step towards a *computational* framework that could be used to quantitatively measure the risk of societal impacts of infrastructure system service interruptions.

The framework is intended to be applicable across hazards and infrastructure types. Specifically, we define infrastructure as sociotechnical systems for the conveyance of materials, energy or information: that is, water, wastewater, electricity, oil, natural gas, transportation and telecommunications. At present, the framework is focused on systems in the United States. Nevertheless, we have used international sources in its development, and it would likely be adaptable to other places, though relative emphases might differ. For example, many places have electricity for only limited hours per day in normal times, so the concept of adaptations would perhaps have different significance in those settings.

2. Uses of the framework

We anticipate at least two main uses of the conceptual framework. First, the framework can serve as a guide to a coherent research agenda that focuses on connecting engineering-based infrastructure risk modelling to societal impacts. Much work remains to develop the computational tools to link *hazards* to *damage* to *system impact* to *societal impact*. Those efforts will be improved by an understanding of how all the pieces fit together and the current state of thinking in each. There are different ways to represent each step in the process (e.g. disruptive events, user adaptations), and they will not connect and ultimately enable the end goal of risk expressed in terms of a societal impact unless they are designed up front with knowledge of the overall process. A conceptual framework thus offers a useful precursor to a computational framework. Given the need to consider infrastructure resilience in the face of acute-onset hazard events, the long-term needs for retrofitting and the tremendous future costs for infrastructure system rehabilitation, utility operators and public officials need sophisticated methods for prioritising the necessary ongoing system modifications that will yield satisfactory community functioning.

Second, the framework can be a tool to stimulate dialogue within utility and emergency management organisations and the larger community and a structure for organising other resilience initiatives (e.g. Slemp et al. 2020). For example, the Composite of Post-Event Wellbeing (COPEWELL) resilience model 'fostered a partnership between the [New York City Department of Health and Mental Hygiene's (DOHMH'S)] Bureau of Environmental Surveillance and Policy and the Center for Health Equity's Bronx Neighborhood Health Action Center on building social networks to identify populations vulnerable to intense heat hazards' (Slemp et al. 2020, 569). In that effort, the project partnership used the COPEWELL model as a guide for conducting and analyzing focus groups with community organisations. Results, in turn, stimulated development of interventions focusing on heat emergencies. In broader terms, 'COPEWELL helped DOHMH staff members and community partners better grasp the concept of community resilience and postevent functioning, helping them "get their minds around the[se] concept[s]"' (Slemp et al. 2020, 568). Another use for the COPEWELL model was in developing, in collaboration with local officials, rubrics that communities could use for self-assessment of their disaster preparedness and resilience (Schoch-Spana et al. 2019). These rubrics, in turn, can help communities to organise and prioritise where they are strong and where they need to make investments. We anticipate analogous usefulness of the framework introduced herein for policymakers.

3. Background

Critical infrastructure systems provide essential goods and services to meet societal needs. They are vital to the economy, national security and public health (Department of Homeland Security 2013), and therefore must be designed, managed and operated, so they function reliably and efficiently even in the case of an earthquake or other extreme event. At the same time, the U.S. infrastructure is in disrepair (Kendra, Knowles, and Wachtendorf 2019). The American Society of Civil Engineers (2021) has regularly assigned failing grades to U.S. infrastructure systems, with estimated costs to repair in the trillions of dollars. Challenges across the country and internationally are regularly revealed, often in the context of extreme events, whose prevalence is expected to increase.

The mistake in focusing only on physical artefacts and service provider decisions is that choices about infrastructure extend far beyond the owner/operator of the system, and these decisions are integral to community function, resilience and well-being. One interpretation of this observation is that choices on design, materials, construction, reconstruction and maintenance of infrastructure systems should encompass the impacts on overall societal functioning. Such an observation has yet another implication – the infrastructure as we presently understand it does not stop at the metre. Users are, in fact, system operators in their own right – albeit independent, distributed and largely uncontrolled. Their decisions are critical to system functioning and thus community functioning. Voluntary conservation measures are a well-known strategy for reducing stresses on a system, for example. Normally it is convenient to ignore these decision makers, but in times of operational precarity, the factors that these 'operators' consider can make the difference between a system that is resilient and a system that fails, and the ability of a community to maintain its function.

In this paper, we emphasise the idea that community function is served by infrastructure systems and in doing so, build on previous work that has similarly highlighted this point. Bruneau et al. (2003) offered an early conceptual framework that similarly addressed the resilience of communities and the infrastructure systems they rely on and similarly offered a guide for future research. The Bruneau et al. (2003) framework considers resilience to include four properties (robustness, redundancy, resourcefulness and rapidity) and four dimensions (technical, organisational, social and economic). The framework presented herein adopts many ideas from Bruneau et al. (2003), but offers an alternative way of considering the topic, emphasising user adaptations to service interruptions, alternative ways of representing societal impacts and the importance of context; and updating the thinking in each area almost twenty years later.

Several other more recent reports and papers have highlighted the importance of connecting societal functioning and infrastructure systems and advanced related concepts. The NEHRP roadmap for earthquake-resilient lifelines (NEHRP 2014) proposes the need for a 'framework for the establishment of lifeline system performance and restoration goals' and discusses societal expectations, benefits and costs associated with lifeline performance. Hasan and Foliente (2015, 2163) call for future work 'to model infrastructures and assess the socioeconomic impacts in a harmonized framework'. ATC (2016) discusses societal considerations and expectations related to lifeline performance extensively, enumerating factors affecting lifeline performance expectations, including a brief mention of substitutability and need, which relate to our concept of user adaptations. Links et al. (2018) offer conceptual and systems dynamics models of community functioning. They similarly address the societal impact of damage to infrastructure networks, but from a macro perspective, without including the details of lifeline performance in engineering terms. Among other research needs, Rojahn et al. (2019, 41) also propose first, to 'systematically study the relationships between service disruptions and societal impacts and expectations to better understand lifeline system performance'. Focused on the idea of functional recovery for individual buildings and lifelines, NIST (2021) suggests that basic intended functions are less than pre-earthquake functionality, implicitly supporting the importance of user adaptations in determining performance in societal terms. Davis's (2021) distinction between 'functionality' and 'operability' also highlights the idea that infrastructure system performance in engineering terms differs from that in societal terms. Together these works support both the potential usefulness of an ability to assess the performance of infrastructure systems in societal terms and the need to continue to improve methods to do so.

4. Conceptual framework overview

Figure 1 summarises the conceptual framework, with each arrow from Box X to Box Y indicating that X is an input required to determine Y. It refers to one infrastructure system but

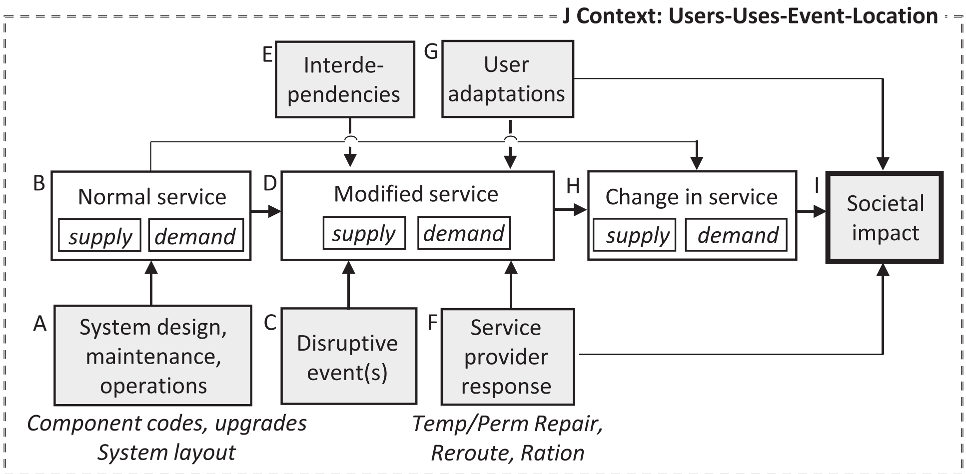

Figure 1. System-level conceptual framework of societal impact from infrastructure system disruption.

could be applied simultaneously to multiple systems, ensuring the hazard and context are consistent across them. The starting point (Box A) is the design and construction of the infrastructure system according to applicable codes, standards, and current practices (e.g. roads, substations are built). During normal times, components may be upgraded, and in general, the system is maintained and operated following relevant regulations, thus producing the normal level of service (Box B). While most of an infrastructure system is a formal network maintained and operated by a company or public agency, the boundaries can extend beyond that, as when households have solar panels on their home or use rain barrels to help meet their water needs. Here we consider the system to include all mechanisms that provide the services in normal times, although we focus in particular on the formal network. For each user, service is often defined in binary terms as being provided or not, with a service interruption then defined in terms of its duration. To be more precise, service (or system functioning) can also be described, for example, in terms of multiple *basic service categories* or dimensions of service that an infrastructure system provides, such as delivery, collection, quantity and quality (Davis 2021). For example, if water is provided but is not potable, delivery and quantity are met, but not quality. For the system as a whole, service could be defined, for example, in terms of the percentage of users or demand satisfied or percentage of users who receive each type of basic service. To capture the changes in these quantities over time as delayed effects propagate through a system (e.g. as tanks empty in a water system) and actions are taken in response, a restoration curve can track their values over time.

When a disruptive event occurs (e.g. earthquake, hurricane or wildfire) (Box C), physical components, such as cell phone towers or wastewater pipes, are typically damaged. In some cases, the service may be interrupted without widespread physical component damage, as in the 2003 Northeast U.S. blackout. In other cases, service may even be deliberately reduced to prevent system damage or environmental impacts (e.g. North Texas Freeze Event of 2021 (Marfin, Jiminez, and Steele 2021) or Pacific Gas & Electric's (PG&E) suspension of service to mitigate the possibility of fire ignition in 2020. The post-event *modified service* (Box D) is also affected by interdependencies with other infrastructure systems (Box E), as when an electric power outage affects telecommunications service. The planned and unplanned ways service providers and users respond to changes in service also have an important impact on the modified service over time. The former aim to reduce disruption by rerouting service around damage, implementing temporary and permanent repairs or possibly rationing service (Box F). The latter implement adaptations (Box G). They may address a modified level of service by reducing, delaying or relocating demand (e.g. skipping a shower or postponing laundry) or by augmenting water supply by buying bottled water or replacing electric supply by using a generator). User adaptations may be implemented by households, businesses or organisations in the community, as when a company or municipality provides warming/cooling centres. Adaptations are often not a perfect replacement or substitute for the disrupted service. They may be possible only for a limited duration or may support some but not all uses of an infrastructure system service. Candles, for example, can substitute for the light provided by electricity, but not home heating or cooking.

Although they appear as separate inputs required to determine to the modified service (Box D), the disruptive event, interdependencies, service provider response and user adaptations all interact dynamically during the post-event response and restoration period. Some adaptations will interact with other systems, for example, which may in turn stimulate other adaptations. For example, the loss of electricity in the Ottawa Ice Storm of 1998 provoked the use of woodstoves, which in turn led to officials to develop a wood distribution system (Scanlon 1999). The operational decisions of service providers and the adaptive actions of users interact with each other as well. Voluntary compliance with electricity conservation requests can lessen the imposition of other less voluntary steps, such as rolling blackouts.

The difference between the modified service (Box D) and normal service (Box B) is the change in service (Box H). While the damage-caused reduction in supply leading to unmet demand is perhaps the primary concern, the change in service more generally may include changes in the magnitude, type and/or location of supply and/or demand, likely varying over time.

Change in service can then be translated into societal impact, that is, the effect of that change in service on the ability of businesses to operate; emergency services to perform their duties; households to get to work and school; individuals to eat, drink, and bathe; and communities to function normally (Box I). The difference between the change in service and the societal impact recognises that an hour without electric power, for example, could have almost no noticeable effect for one household but a major life-threatening effect for another in other circumstances, for example, if it means an elderly person goes without heating or cooling in a severe climate. In addition to the effects of the change in service, the societal impact includes any cost in terms of finances, time, effort or other resources, of implementing service provider responses and user adaptations, represented by arrows from Box F to Box I and Box G to Box I, respectively.

The implementation of adaptations, societal impact and most everything that affects it depends on the context, including attributes and preferences of the users and characteristics of the event and the location (Box J). Adaptations, for example, may differ if the disruptive event is localised or more widespread, causing many other regional effects. They may differ based on the climate and population density of the location.

Finally, within this framework, infrastructure service providers can intervene in many ways to minimise the societal impact of disruptive events, both before and after an event, with examples noted in italics below Box A and Box F, respectively. The interventions vary in implementation timing, cost and magnitude and nature of the benefits they provide. For example, component-level codes and standards such as the 2017 National Electrical Safety Code affect construction of new components; whereas operator-imposed rationing of services does not affect the level of component damage (and therefore cost of physical repairs), but can influence the extent to which disruption of system functioning translates into disruption of societal functioning.

Sections 5–10 discuss the key concepts of disruptive events (Box C), interdependencies (Box E), service provider response (Box F), user adaptations (Box G), societal impact (Box I) and context (Box J) in more detail in turn. Note that these concepts vary widely in how mature and how quantitative the related research is, and which disciplines have focused on them.

5. Disruptive event(s) (Box C)

Box C in the framework involves describing: (1) the magnitude and nature of the disruptive event (i.e. the hazard), (2) any resulting physical damage to the components that comprise the infrastructure system and (3) the effect on the level of service through change in supply and/or demand. Depending on the particular application, the analysis may be deterministic, in which a single event is described, or probabilistic, in which all possible events and their relative likelihoods are represented. For resource allocation decisions, for example, probabilistic analysis is preferred because the best designs or policies often differ depending on which hazard event occurs. For an emergency response planning exercise, a single scenario may suffice.

Probabilistic analyses involve some complexities. They must allow assessment of the performance of the system as a whole and address the spatial correlation of the components. As a result, scenario-based approaches, in which the joint performance of all components is assessed for one hazard event (e.g. earthquake or hurricane) at a time, are preferred over approaches in which each component is individually evaluated for many events, and then the risk of the components are combined (Crowley and Bommer 2006; Han and Davidson 2012). Although probabilistic hazard analysis methods have been available for years, combining them with scenario-based analysis leads to computational challenges (Han and Davidson 2012).

The most straightforward way to accomplish probabilistic scenario-based analysis is using conventional Monte Carlo simulation, in which an event, hazard effects, component damage, system performance and possibly societal impact are simulated in turn; the process is repeated many times, and the results are combined. To capture the more intense, less frequent events, however, requires many replicates. With computationally intensive models of system functioning (e.g. traffic model for the highway system), this approach becomes highly inefficient if not intractable. Recent research has addressed these issues by developing methods to identify a computationally efficient set of hazard and damage scenarios, each with an adjusted annual occurrence probability, that can be used for probabilistic analysis of spatially distributed infrastructure.

In that approach, a relatively small set of hazard scenarios are developed that together, when combined with their adjusted occurrence probabilities, represent the full probabilistic hazard. Each hazard scenario is a map depicting a physically realistic possible realisation of the hazard effects associated with a single event, such as a hurricane (Han and Davidson 2012). Similarly, in cases involving extensive physical damage, a relatively small set of system damage scenarios are developed that, when probabilistically combined with the adjusted occurrence probabilities, create component damage distributions conditional on the hazard that match the 'true' ones. Each individual damage scenario specifies the damage state of each component of the infrastructure system in a way that is physically realistic and consistent with the associated hazard scenario. Another benefit of this approach is that the same hazard scenarios can be used to analyze multiple infrastructure systems in the region to ensure consistency and minimise effort.

Multiple specific methods can be applied or adapted to produce these scenario ensembles, including, for example, Jayaram and Baker (2010), Apivatanagul et al. (2011), Han and Davidson (2012), Du and Wang (2014), Manzour et al. (2016), Christou et al. (2018) and Soleimani et al. (2021). Brown et al. (2013), Gearhart et al. (2014), Miller and Baker (2015) and Soleimani et al. (2022) describe methods to develop a computationally efficient set of damage scenarios, each with an associated adjusted occurrence probability. The best method will depend on the particular application, considering time, data and computational resources available; hazard setting; infrastructure system type, size and complexity. In addition, it is important that the hazard, damage, and system function modelling fit together, which requires the metrics used in the hazard scenarios to be the same as those required by the damage model used in developing the damage scenarios, and that damage models exist for all physical components required to evaluate the system functioning associated with such damage. Finally, to examine interventions to improve the design of new components, retrofit of existing components or modification of the system layout, the damage model must assess damage both in the system's current state, and as it would be if its design is modified, its components are retrofitted, or its layout is changed. An advantage of the Brown et al. (2013) damage scenario method is that it includes, within each damage scenario, all the information to evaluate every possible combination of component retrofit or replacement strategies.

The last step in describing the disruptive event(s) is to translate physical system component damage into effects on users' service, which depends on the location and magnitude of damage, the system layout and functioning, and any changes in demand post-event. Damage on a large transmission trunk will affect more customers than damage at the end of a radial line, for example. Who gets services (e.g. gas or water) in a damaged system, can be modelled in many ways, including using connectivity- or flow-based approaches (Cavalieri et al. 2014). The former assesses performance through analysis of system topology changes; the latter considers the flow of goods too. Connectivity-based approaches (e.g. Li and He 2002; Crucitti, Latora, and Marchiori 2004), which may be enhanced to consider some features of flow (Bompard, Wu, and Xue 2011) can be simpler and less computationally-intensive but may fail to accurately capture performance. In flow-based approaches, models specific to the infrastructure systems are used, such as power flow (e.g. IPFLOW), hydraulic (e.g. EPANET) or traffic (e.g. user equilibrium) models. For water, applying a standard hydraulic network model to a heavily damaged system results in unrealistic negative pressures that can produce inaccurate flow, so special methods may be used to address that (e.g. Shi 2006).

6. Interdependencies (Box E)

Interdependencies refer to connections among different infrastructure systems. As an example, most other systems depend on electricity, which can be an important limiting factor in their functionality (Tierney 2006), the loss of which would provoke other shortages and needs for adaptations. Loss of electricity can hamper telecommunications; impede distribution of natural gas; and affect water. Generators require fuel, which may depend on fuel distributors' ability to maintain their own operations. Other dependencies may be geographic rather than operational in that a broken water pipe can trigger other failures in proximate systems that would otherwise have no dependencies. The interdependencies between systems can be cascading.

The nature and magnitude of interdependencies among infrastructure systems has been a major area of study since Rinaldi, Peerenboom, and Kelly (2001) enumerated their many forms, including physical, cyber and geographic. Studies have included empirical analyses of observed interdependencies in past events (e.g. Krishnamurthy, Kwasinski, and Dueñas-Osorio 2016) and many models of such behaviour (e.g. Adachi and Ellingwood 2008; Franchin and Cavalieri 2013). Hasan and Foliente (2015), Ouyang (2014), Yusta, Correa, and Lacal-Arántegui (2011) and Griot (2010) offer recent reviews of this work.

7. Service provider response (Box F)

When a disruptive event occurs, infrastructure service providers respond in planned and unplanned ways to minimise its effects. Methods typically used include rerouting service (e.g. vehicles, electric power) around damage, isolating damage to prevent propagation of negative effects (e.g. water draining from damaged pipes), making temporary and permanent repairs and providing temporary auxiliary supply (e.g. deploying mobile telecommunications towers or water in tanker trucks). The operators' abilities to respond vary depending, for example, on the size and nature of the system and damage it experiences, past experience with disruptive events, resources available and mutual aid agreements in place. Many infrastructure systems interdependencies exist (Section 6), requiring coordination among responses of different affected systems, such as when pipes, wires and roads are all collocated.

Notably, many of these response and recovery efforts aim to preserve the service even while physical damage to the network, which typically takes longer to repair and costs more, persists. This phenomenon implicitly recognises the primary importance of service provision over the condition of the physical system. In some cases, these responses are quite effective, ensuring outages are limited in geographic scope and duration. Electric power systems, for example, tend to allow a great deal of flexibility in rerouting around damage, helping to ensure that interruptions in the electric power system tend to be shorter than in the water system, for example, in which rerouting is not possible in many situations and usually cannot be implemented remotely or automatically.

Service provider response actions are expensive in terms of labour and materials, which can be translated into economic costs. They can also create costs that are less easily quantified, such as damage to the company's reputation and political capital. PG&E, for example, suffered reputation damage following responses to windstorms in Fall 2019 (Pritchard and Liedtke 2019). All of these contribute to the overall societal impacts of infrastructure system disruptions, as noted by the arrow from Box F to Box I in Figure 1.

Many of the service provider response efforts are preplanned, if not in the details, which depend on the particulars of the event, at least in the general types of efforts, roles and procedures. Since the service provider responses are a key point of control within the system, much engineering research has focused on developing tools to help optimise them (fuel in Duque, Yang, and Morton (2020), transportation in El-Anwar, Ye, and Orabi (2016) and water supply in Brink, Davidson, and Tabucchi (2012)). Some service provider responses may represent unplanned or loosely-planned improvisations as well, similar to those undertaken by users. As an example, after the 9/11 attacks, telephone providers stretched phone cables over the ground around the World Trade Centre area in New York City. After the 2003 Tennessee tornadoes, infrastructure service providers worked with public works to build roads to access remote electric poles.

8. User adaptations (Box G)

Following an emergency that damages or threatens critical infrastructure systems, users implement various adaptations to preserve the functions that are supported by the now-curtailed service. Users can adapt to electric power outages with flashlights, candles or portable generators, for example. They can go to a hotel or even move away from an affected location. The menu of potential adaptations is vast, limited only by the imagination and the ability to find inspiration in the local environment and online sources (Kendra and Wachtendorf 2003). In general, we define user adaptations as *actions taken by the recipient of an infrastructure service to fulfill their needs with methods other than those normally used.* They relate to what Bruneau et al. (2003) termed 'resourcefulness', what Luhmann (1989; cited in Comfort 1999, 29) termed autopoiesis (creative renewal), and what others have termed improvisation or bricolage (making do with what is at hand) (Weick 1993). While the concept has been around for years, interest in studying it and connecting it to engineering research has grown recently (e.g. Palm 2009; Chakalian, Kurtz, and Hondula 2018).

To understand the important role of user adaptations requires understanding the: (1) full accounting of possible adaptations, including how to classify them; (2) how each ameliorates a service outage situation; and (3) requirements to implement them. Each is discussed in turn in Sections 8.1–8.3.

8.1. Enumeration and classification of adaptations

A first step in understanding them is enumerating a list of possible adaptations. While no comprehensive list exists, many adaptations have been identified through prospective (what would you do), contemporaneous (what are you doing) and retrospective (what did you do) surveys, field observations and social media data analyses (e.g. Chakalian, Kurtz, and Hondula 2018; Palm 2009). In addition, several broad classifications of adaptations are available based on the literature, either proposed by researchers explicitly looking at adaptations or available from other relevant areas of study. These include those based on: (1) resource types used, (2) capitals and (3) effect on supply and/or demand.

For example, Chakalian, Kurtz, and Hondula (2018) cited *material*, *social* and *intellectual* resources applied by residents without electricity after Hurricane Irma. Some researchers have found psychological or affective adaptations. For example, Heidenstrøm and Kvarnlöf (2018), studying power outages in Sweden, reported that some households found the outage, and the subsequent reliance on stoves, candles and fireplaces, created a feeling of 'coziness', an agreeable change of routine.

Disaster research has sometimes taken a 'capitals' approach, and thus possible adaptations can be grouped by the kind of capital that is mobilised. Social capital is closely aligned with resilience (Dynes 2005; Aldrich 2011). Emergent groups are a regular feature of the post-disaster social landscape. Moreno and Shaw (2019) reported numerous self-help groups after the Chilean earthquake. In addition to social capital, scholars such as Gill and Ritchie (2018) have applied the Community Capitals approach, which also includes political, economic, natural, human, physical and cultural capital. Within the context of adaptations, collecting firewood or drawing water from an ephemeral stream mobilises several kinds of capital: natural capital, which could be a stream of water or grove of woods; cultural capital, which is knowledge of these sources; and economic capital or having the wherewithal to purchase the equipment needed for these tasks (Moreno and Shaw 2019).

Another possible classification of adaptations is their effect on supply and/or demand in the infrastructure deficient setting. In general, we can think of adaptations that reduce, delay or relocate demand for a service, or supplement the supply of a service. For example, one might reduce electricity demand by not watching a television show, delay demand by going to sleep early instead of working on the computer, relocate demand by going to a friend's house and using their electricity or augment supply by using an outdoor gas grill to cook, a candle for light or a generator for multiple electricity needs.

8.2. Adaptation benefits

Adaptations differ in the nature of their positive effects, in particular: (1) which type of infrastructure system disruption they are effective for, (2) the quality of the replacement service they provide, (3) the uses they support and (4) the duration of their effectiveness. Some adaptations, such as temporarily moving out of town, can address outages in multiple systems; others only work for one type of system outage (e.g. port-a-potties help with wastewater outages only). The quality of the service provided may vary as well, as when using water from a nearby lake or stream provides supplemental water, but unlike water from the piped network, it is not potable. Similarly, the uses that they support vary. Candles can offer some level of light that electricity typically provides, but they cannot help a computer function. Adaptations vary in the duration of their effectiveness as well. As examples, in most places, woodstoves would not be a long-term substitute for heat and flashlights eventually need batteries through a refurbished supply chain. Bolin (1994, 118–119) found families typically can stand to 'double up' for about a month before stresses develop, meaning that adapting by moving may actually require multiple moves and accommodation types.

8.3. Requirements to implement adaptations

All adaptations come with costs and constraints as well, although they vary greatly in magnitude and type, which may be in terms of required money; effort/time; equipment/special resources; stress; health effects; or effects on other facilities, systems or users. These costs all must be factored into the overall societal impact, as represented by the arrow from Box G to Box I (Figure 1).

While some adaptations are free (e.g. reducing demand or using water from a lake), some require money (e.g. buying bottled water or staying at a hotel). Some require effort or time, such as collecting firewood or going to a distribution location to collect government-distributed water from tanker trucks. Some, such as going to a neighbours' home to use the bathroom (wastewater system), put a strain on social relationships. Certain adaptations are only possible if one has special equipment or resources. An individual can only use a gas grill to cook if they have one. Other adaptations bring a cost in terms of inconvenience, as going to a coffee shop or public library to use the Wi-Fi when telecommunications systems are down. Candles and propane heaters can bring their own possible health effects, including the risk of fire and carbon monoxide poisoning (Klinger and Landeg 2014). Use of streams or other open sources of water may create a risk of waterborne disease if not treated – and boiling water may not be possible.

Finally, with the interdependencies of various systems, adaptations can have ramifications beyond the immediate user. The 2021 North Texas ice storm led many people to trickle water through their taps to keep the pipes from freezing, but so many did this that the water suppliers noted a drop in pressure sufficient to necessitate water purification advisories, at a time when electricity, often used to boil water, was not available. Improperly used generators can backfeed electricity *into* the electric supply line, reversing the normal flow of electrical power and posing a hazard to utility workers. Similarly, some user adaptations can put stress on other facilities. After Hurricane Sandy (2012), many people went to hospitals not because they were ill or injured but because they imagined hospitals would have emergency power for them to charge their medical devices. During the aftermath of Hurricane Maria in 2017, many people routinely travelled to places along the highway to access cellular service, which created a hazard within the transportation system.

9. Societal impact (Box I)

Societal impacts of infrastructure system disruptions are an active area of research that includes efforts to define the concept, to develop metrics to quantify it and to use those metrics to better understand societal impacts (e.g. magnitude; distribution across geographic areas, population groups and time; relationship to impact as defined in engineering terms). No consensus exists on the definitions and metrics, and the best ones likely depend on the particular application.

9.1. Definition

Here we define the concept of the societal impact of infrastructure system interruptions broadly as the *difference between life with the disruptive event and life without the event*. It is meant to capture not how much service has changed (e.g. change in percentage of customers served (Box H)) but the implications of those changes for the normal activities of households, businesses, organisations and communities.

We typically think of the impact in terms of the supply of the service being reduced and thus demand not being met. However, as noted in Section 4, in actuality both supply and demand change in multiple ways, and both the difference between the two and the differences for each between post-event and pre-event matter. Thus, contributions to societal impact can include (Figure 2): (1) demand not met, (2) demand met but not fully, (3) modifications to demand (i.e. relocating it in time and/or space) even if it is met, (4) cost of implementing service provider responses and (5) cost of user adaptations. When a restaurant requires electricity to refrigerate its food and that demand is not met, clearly there is a financial impact. In some cases, the demand may be met, but not fully, by adaptations implemented, such as when a household uses a flashlight to meet their lighting needs. The lighting is provided but not at the same quality as usual, and thus a cost is incurred. Users may adapt to a service interruption by delaying or relocating their demand (e.g. postponing the use of gas for cooking or doing it at a relative's house). Although in a sense, the demand is met in those cases, there may still be a cost associated with the change. In this case, the relatives incur the costs of supplying the gas, supplying the space and curtailing their own routines. Finally, there are clearly costs associated with implementing service provider responses (e.g. repairing damaged telecommunications towers) and user adaptations (e.g. buying a generator or bottled water), represented by arrows in Figure 1 from Box F to Box I and Box G to Box I, respectively. These may come in financial terms, in terms of time and effort required to implement, in terms of stress or in other ways.

Adding to the complexity of accounting for societal impacts, the implications of service interruptions can be considered along multiple dimensions, including financial, health and safety, time, effort, stress, environmental and political (Figure 2). According to Jenkins (2021), blame for the North Texas power failure extended to political officials and regulators. Kasperson et al. (1988), in their social amplification of risk model, hold that failures in one technical domain can reduce trust in other technologies seemingly

Contributions to societal impact

- Demand not met
- Demand met but not fully
- Modifications to demand even if met
- Cost of implementing operator responses
- Cost of user adaptations

Dimensions of societal impact

- Financial
- Health and safety
- Time
- Effort
- Stress
- Environmental
- Political

Figure 2. Contributions to and dimensions of societal impacts of infrastructure system disruptions.

not at all related, a cost that can extend far afield from the original failure. In theory, all should be considered. While financial costs may be easiest to quantify (though not easy), Stock et al. (Forthcoming) indicate that the time, effort and stress associated with responding to electric power and water supply outages influence households' perceived level of unhappiness more frequently than financial and health concerns, suggesting that multiple dimensions are important.

9.2. Macro vs. micro approach

Efforts to identify and quantify societal impacts can be grouped based on the scale at which they occur – macro or micro (Chang 2016). The macro approach aims to understand impacts directly for a community or region as a whole; the micro approach aims to enumerate impacts for individual businesses, organisations or households within a community, then aggregate them up to a larger scale if desired.

The macro approach includes using economic modelling techniques, such as input-output (IO) and computable general equilibrium (CGE) models, to evaluate societal impacts of infrastructure disruptions in economic terms (e.g. Okuyama 2007; Chang 2016), such as, Boisvert (1992), Cochrane (1997), Sohn et al. (2004) and Rose and Liao (2005). Other macro-level efforts have attempted to capture societal impacts more broadly. These include notable theories of resilience and well-being that integrate societal functioning and physical systems to understand community functioning. For example, Bruneau et al. (2003) unite social and technical systems in their theory of community resilience, and in fact, of the four domains of community resilience that they identify – technical, social, organisational and economic – three are explicitly about societal function. Links et al. (2018) posed a concept of community well-being whose centrepiece was the idea of community functioning. In developing both a conceptual and a system dynamics model of community resilience, they argued that resilience was a latent variable that could only be observed when the system became disrupted. The phenomenon of actual analytical significance was in the accompanying diminished community functioning (a measure of societal impact). They argued that the level of community function could be measured in advance by looking at the operation of multiple community systems. The level of disruption experienced during a disaster, that is, the loss of community function that a community would face was dependent on both social characteristics and physical characteristics (Links et al. 2018). To prepare for disaster, communities should invest in their social function, just as they should invest in their physical infrastructure. Taking both together would reduce the personnel, material, labour, money or other resources that would be required to restore system operations.

The micro approach tends to focus on businesses (Tierney and Nigg 1995; Webb, Tierney, and Dahlhamer 2002; Kajitani and Tatano 2009; Nocera and Gardoni 2019), households (e.g. Coleman, Esmalian, and Mostafavi 2020) or possibly other organisations (Chang 2003). It typically uses one of two main methods: (1) needs-based or (2) reaction-based. In the former, a list of needs or uses the infrastructure system service helps a household, business or organisation meet are enumerated (e.g. survival, hygiene, earning income and cooking), and the impact is defined in terms of the extent to which those are met (e.g. Tabandeh et al. 2019; Yang et al. 2021). The needs may be defined more specifically or generally, and their definition may depend on the infrastructure system and location. In the reaction-based measures, the impact of the service disruption is captured in terms of the household's or business owner's reaction to it, how they interpret the severity of the interruption and its implications (e.g. Dargin, Mostafavi, and Linkov 2020, Stock et al. Forthcoming). They typically implicitly include the effect of both any reduced level of service that exists even after adaptations and any negative experience associated with implementing the adaptations (e.g. cost of a generator or time spent getting water from a tanker truck). Most studies using the micro approach have relied on self-reported measures in data collected from surveys or interviews.

The macro approach may require less data and avoids concern about omitting people, groups or organisations in the counting. A challenge to the macro-scale approach, however, is that it tends to capture only phenomena with a signal in the data sources that are used, large data sets gathered at a large scale, often by government sources. These can lack the granularity to capture experiences at a higher geographic resolution, which is needed to explain why people make certain adaptation choices and not others, and to account for the extent of the losses experienced by users. It can also be difficult to make the direct link between infrastructure system interruptions and the societal impacts they cause (as opposed to societal changes with other causes). For this purpose, micro-scale approaches, oriented to households and firms, are needed.

10. Context

All aspects of the framework (i.e. all boxes in Figure 1) depend to some extent on the context. As an example and for brevity, we describe here the importance of the context on the implementation of user adaptations. Not all adaptations are equally likely to be implemented by all people in all situations. In a general sense, the decision to do an adaptation or not depends on a trade-off between the benefits (Section 8.2) and the requirements to implement (Section 8.3). These, in turn, depend on attributes of the users of the infrastructure system service, the uses of the service, the event that led to the service interruption and the location affected.

Users. The knowledge, experiences and resources of users can be expected to influence the adaptations that are available to them. Adaptations will emerge from these user characteristics, which in turn will point to the ease or sufficiency of the adaptations. Recent analysis of survey data from Los Angeles, for example, suggests that people with higher income are more likely to do adaptations that involve moving and people with elders in the household are less likely to move out of town (Abbou et al. in review).

Uses. Many infrastructure systems support multiple uses, some more critical than others. Many adaptations offer workarounds for some uses but not others. Thus, how users use the service may affect the rate at which different adaptations are implemented. If one uses electricity to work from home, electric power adaptations may play a different role for that person than for someone who does not. User attributes influence infrastructure uses as well. People with medical conditions may need reliable refrigeration or the operation of different in-home medical appliances, for example, some of which may not be amenable to easy adaptations, and which would therefore require the resident to move elsewhere.

Event. The characteristics of the event bear on the suitability of possible adaptations as well. The nature, geographic extent, timing, and duration of impact, for example, can all be expected to influence adaptations. For example, an earthquake, which may cause widespread damage to buildings and multiple infrastructure system types simultaneously, would present a different situation than a power outage like the 2003 Northeast blackout, which affected a large region, but without the accompanying structural damage. Season can also affect adaptations, as the feasibility of some depends on weather conditions (e.g. using rain barrels to supplement water). Adaptations may be suitable for short-term but not long-term implementation, and may or may not require setup time, making the duration of an event important as well.

Location. Location provides the climate, economic, social, cultural and political context in which adaptations occur. Many adaptations will be common across all locations (candles, flashlights), but others may be more specialised or place-specific (e.g. gathering firewood and hand-milking cows). Adaptations common in one climate or location may be untenable in another. For example, there are not always local streams from which to draw water. Similarly, in hot climates, adaptations that enable cooling when electric power is interrupted may be particularly common, as they were following Hurricane Irma in 2017 and Hurricane Ida in 2021, where residents sweltered (Chakalian, Kurtz, and Hondula 2018; Wendland and Chatlani 2021). Government and non-profit emergency management organisations, which also vary across locations, have a role to play in facilitating adaptations, such as establishing warming and cooling centres, funding hotel stays and making food and water available, making them influential in the adaptation landscape.

11. Conclusions

Many places will see future failures of infrastructure services, either from sudden-onset disasters or as the outcome of either slow degradation or environmental shifts that exceed the operational expectation and capabilities of the system. All levels and sectors of society will therefore face choices regarding how to manage the demands on their infrastructure systems. Any choice will have societal impacts; almost by definition, a choice implies finding a benefit but leaves some regret and disappointment and has an inherent opportunity cost. To navigate through these choices requires a framework that portrays the relevant systems as clearly as possible. Apart from making decisions, influential institutions will have to justify those decisions to perhaps-skeptical constituents. Decisionmakers and stakeholders can use models and frameworks in strategic planning and to organise options and priorities. Reduction of the asymmetric information between policymakers and constituents (or the public) may lead to more efficient outcomes.

Linking engineering analysis of system functioning to societal functioning is a difficult task, especially with the dynamic, heterogeneous intervening effects of infrastructure system interdependencies, service provider interventions and user adaptations. Different combinations of approaches to addressing each concept are possible and no single solution is likely to serve all purposes. The system-level conceptual framework presented in this paper aims to catalyse research and thinking across this large challenge in a way that moves those topics together towards the development of a clear basis for infrastructure system performance goals expressed in terms of societal functions, a method to assess the current performance of the nation's infrastructure systems in societal terms and a pathway to achieve the expressed societal performance goals. Implementation of a case study application of the framework would be valuable future work.

The framework that we have outlined is intended to be applicable to any hazard and to any infrastructure system. With sizable investment decisions to be made by public and private system operators, advanced methods are needed to guide choices that optimise the well-being of their communities. The work presented here is a step toward that goal.

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