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Constructs in Infrastructure Resilience Framing – From Components to Community Services and the Built and Human Infrastructures on Which They Rely

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Elise Miller-Hooks holds the Bill and Eleanor Hazel Endowed Chair in Infrastructure Engineering at George Mason University, is an advisor to the World Bank Group, and is founding Editor-in-Chief of IFORS/Elsevier's *Sustainability Analytics and Modeling* journal. Dr. Miller-Hooks previously served as a program director at the U.S. National Science Foundation and on the faculties of the University of Maryland, Pennsylvania State University and Duke University. Dr. Miller-Hooks received her Ph.D. in Civil Engineering from the University of Texas – Austin and B.S. in Civil Engineering from Lafayette College. She has expertise in: multi-hazard civil infrastructure resilience quantification and protection; disruption planning and response; transportation systems engineering; sustainability; intermodal rail- and maritime-based freight transport; real-time routing and fleet management: paratransit, delivery, ridesharing and bikeways; stochastic and dynamic network algorithms; and collaborative and multi-objective decision-making.

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Abstract

This paper describes five constructs for framing infrastructure resilience estimation. These constructs range from the consideration of a single component to a community service provided through a set of buildings whose functionality relies on interdependent supporting lifelines. A key aim is to explore how the construct that is adopted affects resilience understanding. It discusses the value of reframing the resilience computation around services that are provided by built environments rather than around the built systems themselves. The built environment would provide little in the way of services if not for human involvement and other needed resources. A construct for framing resilience is expanded to incorporate the role of humans as infrastructure, as well as permanent and consumable limiting resources, in creating service capacity. Taking a service-based viewpoint induces a change in perspective with rippling impact. It affects the choice of metrics for measuring resilience, adaptation strategies to include in assessment, baselines for comparison, and elements of the built environment to incorporate in the evaluation. It necessitates consideration of socio-technical concerns. It also brings hidden issues of inequity to the foreground. This paper suggests that underlying many resilience studies is an implicit construct for framing resilience, and explores how the construct affects and enables resilience understanding.

Keywords: Resilience, community services, built environment, human infrastructure, critical lifelines, socio-technical system

1. Introduction

Buildings provide shelter to sustain life and support community services, including, for example, business, manufacturing & production, health care, education, religion, judicial action, law enforcement, fire response, entertainment, shelter, and other necessary or enriching activities. The ability to support these functions depends, too, on access to functioning power, water supply, modes of transportation, and communications, as well as wastewater and sanitation services. Buildings and their supporting lifelines, though, are subject to disruption events that induce damage as might be caused by earthquakes, tsunamis, hurricanes/cyclones, flooding, and other natural occurrences, accidents, engineering and technological failures, and human-induced events of malicious cause. As such, many works in recent years have proposed methodologies for measuring or enhancing infrastructure-related resilience (see Sun et al. (2020) for a recent review). These works focus almost entirely on building or maintaining resilient structures (buildings, roadways, bridges) or civil lifelines. The underlying assumption is that the service that will be provided will be more resilient if the physical buildings and lifelines that support them are resilient.

Resilience of a system can be described in terms of its inherent coping capacity and its adaptability (Rose, 2004), and actions that can be taken to improve resilience are pre-event or post-event (consider the resilience action framework described in (Faturechi and Miller-Hooks, 2014a)). Questions of prevention and preparedness versus response have been studied in a variety of contexts, including, for example, treatment in animal disease (Elbakidze and McCarl, 2006) and abatement action to reduce or ameliorate climate change impacts (Heal and Kistrom, 2002).

Pre-event actions can be mitigative, increasing the ability of the system to absorb shock through, for example, excess capacity or greater resistance, and increasing system robustness, or they can be only preparatory. Preparedness actions may have no direct effect other than to support post-event response. They can include prepositioning equipment or people to have at the ready, training personnel for response or to substitute in if needed, and memoranda of understanding with suppliers. Pre-event actions ensure continuance (or quick return) of operations. Post-event, response actions are taken in the immediate aftermath of a disaster event (where external resources are required to cope with its aftermath); they impact rapidity - a measure of the speed at which the system recovers. Resilience is evaluated with an understanding of not only the system itself, but the human and physical options that are ready for quick and cost-effective deployment at the time of a disaster event. These “at-the-ready” options are often as critical to building resilience as is hardening a structure to withstand disaster impact, and may arise from emergent behaviors of system providers and users. For example, a community member has the idea to use social media to request that people within his or her network send personal drones to the location for increased situational awareness in a flooding event around a building. Such human innovation in a disaster event has additional impact on rapidity and in wider community resilience (O’Rourke (2007)).

Resilience may be measured as a function of performance achieved by a certain point in time (point performance) or total level of recovery achievement over a time period (period performance) (Faturechi and Miller-Hooks, 2014a). Sahebjamnia et al. (2015) propose a multi-objective, mixed-integer, linear program to allocate resources for maximizing recovery point and minimizing recovery time objectives in resuming and recovering of operations after disruption in the context of business contingency planning. Similarly, but in relation to importance metrics toward inland waterway resilience, Baroud et al. (2014) consider tradeoffs between bi-objectives of “time to full network resilience” (a point performance indicator) and recovery cost (a type of period performance indicator). Long-term recovery from population migration and land use changes (Fussell, 2015) might also play a role in resilience estimates, but is not considered herein. Here, the focus is on immediate service delivery, rather than long-term community recovery, and, thus, the emphasis is on the first three (mitigation, preparedness or response) of the four phases of the disaster management lifecycle (Waugh, 2000).

Alternatively, resilience can be viewed in terms of the time to component or system recovery to a particular state or performance level. The United States (U.S.) Department of Homeland Security defines resilience in terms of the ability to withstand a disruption event with little loss in function or the ability to rapidly and efficiently restore functionality if loss is incurred (Presidential Policy Directive/PPD-21). Resilience is defined by the European Commission as the ability to withstand, cope, adapt, and quickly recover from an event without compromising long-term development (European Commission, 2014).

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These concepts are captured in early work by Bruneau et al. (2003) who depicted resilience in terms of initial reduction in performance due to a shock and time to re-establish normal performance, i.e., recover. Thus, they considered a resilient system to be one that has reduced probability of failure, reduced consequences as a result of failure, and reduced time for recovery to normal operational levels, which they cast more broadly in terms of the four R's: robustness, redundancy, resourcefulness, and rapidity. McDaniels et al. (2008) proposed the use of decision flow diagrams that integrate pre- and post-event actions that impact system robustness and rapidity (two of the four R's). In earlier work, Haimes et al. (1998) described the hardening of water supply systems in terms of security, redundancy, robustness and resilience. Resilience was defined as the ability to operate post-event technically and institutionally at near design levels with reasonable economic losses. Consistent with these various definitions, the idea that a system is resilient if it can maintain or re-attain an acceptable level of functionality considering the hazard event scale and type at a reasonable cost and level of effort in an acceptable amount of time underlies the discussion herein.

This paper structures the infrastructure resilience discussion around several distinct constructs, including an alternative framework for evaluating and building resilience that focuses on community services and the people who use them. It suggests that inherent to many resilience studies is an implicit construct for framing resilience, and explores how the construct affects and enables resilience understanding. Following a description in the next section of framing resilience around these constructs, aspects of resilience evaluation that impact, or are impacted by, the perspective taken are considered. These include: hazard event considerations (Section 3), the role of performance measurement and agnostic metrics (Section 4), adaptive capacity (Section 5), and equity concerns (Section 6). The paper wraps up with conclusions and extensions (Section 7).

2. Constructs for Framing Resilience

Five constructs for framing resilience in the context of physical, infrastructure-based systems are described. These constructs are based on: (1) a single structure or system component, e.g., a bridge in a roadway network, a substation in a power network, or a pump in a water supply network; (2) a single lifeline, such as a roadway or an electric power distribution network, including numerous components, considered as a technical or engineered system; (3) multiple, interacting (interdependent) infrastructure systems, e.g. water, energy and transportation, considered simultaneously; (4) single or multiple infrastructure systems that support a service for users, creating a socio-technical system; and (5) a network of buildings with similar function supported by interdependent lifelines that together enable the provision of a service, e.g., health care delivery or governance, termed Critical Infrastructure-based Societal Systems (CIBSS) herein.

In an age of digital-based services, the CIBSS-based construct could frame resilience of virtual gatherings and workspaces in terms of the geographically dispersed buildings that house individual participants with services that rely on lifelines, especially power and communications. In this case, however, the supporting lifelines may not be interdependent as typically regarded, as they may exist across wide areas of the globe.

These five constructs are illustrated in Figure 1. The figure depicts the first construct of a component through a single suspension bridge. The bridge and pavements together create a roadway system used to illustrate construct 2 (a system). Construct 3 is given by interdependent networks through roadway and power distribution systems, where dependencies and interdependencies can arise in their operations and post-disaster repair. These first three constructs underly most infrastructure resilience works.

The fourth and fifth constructs that focus on service provision rather than technical component or system functionality require a user- or service-based viewpoint, which induces a change in perspective with rippling impact. It affects the choice of metrics for measuring resilience,

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adaptation strategies to include in assessment, baselines for comparison, and elements and systems of the built environment to incorporate in the evaluation. It necessitates consideration of socio-technical elements and brings hidden issues of inequity to the foreground. Many of these aspects may be omitted from consideration if a purely engineering component (e.g., structure) or technical systems (e.g., a single lifeline) viewpoint (following construct 1, 2 or 3) is taken.

Taking a user perspective in investigating the resilience of a single technical system as in the fourth construct can also induce interdependencies with other systems that may not be recognized from a technical system perspective (Vodopivec and Miller-Hooks, 2019). As portrayed in the example in the figure, a user of the bus transit system will use the internet to obtain information in support of taking adaptive actions during a disruption. If the system were considered only from a technical perspective, interdependencies associated with the telecommunications system used by riders would not be recognized. This is discussed in greater detail in Section 4.3.

Architects, engineers, urban planners and governments design and build civil infrastructure, including buildings, connections and supporting lifelines, to enable and protect community function. The functionality of these buildings depends on the functioning of the lifelines (the fifth - CIBSS - construct). For example, to serve its students in person, a school requires power, water, access (transportation links), sanitation services, and more. The lifelines that support the buildings and their activities depend also, sometimes reciprocally, on each other (e.g., pumping water requires power and power can require water supply) (the third construct). Such interdependencies have been studied in detail in numerous works (e.g. Reed et al., 2009), a comprehensive review of which is given in (Ouyang, 2014). Capturing the functioning of the built environment with its reliance on interdependent lifelines through the CIBSS resilience-framing construct (the fifth construct) puts the community function or service at the center of the resilience evaluation. The figure also illustrates the CIBSS concept in which the services provided from buildings (the built environment) rely on the ability to sustain functionality of the services of interdependent supporting systems (combining aspects of constructs 3 and 4).

This CIBSS approach of construct 5 to evaluating and enhancing resilience of our civil infrastructure systems and their services was described by Mieler and Mitrani-Reiser (2018) and Tariverdi et al. (2019a) in the context of post-earthquake loss of functionality in buildings and emergency hospital services, respectively. Mieler and Mitrani-Reiser developed functionality-restoration curves to depict recovery of buildings given the functioning of building components and supporting lifeline systems. They describe a performance-based approach to resilience considerations for buildings. Tariverdi et al. proposed a multistage stochastic, mixed-integer program with embedded hospital wait time metamodel to model the hierarchical problem of maximizing the health-care network's resilience to potential hazard-demand-damage scenarios accounting for the hospital's dependence on interdependent supporting lifelines of water, power, sanitation, communications and access via transport links. The metamodel was parameterized from outcomes of runs of a multi-unit, patient-based, discrete-event simulator replicating key hospital functions under surge demand (Tariverdi et al., 2019b). In their work, concurrency in operations across lifeline systems is captured through the mathematical modeling of shared states as suggested by Haimes (2018).

The ability to provide services, including services of supporting lifelines, relies on the availability of resources, including equipment and human capital. Consider that manufacturing plants require machinery and materials for production, schools require learning environments and materials for teaching, and hospitals require beds for serving patients. Additionally, even in highly automated systems, manufacturing plants cannot function without operators, schools can house desks, but without teachers, educational goals cannot be met, and hospital beds cannot be used to serve patients if they are not adequately staffed.

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Numerous works have noted the importance of human activity and human action in building resilient communities (e.g., Godschalk, 2003). Taking this a step further, Mieler and Mitrani-Reiser (2018) recognized the role of human action, whether as individuals or organizations, or more abstractly through policy and regulation, in loss of functionality and downtime of buildings. They describe this role using the term "human infrastructure." The U.S. House of Congress $3.5 Trillion Human Infrastructure Bill, H.R.5376 117th Congress (2021-2022), known as the Build Back Better Act (U.S. Congress, 2021), also explicitly recognizes the importance of humans as integral elements of the infrastructure or even as infrastructure themselves. Interdependencies between healthcare and kindergarten through high school (K-12) education in building community resilience is studied in (Hassan and Mahmoud, 2021). Their work explicitly acknowledges the providers, patients, regulators, payors and suppliers of the healthcare system and the teachers, students, parents, administration, community, regulators and suppliers of K-12 education as main components of these systems. They integrate this human role through the use of agent-based simulation modeling (ABM) in assessing social services stability and show the importance of recognizing that these service systems are interlinked in facilitating community recovery.

In a more general sense, the human role in resiliency has long been recognized. Haimes et al. (1998), for example, describe the importance of delegating authority to support response. In a study of past catastrophic events effecting transportation systems, Deblasio (2004) states the need for redundancy in trained personnel for creating resilient systems. Human action was noted to be key to organizational resiliency, one of the two key elements of system resiliency noted in (McDaniels et al., 2008). More directly related to humans (and other resources) as infrastructure in resilience computation, Shahverdi et al. (2020) account for the effects on service capacity and resilience level of resource shortages and enhancement strategies in a hospital system.

Taking a space- and service-based perspective as through a CIBSS' (construct 5) framing enables the incorporation of human capital, equipment and consumable resources. Thus, the earlier CIBSS concept in (Mitrani-Reiser (2018) and Tariverdi et al. (2019a)) is expanded here to incorporate this "soft infrastructure" as integral components of the built environment, further embracing the idea of humans as infrastructure.

Consider each building element as a gear that contributes to the function of a larger service system as illustrated in Figure 2a. Each building gear is housed in the physical space of the building in which human capital, permanent equipment and consumable supply gears operate together to create a service. A similar conceptualization of the supply chains and logistics systems that provide resources to the buildings is given in Figure 2b.

Building on the gear analogy, Figure 3 illustrates the expanded CIBSS framework, where buildings function together to provide a community service. Resources at the buildings are stocked from functioning supply chains and logistical operations that, too, depend on staffing, drivers, operators and resources (raw materials and middle products) for manufacturing and production, as well as transportation to end users. The buildings and supply chains also rely on infrastructure lifelines that work together to provide critical support. If any element of the buildings or supply chains and logistical operations is stalled due to physical damage or staff shortages, service capacities will be diminished. This figure aims to illustrate the service as a product of the interconnected built environment. Resilience of the service is, thus, dependent on the functionality of all physical and human infrastructure that are needed to provide and support the service.

The resilience of this system of built and human infrastructures can benefit from excess capacity (created through the physical infrastructure (e.g., space), excess equipment, supplies and staff), hardening, increased adaptability (e.g., substitutions or quick repairs), and innovation. As time-of-day and season can affect staffing, resilience can also be measured as a function of disaster event timing. A hospital, for example, will have more staff during usual business hours than in the

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middle of the night, creating greater daytime capacity for handling a mass casualty incident (MCI) than one that would occur at night or on a holiday.

Figure 4 provides a general framework for building a mathematical model for computing and optimizing resilience of a particular CIBSS that is expanded to explicitly incorporate space (the building), staff (human capital) and stuff (other resources needed to supply provided services). The model is bi-level, involving an upper-level government or private company that invests in the infrastructure and resources to support services from the CIBSS. Staff and stuff are embedded within the model through mathematical equations that map personnel (e.g., doctors, nurses, technicians, administrators in a hospital), equipment (e.g., computers, beds, ventilators, laboratory equipment) and consumable resources (e.g., blood, oxygen, medications, saline, clean linens) to service capacities. In the hospital example, service capacity is a function of number of staffed beds and limitations on needed physical (space) and personnel resources (staff and stuff).

The model can incorporate patients with different needs by indexing patient classes. Staff can be assigned to hospital units based on needed skills. A lower level can provide a feedback mechanism for assessing service experience by users of the CIBSS under considered, probable hazard impact scenarios, which can cause physical damage to the CIBSS, absenteeism, and supply chain disruptions, all of which may have differing impact on patients with differing needs. The scenarios are fully realized in the last stage of the multi-stage stochastic program in the upper level. Multiple stages can capture investment decisions and adaptations taken in each of the phases of the disaster management lifecycle, as well as stages of the recovery process (Tariverdi et al., 2019a). The multistage, stochastic program in the upper level also enables a multi-hazard analysis as discussed in Section 3. The inclusion of staff and stuff in the mathematical constraints facilitates the modeling of secondary and tertiary hazard effects as discussed in the next section.

The other four resilience-framing constructs can readily be cast through various simplifications of this CIBSS-based mathematical modeling framework. Their specification depends not only on the resilience framing, but also on the application as discussed in Section 4 (Table 3 in particular). An infrastructure-light application with digital-based services and geographically dispersed participants could apply the same modeling approach, but with careful consideration of the dependencies and interdependencies between a broader application incorporating supporting lifelines that are both centralized (supporting the online meeting platform) and decentralized (supporting power at geographically separated service recipients) and the lifelines that interconnect with these services.

3. Hazards and their impacts

The vast majority of works consider resilience of a component (e.g., bridge (Bocchini and Frangopol 2012)) or system (e.g., water supply (Haimes et al., 1998) or electric power (Ouyang and ue s-Osorio (2014)) to a specific type of hazard (e.g., flooding (McClymont et al., 2020) or malicious attack (Barreto et al., 2014)), or the occurrence of a specific, deterministically defined hazard event (a what if prespecified scenario, e.g. from a specific hurricane event as in (Mensah and Dueñas-Osorio, 2016) or a flooding event that roles out dynamically as in (Zhang et al., 2022)).

Infrastructure systems and components and the services they facilitate may face hazard events with a variety of causes. These hazards may be of natural cause with notice, e.g., hurricane/cyclone, wind, sea level rise, storm surge, drought, fire, or without (e.g., earthquake) or with limited warning, e.g., flash flooding or tsunami. They may arise from malicious intent and be targeted or coordinated, or physical or cyber in nature. They may occur as a result of an accident, technical system error, human error, implementation failure, aging of materials, failed parts, production mistakes, bugs in code, organizational challenges, technological interruptions, and more. They may be specific to the application, such as vessel shoaling and grounding in navigable waterways in a maritime system, a

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train derailment in a rail system, or a hazardous-materials release from a chemical plant. Last, the hazard may be a pandemic, such as the COVID-19 pandemic, that leads to intermittent workforce reductions, directly affecting the ability of the system to provide service or indirectly impacting these services through reduced function of supporting lifelines and critical supplies from affected supply chains. Along these lines, but prior to the COVID-19 pandemic, Shahverdi et al. (2020) evaluated the impact of absences of nurses in hospitals due to illness during a flu outbreak on the resilience of hospitals in a region.

Resilience to one type of hazard does not make for a resilient component, system or service. Moreover, readying a system for one type of event or one event realization can worsen the system's performance to a different event realization or type. For example, hardening a structure to withstand a blast of a specific load can reduce the structure's flexibility and make the structure more vulnerable to collapse in an earthquake. Likewise, the protocols to follow under one type of event may differ from that under another type, and the environment in which the systems operate can affect these protocols. In an earthquake in a suburb, it might be advisable to move people to open land; whereas, in a large, dense city near water, it may be best to send them to the top of their buildings to avoid being crushed or to high ground due to risk of tsunami. Similarly, locating generators in a basement for decreased public accessibility and, therefore, greater security, can leave the generators vulnerable to flooding. In a fire, it is best to leave the building; while in an attack, it may be best to shelter in place. As no location is prone to only one type of hazard, it is critical to design, enhance and prepare for multiple hazard types and impacts. Thus, a resilient component or system will not be prepared for an event of only one hazard class (e.g. earthquake) or with only one effect, but rather for the effects of a host of possible events of varying causes. Moreover, it will be ready for not only one realization of the event impact, but rather many. This need for readiness through an all-hazards approach for creating resiliency is discussed in, for example (Paton, 2015).

Even if the types of hazards to plan for are clear, the precise impact on the infrastructure and the location of people and/or animals at the time of occurrence can at best be known with uncertainty. Thus, a multi-hazard approach that is both all-hazards and accounts for the possibility of numerous actualizations of the hazard event is essential. Such an approach takes mitigative and preparedness actions to hedge against a host of possible eventualities, each with its own probability of occurrence. Risk-neutral (e.g., expectation), probabilistically robust (e.g., worst-case) and reliability (e.g., maximum worst-case service level) metrics can guide decisions (Asadabadi and Miller-Hooks, 2020). The role of risk aversion in pre- versus post-event action is discussed in (Heal and Kristrom, 2002) in the context of economic modeling toward countering climate change. With a sufficient number of potential scenarios (event impact possibilities) considered, stability in the metric can be assured (Chen and Miller-Hooks, 2012). When resilience is measured to only a few or select scenarios, the system should be considered resilient to these specific events or events with similar characteristics.

There are additional uncertainties in everyday operational attributes of a system. Zhou et al. (2021), using a digital port twin within a port resilience computation framework, account for such uncertainties, where the exact duration required for operations within the port, such as the exact time it takes for a ship to berth, is known only probabilistically *a priori*.

Hazard types mentioned thus far are presumed to arise from extraordinary events. In reality, small, more typical events may arise with similar effect. Consider, for example, a case involving construction work, where a water supply pipe is cut. That water supply may be required to support the lavatories of an operation, such as a port. Without water, the lavatories will be closed and, depending on labor laws in the region, workers may need to be sent home and operations shut down. That is, the port may be temporarily closed in its entirety due to a rather mundane event. Hazard events may also be only threats of events, e.g., a bomb scare or a cyberattack warning. They may also be compound events, where two hazard events arise simultaneously, such as a cyberattack on a

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hospital that is in the midst of serving a surge in emergency patients from a bad flu season, COVID-19 or a MCI. Or perhaps one hazard event follows another, for example, fire after a blast, power loss caused by a crippling cyberattack, or gas leak in the aftermath of an earthquake. Last, the hazard may be slow growing, gaining larger and larger impact over the long run, as is the case in climate change.

In considering resilience in terms of a societal function or service as in construct 5, hazards might also be categorized as primary, secondary or even tertiary. Examples are given in Table 1 for such a service perspective. Secondary and tertiary hazard events are often described as primary hazards with cascading impact and are a consequence of dependencies or interdependencies between systems that affect supply-side structure or capability, the workforce (or human infrastructure) that creates service capacity, and supplies needed to provide service, i.e., space, staff and stuff, respectively. A hazard event may also arise as a direct consequence of a severe change in demand for a service. Building systems and the services they support (CIBSS) are, thus, affected by hazard types at primary, secondary and tertiary levels. Rinaldi et al. (2001) considered n^{th} order effects related to interdependencies. As CIBSS rely on interdependent infrastructure lifelines, these direct and indirect hazard events and n-th order effects from interdependencies are particularly relevant.

Many secondary and tertiary effects are the consequence of indirect effects from human involvement in service provision. These effects occur when the service capacity of one service system can impact the service capacity of a second system. Vugrin et al. (2017), in considering resilience of the electric power grid, while not explicitly modeled, list as an effect of a power outage loss of critical emergency functions, including police, fire and hospital services. In another example, the capacity of a healthcare system in a region can lead to increased absenteeism by staff and students in K-12 education, reducing educational outcomes (Hassan and Mahmoud, 2021). Casting human capital and human impact on service provision and service capacity as integral to the CIBSS enables these secondary and tertiary effects to be captured.

Note, too, that the facilities of the CIBSS themselves may not be impacted by the event, but the event may incur disruptions in supporting services. Failure mechanisms that may cascade across interdependent lifelines have been studied in detail (see, e.g., Hernandez-Fajardo and Duenas-Osorio (2013)). Additionally, supply chain disruptions can impact resilience of services provided from within buildings. For example, a delay in the supply of clean linens could potentially shut down a hospital if that hospital does not have alternative suppliers or physical access to alternative supply sources.

4. Performance metrics and agnostic measures

4.1 The Role of Performance Metrics in Resilience Assessment

Revisiting resilience in terms of continuity of service reveals the role of performance metrics in resilience assessment. A technical component or system (using constructs 1 or 2, respectively) is resilient if it continues to function in the face of disruption, whether due to post-event adaptation or built-in redundancies, excess operational capacity or other inherent system properties. In some circumstances with great consequence, a more sizeable drop in functional capacity or service quality may be acceptable if the drop is small in comparison to the disruption level; that is, if continuity of service is at an acceptable level for the circumstances. That system's resilience might, instead, be measured against an acceptable threshold value, or by its ability to speedily bounce back to close to pre-event service levels. Note that the measure of resilience is in terms of the system's ability to provide service and not in the physical state of the system or system components themselves. Focusing on service, such as regional health care system delivery, the resilience of that service will be given in terms of continuity of service rather than the state of the built environment in which care is given or the state of its supporting lifelines. If alternative measures are in place to support continuity of service, then the health care system may still be resilient. On the contrary, and

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indicative of the importance of a service-based approach, as demonstrated in early 2022 with staff shortages due to the COVID-19 pandemic across sectors, even if the built environment is unaffected or minimally affected by a hazard event, that event may reduce the availability of human capital and cripple the built environment's capacity to provide service.

This idea of measuring resilience in terms of continuity of service suggests that the resilience of a technical system can be judged based on key performance metrics relevant to that system and the services it provides. For example, a measure of continuity of service built on throughput may be appropriate for measuring resilience in rail-based cargo transport, while travel delays may be better suited to an application in roadway networks with independent drivers. Moreover, the resilience of services provided through CIBSS will be measured on relevant, service-based performance metrics, e.g., wait times at emergency departments in hospitals, despite that the CIBSS' resilience depends on the performance of the buildings and their supporting lifelines. Performance measures that might play a role in resilience computation for a variety of applications are given in Table 2.

Mathematical representation needed for resilience quantification typically, thus, depends on the application. Numerous works discuss resilience as a function of system performance generically. See (McDaniels et al., 2008) for an example. However, the use of such generic constructs in actual resilience measurement requires models that capture the application details. Table 3 gives example applications where performance is specified for a particular system, the performance measures used within their resilience measurement, and the mathematical modeling approach used to capture these details. While a comprehensive list of applications with metrics and mathematical models is beyond the scope of this article, as the resilience literature has grown exceptionally large in recent years, the contents of this table suffice to illustrate the need for detailed modeling of the application in resilience computation.

There are works, some of which are listed in Table 3, that take an economic loss approach to computing resilience. Such losses can be obtained through computable general equilibrium (CGE) or input-output (IO) modeling. A comparison of economic losses by sector due to a historical rainstorm event from 2012 in Beijing as computed by these approaches is given in (Tan et al., 2019). They estimate losses across 13 sectors: agriculture; mining; manufacturing; production of electricity, fuel and water; construction; wholesale and retail; transportation; accommodations and catering; finance; real estate; technical, commercial and other services; and education, health and publication administration. These more macroscopic methods may not be sensitive enough to assess the value to system resilience of very specific resilience enhancement actions.

4.2 Agnostic Metrics and Baselines

Resilience can be quantified through agnostic metrics that aim to provide consistency, generalizability and broad applicability (NASEM, 2021). Beyond Bruneau et al. (2003) and taking a similar approach wherein resilience is thought of in terms of both the system's inherent coping capacity and ability to adapt post-disruption, Nair et al. (2010), building on concepts from Chen and Miller-Hooks (2012), describe resilience in terms of the fraction of pre-event performance that can be achieved post-event with limited resources in a short response time. Vugrin et al. (2011) proposed a qualitative resilience analysis framework that assesses absorptive, adaptive and restorative capacities and builds on a resilience definition based on the system's ability to reduce the magnitude of deviation from, and efficiently return to, a target performance level. Considering the ability of a system to bounce back from an event, a time-varying ratio of recovery to loss measurement is proposed in (Henry and Ramirez-Marquez, 2012). This approach relies on a performance metric representing some element of functionality, such as origin-destination connectivity or length of usable roadway links, and a baseline. In an investigation into unifying concepts of resilience and sustainability, Bocchini et al. (2014) reviewed several of these and other general approaches. A review of resilience measure definitions can be found in (Hosseini et al., 2016). These metrics of

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system resilience, while agnostic, still implicitly or explicitly rely on a measurement of the system's ability to perform and a baseline for comparison, which typically, inherently assumes pristine conditions.

As with performance measures that underlie a resilience analysis, the choice of baseline for comparison in resilience measurement can greatly affect the final outcome. In the context of infrastructure lifelines and the built environment, it is reasonable to expect that most system elements are at least partially deteriorated from their new condition, and maintenance actions may or may not have been undertaken recently (Levenberg et al., 2017). Thus, in most cases, presuming a pristine baseline is fallacious. In fact, the condition of the infrastructure is in constant flux as a result of natural deterioration and maintenance or rehabilitation activities. Consequently, resilience may vary over time and can depend on the timing of the hazard event in relation to the state of the system components. Levenberg et al. showed that rather than providing a single resilience metric, a range of metric values or curves might be offered that each accounts for the damage incurred depending on the timing of a hazard event and its relation to the age of the system's components, along with past maintenance and restoration applications. Resilience metrics that directly measure the ability of the component or system to bounce back, would, thus, need to recognize the state of the system at the time of event impact.

A resilience analysis of a CIBSS should similarly account for the state of its built components supporting systems, including supply chains, at the time of hazard impact, as well as the status of its human infrastructure, which may depend on the time-of-day or season in which the hazard event strikes.

4.3 Whose Resilience?

When more than one system, each with their own service goals, interact and both are considered simultaneously, a question of which infr structure's perspective to take in measuring resilience arises (Fotouhi et al., 2017). Consider, for example, two lifelines, such as power and an arterial roadway network. As power is needed to enable the operation of traffic signal control devices and the roadway network supports repair crews post-disaster, these networks are interdependent. The actions taken to bring back one system can impact the performance of the other. While resilience measurement for each system may not change as a result of considering these systems simultaneously, which adaptive actions to prioritize either pre- or post-event will depend on which system is the focus of resilience improvement. Thus, the question of whose resilience to consider arises. Should traffic performance be the focus or unmet power demand? The impact of focusing on one system over the other can be abated by using a multi-objective approach, but whose preference function should be used in constructing a value (utility) function (the objective in a related optimization) or in choosing a best compromise solution among Pareto-optimal solutions?

Consider, now, refocusing on a specific community service with its lifeline supports (construct 5). Suppose the focus is on a regional K-12 education system. The CIBSS from which education is delivered requires power, clean water supply, sanitation, sewer, suppliers of, for example, meals, and transportation (access and school bus transport). Resilience of this regional education system to disaster requires pre- and post-event action on the CIBSS. Rather than organizing investments to support mitigation or adaptation in any one system, optimal investments to enhance resilience of K-12 education will focus on keeping the school system's buildings and transport services open and operating. Post-event, this means that coordinating the repair and restoration actions across lifelines will be required, and each lifeline may need to forgo or delay actions that it would choose if operating in isolation to protect or aid recovery in other lifelines and to best support the quick recovery of the education system if schools are prioritized. In fact, in discussions with state maintenance engineers in Virginia, U.S., in a disaster event (e.g. even in a major snow storm) that occurs while the school buildings are in use, or when used as shelters in a

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disaster event, protecting the occupants and securing access to and from these buildings is a core priority for communities.

Different users may experience a system differently in both routine operations and a disaster event. In a disaster event, each user will have unique coping capacity and adaptive capability. Taking a user perspective (through construct 4) in assessing resilience, thus, will provide greater insight into the system's or community function's ability to provide adequate services. Consider users of a rail transit system in a dense urban area. These users are diverse. Some may be mobility challenged and may need support in navigating the system and its stations. Others may be local to the area and savvy users of ride hailing services. A third group may be visitors who have little knowledge of how to use alternative services in the area, such as local bus transit. An outage that affects elevators and escalators may have little impact on the service level provided to the second two populations, while the first population may be entirely precluded from accessing the system. Local users and those who readily access services of ride hailing apps may have adaptive actions that visitors or those who have not previously used ride hailing may not have. Considering services provided rather than technical system functionality in resilience analysis may engender a need for multiple resilience estimates, each relevant to a different population of users. This infers, too, that the pre- and post-event resilience enhancing actions that might be taken could differ depending on the target population of the system users. But the analysis is not as simple as this suggests. Resilience of the technical system cannot simply be re-considered from the perspective of a a single vantage point, i.e. a single group of users with common attributes, because users of different populations simultaneously use the limited capacity of the system and alternatives that support adaptation action. This is discussed in more detail in (Vodopivec and Miller-Hooks, 2019).

Resilience values may vary by stakeholder, as well. In a maritime system, shippers may measure resilience as a function of cost, while ports may focus on throughput, and a system perspective might focus on system-wide social welfare metrics, such as origin-destination demand served (Asadabadi and Miller-Hooks, 2018). In these circumstances, the system may appear resilient under a disruption event or set of events to one stakeholder while not to another. Likewise, in considering the resilience of a hospital as a technical system, the hospital may be considered resilient, but from the viewpoint of the larger community, where resilience may be measured in terms of the health of the population during the disaster event (as considered in Cimellero et al., 2010), it may not be.

That resilience is a matter of perspective also impacts the choice of a baseline in agnostic resilience computation discussed in Section 4.1, because the choice of a single baseline for comparison presumes that acceptable or pre-event conditions are the same for every user. In the transit example, the baseline for some users may be much lower than for other users, e.g., a user relying on working elevators in the transit system may experience more disruptions in routine conditions than other users. There also may be ordinary disruptions in some working systems, and one population may fare better when one fares worse. Resilience of the system from an individu l' s perspective may be a matter of the population into which a person falls.

Considering resilience of services as suggested herein, rather than focusing on resilience of the contributing engineered system, supports the need for such user-based, perspective-driven resilience analyses as described through resilience framing constructs 4 and 5.

5. Adaptive Capacity

Adaptive capacity is key to building a resilient system or service, and the effectiveness of adaptive capacity toward building resilience can be quantified. Adaptive capacity can come in the form of substitution and conservation (Rose, 2004), and can eliminate many worst-case, post-disaster situations (Nair et al., 2010). Adaptive capacity alone is not enough, however. Resilience requires

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time to take adaptive action, which depends on the application, as well as disaster severity. For this, consider the resilience indifference curves in (Faturechi et al., 2014) that show resilience as a function of time and budget/effort allotted for an acceptable response in resilience computation.

In some applications, adaptations may be permitted in certain circumstances that allow performance of the system to exceed its original performance. This can occur, for example, in hospitals in a state of emergency, where crisis standards of care are permitted. Such alternative standards enable reduced wait times to initial service and greater throughput by allowing for lower general standards of care for each individual. With such adaptations, resilience measurements must be carefully constructed. If the measurement is created on a baseline that is aligned with pre-event conditions, the resulting measure may suggest high levels of resilience despite that the delivered service is subpar in terms of services received in routine circumstances (Tariverdi et al., 2019a).

There may be competition across systems for resources to support adaptive actions. Building adaptive capacity in one system may not be sufficient for creating resilience in another interconnected network. Moreover, adaptive actions can induce dependencies and interdependencies as was created through a user perspective on resilience of a transit system discussed in the prior section.

Adaptive action may contribute to, but could also weaken, system resilience, and the action's effectiveness depends on implementation (Arctic Council, 2016). Consider that the effectiveness is a function of implementation skill, institutional relationships, access to resources and technologies, support, and social networks. Effectiveness is also a function of time and place. The Arctic Council (2016) suggests the existence of seven interlinked and interacting sources of adaptive capacity that are categorized as: (1) Natural capital, guided by international and bilateral agreements; (2) social capital, i.e., the ability for people to work together as governed by social norms and mutual trust (Coleman, 1990; Putnam, 2000); (3) human capital; (4) infrastructure; (5) financial capital, including subsistence and sharing economies and formal monetary economies (Larsen and Fondahl, 2014); (6) knowledge assets, which shape our understanding of the circumstances; and (7) cultural capital, including belief systems (Blumer, 1969). Resources are considered a precondition for the ability to activate these capitals of adaptive capacity (Bay-Larsen and Hovelsrud, 2017).

An assumption underlying all resilience-framing constructs that the best adaptation strategies will be used in a disaster event may implicitly inform the resilience computation, and optimization-based methods of resilience quantification, such as in (Miller-Hooks et al., 2012), may incorporate best adaptation measures of those considered in the analysis. Resilience computation for CIBSS can, likewise, readily incorporate not only optimal adaptations taken to repair elements of the built environment, but also actions to support adaptations, such as reconfiguration, mobilization of personnel (e.g., from the national guard in the U.S.) and other resources, opportunities for substitution (e.g., Rinaldi et al., 2001), and the role of on-the-fly decision-taking (i.e. innovation, O'Rourke, 2007) or emergent behavior (e.g. Noji, 1997). No matter the vastness of adaptation strategies that may be considered, optimization-based methods provide maximum resilience values by assuming that optimal adaptation decisions will be taken with flawless and effective implementation. In actuality, the effectiveness of even an optimally chosen adaptation strategy may not be known with certainty in advance. Methods that account for uncertainty in the outcome of adaptive actions are needed.

6. Inequities in Resilience

Taking a service-based approach to resilience computation highlights the need to consider potential for inequity that may otherwise be hidden when taking a technical-system perspective on resilience that focuses on whether a system component or wider technical system continues to function. Issues of inequity can come to light when considering services received by populations with different

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demographics or geographical locations in resilience measurement. Inequity issues, however, may be hidden in the actions that are taken to mitigate for, prepare for, respond to, and recover from hazard events. It may be that the actions taken to protect large portions of the community are at the expense of a few and that the few who are affected are disproportionately from a particular location or demographic. Consider the construction of sea walls, where the construction of the walls may protect high-value property while negatively impacting poorer coastal communities.

Likewise, resilience metrics may inadvertently be weighted by population. An underlying bias that shifts protections away from less populous, more rural, and possibly poorer communities could unknowingly be put into effect. Resilience metrics constructed as a function of numbers may also lean toward larger businesses and away from smaller, possibly minority-owned businesses. In the beginning of the COVID-19 pandemic, efforts to help restaurants stay open led to unintended benefits for large chains in this business sector (Lucas, 2020).

Moreover, adaptations that are to be counted on for attaining claimed resilience levels may not exist in some communities. Consider the evacuation of New Orleans at the onset of Hurricane Katrina in 2005. Authorities presumed inaccurately that inhabitants of the area would have the physical and financial means to evacuate (Parenti, 2005). The poor lacked the monetary capital to secure transport and distant lodging that would enable needed adaptive behavior. If there are commonalities in the communities that lack the ability to activate adaptive capacity or that lack needed natural, monetary or social capital, for example, there is likely to be bias, intended or not, in terms of which communities in reality fare well.

A service-based analysis (constructs 4 and 5), particularly if designed to consider different populations of users, and if carefully constructed, can help illuminate some of these hidden biases and eliminate resulting, unintended inequities.

7. Conclusions and Extensions

This perspective paper describes several constructs for framing resilience. These constructs range from the consideration of a single component to a service provided through a set of buildings whose functionality relies on interdependent supporting lifelines (a CIBSS) and required human infrastructure and limiting key resources for the intended services. A key aim of this work is to show the value of reframing the resilience discussion around services that are provided by built environments rather than around the built systems themselves. With a service-based angle, the ability of the built environment to continue to perform the functions for which it was constructed, and difference in service quality or quantity across populations, can be evaluated. Even if all physical components are in pristine condition, the built environment would provide little in the way of services if not for the contribution of humans who are crucial to the creation of service capacity in most civil infrastructure systems. The CIBSS resilience framing of construct 5 is expanded here to incorporate this role of humans as infrastructure. It further incorporates the role of equipment and limited resources, including consumable supplies.

The perspective taken herein suggests the need for a multi-hazard (and all-hazards) approach that recognizes the uncertainty in the timing and impact of disaster events. When possible also recognizing the uncertainties in the effectiveness of adaptation strategies and ordinary circumstances when used as baselines for agnostic metrics should also be carefully considered. Recognizing the uncertainty in performance and possibility of smaller disruptions in ordinary circumstances suggests the possibility of alternative resilience assessment approaches that do not use simple baselines, but might instead compare distribution functions from pre- and post-disaster circumstances. For example, the time required to reach a point at which there is no longer a statistical difference between pre- and post-disaster distributions of performance may serve as a resilience measurement. An alternative probabilistic threshold for meeting a given system performance level may be applied.

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With this approach, a system would be considered resilient if service levels of all populations of users are met at a given point in time based on relevant, population-dependent thresholds.

In summary, this work aims to bring to the forefront the role of perspective in resilience assessment and enhancement. Perspective affects measured values, intentional action, included components and systems, performance evaluation and ultimate conclusions. It enables the consideration of engineered systems with a deeper, socio-technical understanding. Ultimately, it connects the engineering of our systems to the people these systems are designed to serve.

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Data Availability

Not relevant.

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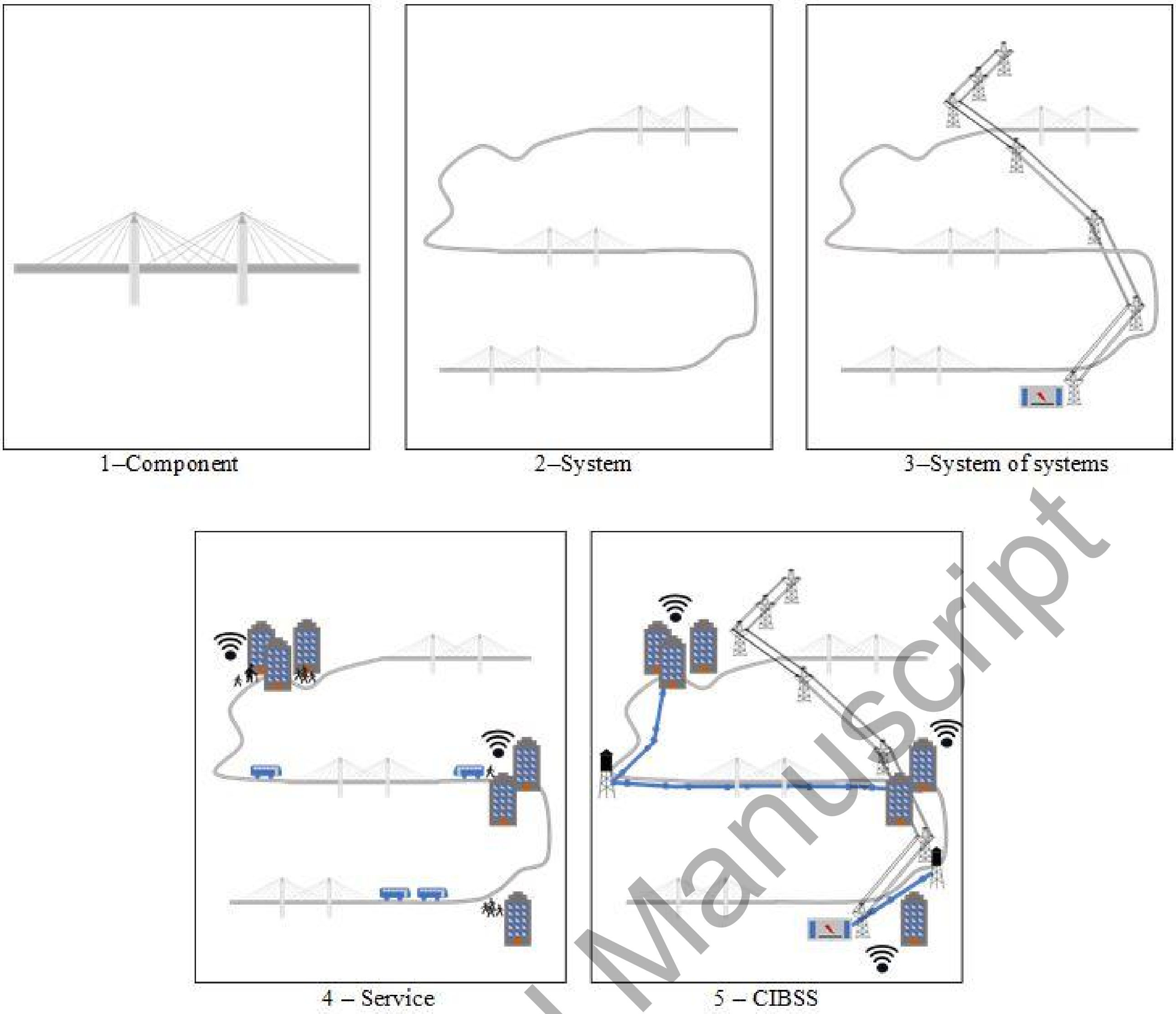

Figure 1. Five constructs for framing resilience of physical systems or their components; Construct 5 can be expanded to include resources and digitally distributed services

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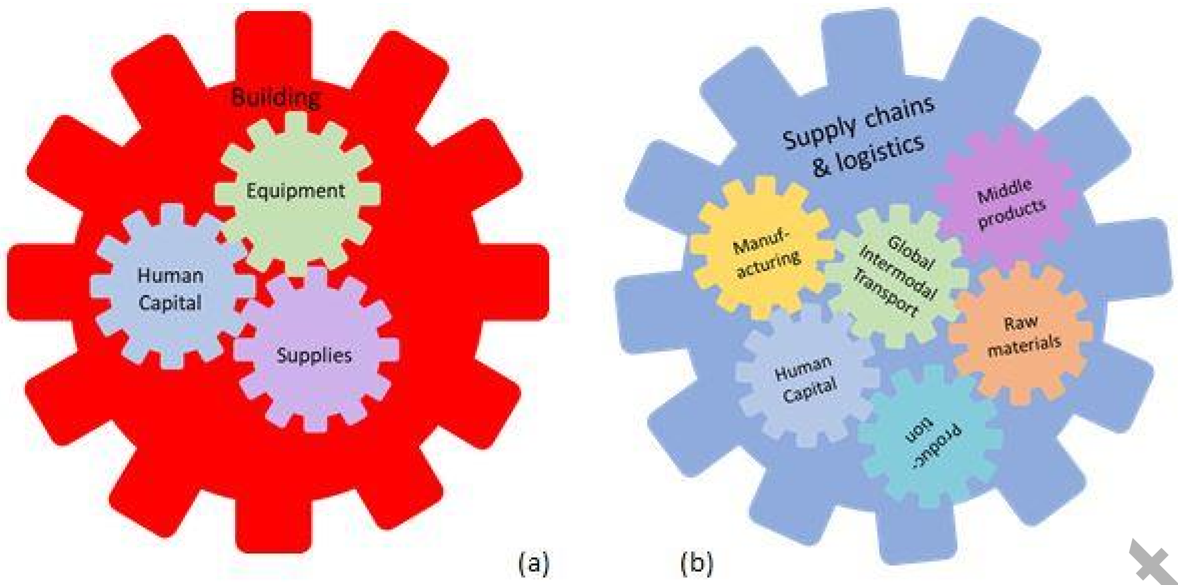

Figure 2. Conceptualizing the buildings and supply chains as gears that contribute to a larger service system

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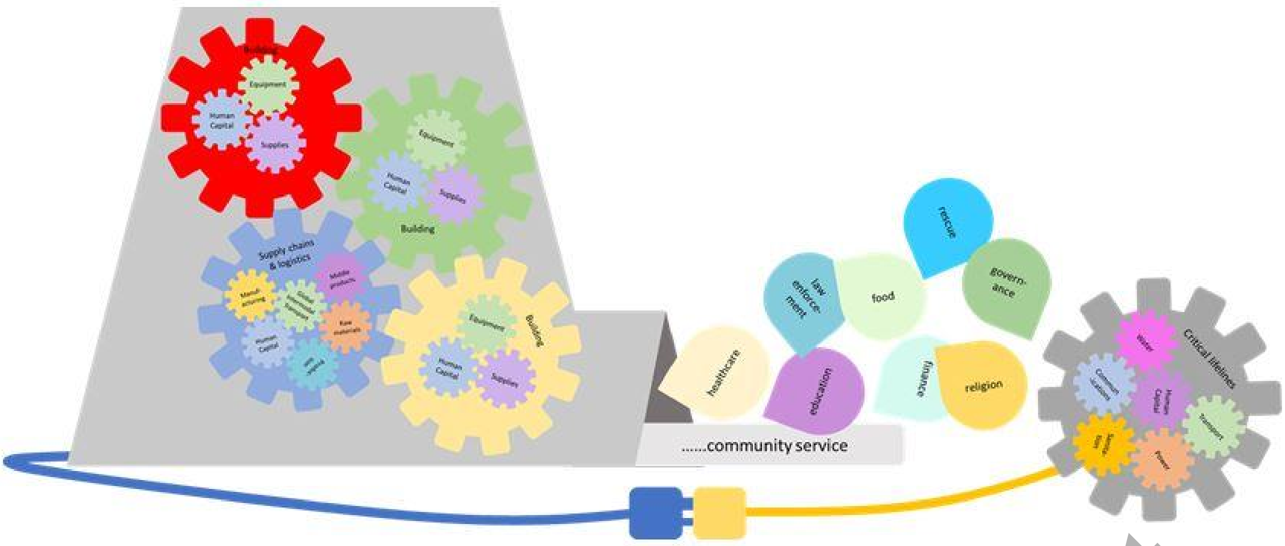

Figure 3. Taking a service-based, resilience perspective given interacting and supporting physical and human systems

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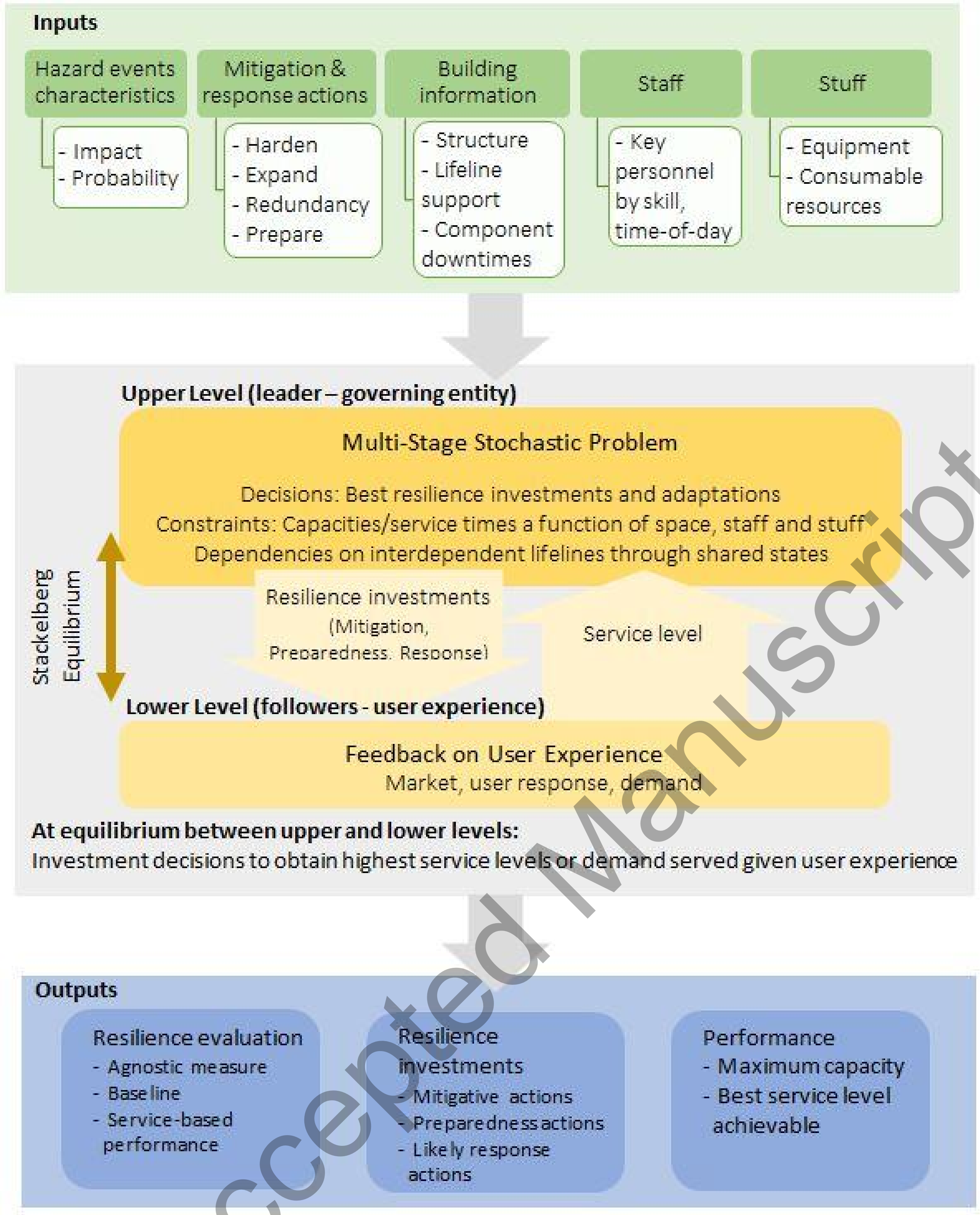

Figure 4. High-level mathematical modeling framework overview for resilience evaluation assuming an adopted expanded CIBSS-based construct (construct 5)

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Table 1. Example hazard events with direct, secondary and tertiary impacts from the CIBSS perspective.

Hazard event	Primary event	Secondary event	Tertiary event
Earthquake	Hospital damaged by earthquake	Gas and water pipelines are damaged by earthquake and can no longer serve the hospital	Earthquake damages manufacturing plants in a region, severely restricting critical supplies needed to repair damaged pipelines that support the hospital
Pandemic	Pandemic creates huge surge on hospital	School-aged children of hospital staff require parental care, reducing available workforce	Workers overseas sickened by pandemic, cause lower product output, which reduces availability of critical supplies and thereby reduces hospital capacity
Flooding	Courthouses are flooded	Access routes to courthouses are flooded	Roadway repair and cleanup crews sent to flooded access roads create decreased access or block pathways from neighborhoods preventing critical personnel from reaching courthouse.
Cyberattack	Financial servers attacked	Power grid attacked causing power outage at financial institutions	Attack on dam holding water needed for nuclear power plant leading to power outages at key financial institutions

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Table 2. Example performance metrics for resilience measurement appropriate to application and event.

Application	Event	Example relevant metrics
Health care	MCI requiring regionwide emergency care	Fatalities, waiting time, time to first service, access or response time
Power	High winds	Unmet power demand
Water Supply	Malicious event	Volume of water delivery or output
Health care	Cyberattack on hospital	Patients turned away at the emergency department entrance
Airport	Natural hazard or pandemic that affects staffing	Number of takeoffs and landings, flight cancellations, passengers rebooked, total delay, cost
Port	Storm with power outage	Throughput, number berths per hour, vessel accidents
Education	Pandemic	Student contact hours, reading levels, standardized testing scores, enrollment capacity

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Table 3. Applications and implications for mathematical form in performance-based analyses of resilience.

Application	Performance measure	Mathematical form	Citation
Intermodal rail cargo and ports	Throughput; berth on arrival	2-stage stochastic program (SP); digital twinning & simulation	Chen and Miller-Hooks (2012); Nair et al. (2010); Zhou et al. (2021)
Roadway traffic	Travel time delay	Bi-level with 3-stage SP at upper level (UL), partial user equilibrium (UE) at lower level (LL)	Faturechi and Miller-Hooks (2014b)
Maritime transport	Throughput – port perspective; Cost – shipper perspective; Total OD demand service – system perspective	Equilibrium problem with equilibrium constraints	Asadabadi and Miller-Hooks (2018)
Inland Waterways	Commodity flows in tonnage	Stochastic optimization	Baroud et al. (2014)
Airport	Number takeoffs and landings	2-stage SP	Faturechi et al. (2014)
Health care	Waiting time, access time & fatalities; patients who are not served; treatment times; staffed bed; operational capacity; economic loss, casualties and quality of life	3-stage SP; discrete-event simulation; ABM; influence diagrams	Tariverdi et al. (2019a); Shahverdi et al. (2020); Hassan and Mahmoud (2021); McDaniels et al. (2008); Cimellero et al. (2010)
Coupled traffic-power	Delay (unmet power demand)	Bi-level with 2-stage SP at UL, UE at LL	Fotouhi et al. (2017)
Transit	Level of service by user class	Extension of fault trees with multi-valued decision diagram with multi-valued logic functions	Vodopivec and Miller-Hooks (2019)
Water supply	Water service disruption and multi-sector economic impacts; output losses contributing to economic resilience measurement; water delivery volume	Computable general equilibrium (CGE) analysis; vulnerability analysis	Rose and Liao (2005); Rose (2004); Haimes et al. (1998)
Electrical service	Cumulative customer-hours of outages, unmet power demand, customers experiencing outage, monetary losses; economic impacts (e.g.	Multi-step estimates of event consequences; CGE	Vugrin et al. (2017); Wing and Rose (2020)

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	power output, electricity price, welfare)		
Petrochemical production	Market value of production	Cost computations using integration	Vugrin et al. (2011)
Energy infrastructures of electricity, oil and gas	MWh not served, barrels of fuel not consumed, Mcf of gas not delivered; fuel supply continuity; gas flow, pressure and speed	System-specific models to estimate output and consequences for users given defined threats; expert interviews & data synthesis	Watson et al. (2015); McDaniels (2015); Cimellero et al. (2015)
Education	Student outcomes; enrollment capacity	ABM	Hassan and Mahmoud (2021)

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