An Interconnectivity Framework for Analyzing and Demarcating Real-Time Operations Across Critical Infrastructures and Over Time

Abstract

Models and modeling of interconnected critical infrastructures are on the rise. A different framework is provided here for analyzing and distinguishing interconnected operations in real time and over time. Our framework treats interconnected operations as the unit and level of analysis rather than as methodologically distinct operations of conceptually separate infrastructures. We focus on interconnectivity configurations, shifts, connected system control variables, and changing performance standards across important shifts. Implications of the conceptual and methodological refocusing are drawn for policy and management. Our framework allows for a new understanding of reliability in relation to interconnectivity management, including the identification of potential errors in assessing and acting upon interconnectivity shifts. These include failing to recognize when changes in communication patterns need to follow from interconnectivity shifts and neglecting the operational importance of improvisations where system control variables (like electricity frequency or water pressure) overlap or are shared. Larger implications for interinfrastructural and societal safety are drawn throughout.

Introduction

This article addresses the bulleted question in the *Special Issue*'s call: "What is the role of uncertainty in an interconnected, global world where safety problems are no longer isolated to a single sector or organization?" In so doing, we build on insights developed in and since the earlier special issue of *Safety Science* on societal safety, critical infrastructure reliability and intersectoral governance (Volume 118, Part C, December 2018).

Our objective is to bring greater analytic clarity both to the systemwide operations of interconnected critical infrastructures and to implications that follow, including those for societal safety.[1] (Think of interconnected critical infrastructures as core to the societal safety identified and discussed in Almklov et al, 2018). The article seeks to do so by demarcating infrastructural operations and management of system risks and uncertainties in new ways.

Specifically, the notion that an infrastructure more or less stays operating until an intervening incident occurs, misses the fact that societally important interconnected infrastructures encounter variation and continue their operations, even while some of their major technical units are revamped or they are themselves deregulated, reorganized, or pass through bankruptcy, with many real-time interruptions along the way.[2]

The rationale of the proposed framework is set out, discussed and summarized in the next section, with initial implications sketched. The section thereafter is devoted to framework specifics, details and examples, with subsequent sections demonstrating how the framework recasts two major topics for interconnected infrastructure performance: improvisations and

[1] Many of the examples in support of our argument are drawn from research in Oregon and Washington on the potential impacts of a catastrophic earthquake on major critical infrastructures west of the Cascades there. The research is based on extensive interviews with emergency managers and infrastructure operators from late 2021 to the time of writing. Our argument also draws from earlier research on interconnected infrastructures in northern California.

[2] A long-term case study of the California Independent System Operator in balancing shifting interconnectivities precipitated by electricity deregulation and later on by significant market redesign is provided in Roe and Schulman (2008, 2016).

communications. The article concludes by drawing out broader implications for the safe performance of interconnected critical infrastructures.

As for terminology, interconnections are detailed and illustrated in the following pages. Risk and uncertainty are used conventionally here. Risk requires knowing the probability and consequences of a failure (Pf and Cf, respectively). Uncertainty reflects when either Pf or Cf is not known, but the other is ("uncertainty with respect to Pf," "uncertainty with respect to Cf"). Unknown-unknowns reflect neither Pf nor Cf being known (sometimes also referred to as unstudied conditions, ignorance or Knightian uncertainty).

Framework rationale, elements and initial implications

Arguably the most consequential discrepancy in conceptualizations and methodologies for critical infrastructure operations is that, while most everyone acknowledges major critical infrastructures are interconnected, descriptions rely on the single infrastructure as the recurring template for differentiating these operations. Electricity, water, roads, telecoms and the like are typically singled out—"isolated to a single sector or organization," in the words of this *Special Issue*'s call for papers. Just as typically the operations of each are described in terms such as normal, disrupted, restored, failed, recovered, or the like. The framework proposed here, in contrast, starts with interconnected infrastructures as the unit and level of analysis, i.e., "its" operations are "interconnected operations," latently and manifestly from the get-go.

There are conceptual and methodological frameworks that center on interconnectivities (the closest being that of Louise Comfort [2019] in her benchmark contributions to understanding earthquake response; see also Pescaroli et al, 2018 and de Bruijne, 2006). It is, however, necessary to underscore the persisting absence of interconnectivity in the frequently used concepts of safety culture and organizational culture. These concepts (especially "safety culture") often do not encompass inter-organizational networks of connectivity, for example.[3]

The approach offered here parses the interconnectivities and implications differently than is currently the case. Interconnected operations of interest are more complex and include latency and can vary substantively over time and in real time. The types and configurations of interconnections change, along with performance standards and system variables under management, as task environment conditions change, including but not limited to those posed by disasters.

By way of example, consider an up-and-running oil refinery plant for hazardous fuels. To focus on three of the major interconnections, the refinery's electricity from the energy utility, the water for its cooling system from another utility, and the roads (or waterways) for transporting out petroleum coke are clearly linked in the real-time refinery operations. It wouldn't be an oil refinery if it didn't have these and other interconnections, even if some modelers assume away as separate and distinct the energy, water, and transportation personnel and assets for reasons of modeling tractability (Radke et al, 2018).

[3] The concepts and terms "safety culture" and "organizational culture" are by and large directed toward single formal organizations or sub-cultures within these organizations (both of which are stable enough to "have a history" and share "basic assumptions that are taught to new members" (see Schein [2004], Guldenmund [2010] and Antonsen [2009]). The concepts have rarely been described nor applied to shifting cross-organizational interactions. In fact, it is not clear how to grow a safety culture across separate organizations (Schulman, 2020).

Similar reservations apply to the early research and descriptions of High Reliability Organizations (HROs). This article's proposed framework, as shall be seen, extends well beyond precluded event performance conditions for HROs. HRO analysis has also been focused primarily on single organizations, not on shifting interconnections between organizations as in our frameworks.

It is useful to treat the electricity, water and transportation interconnectivities just described as a base condition against which to compare shifts in the interconnections that can and do occur in the face of emergencies and new technological developments, to name two intervening factors. The hazardous fuels transportation sector is a good example of where volatility in companies, organizations and markets, has been a key feature of its ongoing operations (Library of Congress, Oil and Gas Industry Research Guide). Once one adds to the mix an earthquake or flooding induced by rising sea levels and storm surges (Mikellidou et al, 2018), the interconnectivity types, configurations, and standards of performance change and so do their implications. Other infrastructures and stakeholders emerge and become instrumental for ongoing infrastructural operations (not just for the oil refinery, but also for the interconnected water and electricity utilities and transportation structures in the example). These include government emergency management departments and agencies during a disaster and new political players and agendas during recovery.

Our framework starts with base-level interconnectivities (both operational and latent) and includes subsequent changes in interconnectivity configurations induced by shocks such the technological developments or new regulatory regimes.

Four core elements of the framework are identified from previous research on large interconnected infrastructures (Roe and Schulman, 2008, 2016, 2018; Schulman and Roe, 2018). First are the different types of base-level interconnectivity that exist between and among the infrastructures, in this case those for real-time electricity, water (potable and wastewater), roads and telecoms. Second are the points at or phases during which the types of interconnectivity shift and reconfigure.

Third is the criticality of real-time operational behavior involving system control variables, whose interconnectivities can and do shift when the control variables of different systems become shared or overlapping in unusual ways. Think of control variables as actionable features of an infrastructure—e.g. transmission path for a high voltage grid or water releases for dams in a water supply system—used to adjust the condition or state of the infrastructure as operational requirements or the task environment changes. Fourth and for our purposes last, all this is managed to systemwide performance standards for safety and reliability that also can and do shift to reflect changes in interconnectivity configurations and control variables.

Each of the four elements could be and has been studied on their own, e.g. legislating highly variable portfolio standards for renewable energy use (Congressional Research Service, 2021). The approach here, however, considers the four elements together. The argument is that by focusing on the *shifts* in the configurations of interconnectivity readers can better appreciate "the role of uncertainty" in this *Special Issue*'s call, namely:

1. systemwide risks and uncertainties shift with the performance standard and control variables being managed;
2. improvisational behaviors, which by definition have no guarantees, are key when making a real-time match between system demands and resource capabilities; *and*
3. probabilities and consequences in managing causally-understood operations are not the same as "operating blind' and "on the fly" in the face of unfolding events that demand improvisational behavior across interconnected infrastructures.

Nonmeasurable uncertainties that characterize the latter can and often do convey important information for infrastructural operations before, during and after the disaster. Indeed, such information about uncertainties is especially significant when causal understanding is obscure (Schulman, 2021).

Two caveats are in order. The principal research findings used in this article are drawn from different years, different infrastructures and different jurisdictions. In addition, different literatures have their importance for understanding specific infrastructure operations not discussed here, such as repair and maintenance (Jackson, 2015; Gupta, 2020; Ramakrishnan et al, 2021; Curnin et al, 2020; Auclair et al, 2021).

The argument is that, even with the caveats, the framework elements better capture how some shifts are foundational to the safety and reliability of society's critical infrastructures. By way of examples and in terms defined more fully below, we will be illustrating shifts from pooled and mediated interconnectivity to intensive interdependency (as when US Coast Guard telecommunications fail, thereby leaving ships to communicate directly with each other). We also illustrate shifts from sequential interconnectivity in one direction to reversed directional dependency (as in the importance of individual user electricity conservation in emergencies to keep the grid running without blackouts). Last but not least for our framework are shifts from pooled risk mitigation to system risk amplification (as when all energy providers to the transmission grid become hostages to the least reliable generator).

Framework in detail

This section turns to a formal discussion of the four elements, with details and examples. We draw principally from three sources: the 2018 *Special Issue* of *Safety Science*, previous publications on high reliability management (including those already cited), and our more recent and ongoing research on emergency management planning and organization around a catastrophic earthquake scenario for the US Pacific Northwest. The latter research provides the interviewee quotes used hereafter.[4]

Because of their centrality in our interviews and research, the interconnections between lifeline infrastructures of electricity, water, roads and telecoms are the focus. We first differentiate between uni-directional and bi-directional interconnections. We then look at these base-level differences in terms of their shifts from latent to manifest interconnectivity, with more complex interconnectivity configurations and shifts being identified. Especially critical shifts in conjunction with shared or overlapping system control variables are then discussed. We will see how these shifts distinguish or otherwise demarcate interinfrastructure operations over time, including those associated with what is conventionally known as longer-term recovery. After that, we turn to the fourth framework element, performance standards and then to the special features of recovery.

Base-level interconnectivity and types of interest. Think of interconnectivity as uni-directional or bi-directional. In the former, there is a one-way serial dependency, as when a

[4] The Pacific Northwest research, from which are drawn the key informant quotes, is supported by the National Science Foundation under Grant 2121528.

water pumping station depends on an electric provider, while a hospital relies on the availability of that fresh water.

In a bi-directional relationship, the influence and dependency connection is reciprocal, as when a road along a levee depends on the support and strength of the levee, but the levee depends on the road for access of materials and repair crews to repair levee seepage and breaches (Roe et al, 2016). It is common in ordinary language to conflate interconnectivity with interdependence, but the latter term is reserved here for reciprocal, bi-directional connections. "Interconnectivity" is the broader category in this article.

Such interconnections are, to be sure, found within an infrastructure heuristically defined as separate and distinct. One Pacific Northwest water association manager described how a study that made visible the regional (physical) interconnections between the association water providers proved to be useful for developing strategy for moving water among themselves in times of mutual need. That intrainfrastructural connectivity is important, but what concerns us in this article are interinfrastructural interconnections, configurations and related shifts.

For example, one reason some critical infrastructures manage to the avoided events reliability standard—that is, certain events should be avoided, even if they cannot be absolutely prevented—is that they can't preclude failures of the infrastructures they depend upon and which depend upon them. Managing to avoid events that cannot be prevented is characteristic of what are called the lifeline or backbone infrastructures for energy, water, telecoms and roads, defined as such because they are so interconnected and differently so, pre-disaster and post-disaster.[5]

Shifts in configurations of interconnectivity. While base-level interconnections are uni- and bi-directional, actual interconnectivity includes not only *manifest* interconnections, as in the oil refinery's dependence on electricity and water supplies. Just as important are the *latent* interconnections that become manifest, e.g., bringing in the emergency management agencies after a major earthquake has voided the refinery's backbone interconnections. Observed shifts from previously-latent to now-manifest interconnections are a major indicator of notable changes in infrastructural operations. A city water system, by way of example, would have to depend on electricity being in place, were it to fallback to pumping groundwater sources once its gravity-fed system had failed.

It is necessary to note that some latent interconnectivities and their configurations are only "revealed at the time of the incident," as one interviewee with long experience stressed to us. An incident happens—this need not be a catastrophic disaster—and what had been latent is now manifest in real-time operations, then and there. A bridge collapses, consequences of which are to reveal both the full extent of traffic flow affected by that incident and the potential dependencies and estimated risks associated with like bridges thereafter.

A more specific example (Roe and Schulman, 2008) is helpful. A series of incidents were observed where a grid management agency and distribution utilities had to appeal to end-users

[5] For an example of specific interconnectivities, see Oregon's Transportation Assessment: Cybersecurity and Infrastructure Security Agency (2021).

directly to reduce their energy consumption so as to avoid rolling blackouts. Also, generators that were independent contributors to a pool of energy supplied to the transmission grid became reciprocally interdependent on one another to keep running so as to maintain grid balance of load and generation. They were, in effect, held hostage to the least reliable generator among them—this being an already-mentioned major shift in interinfrastructural connectivity.

These latent-to-manifest shifts mean that detecting and managing latency with respect to interconnectivity is a major part of ongoing infrastructural operations. In a scenario familiar to emergency managers, an underground water leak induced by an earthquake can undermine the road bed and eventually lead to collapse of the surface road section. What was a near independency between the underground lines and the road becomes a significant dependency between roads and losses of below-ground water line integrity. The character and duration of the failure are reciprocally interconnected challenges to emergency response efforts to restore both the flows of the water-main and the road. These changes can well serve to trigger operational shifts, in this example from "initial service restoration" to "longer-term recovery" efforts after the earthquake event.

How is it that interconnections that were latent become manifest by virtue of an incident? Underlying latent-to-manifest shifts is the criticality of *single resources and assets having multiple uses*. Telecoms and electricity may share the same utility poles. Different electricity providers can share the same transmission tower. Ferries become an extension of the highway system. The road that is used regularly for transportation also serves as a fire break during wildfires. Crews on the distribution side help with repairs on the transmission side of a major water supply, where the units “have a very interconnected role,” said the manager of one distribution system. Crews on the city’s wastewater side or potable water side are cross-trained to help the other. Water departments and natural gas companies may both have road crews: “When snow comes all crews do it,” by way of clearing and improving the roads, said a water operations supervisor. The interinfrastructural configurations that are manifested later on can be managed in latency (such as through cross-training) beforehand.[6]

There are no guarantees that multiple services occur or emerge. However from our perspective, emerging or creative new uses for existing resources are a major requirement for operating backbone infrastructures: “If [resources and assets] are only there for the emergency, you’re not really using them effectively the rest of the time,” said a former senior water engineer. Park and recreation facilities serve as temporary city shelters when needed. The facility housing the water department is the back-up facility for the roads department, should the latter lose access to its current offices. The water department will clear important roads, even if the roads department cannot, conditions permitting. (To be sure, there are downsides, including added wear-and-tear of facilities and equipment along with staff burnout from having multiple duties and additional responsibilities.)

In addition to latent or manifest, types of configurations become more complex in actual operations, both real time and across time. Their differences also demarcate major shifts and transitions that punctuate interinfrastructure operations. For example:

[6] All quotes, again, are from interviews undertaken as part of our latest NSF-funded research on Pacific Northwest infrastructures of water, electricity, road and telecoms.

· Vessels come into a port and shipments are off-loaded there onto truck and rail for onward transport (sequential interconnectivity with serial dependencies).

· The port may take a more active role in coordinating which vessels have priority, how shipments are off-loaded and stored temporarily, and the modes of transporting onward (mediated interconnectivity by the port as a focal infrastructure).[7]

· At other times the vessels may have to coordinate from ship pilot to ship pilot to coordinate without the assistance of port authorities or others (bi-directional interdependence).

· The Incident Command System (or equivalent emergency management unit activated) may also make coordinating the waterways for emergency uses one of its first priorities (pooled interconnectivity centered around the focal ICS).[8]

It would be a mistake if readers thought the shifts from sequential through to mediated and reciprocal and pooled interconnectivities and then back to sequential interconnectivity constitute a repetitive or exemplary cycle of interinfrastructure operations.[9] Such sequences have been observed, but determination of any sequence of shifts and their configurations is an empirical question, case by case (e.g., the ICS, once activated, also has important sequential communications up and down its hierarchy). The point here is less one of identifying specific or

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[7] By way of another example, waterway re-openings were also mentioned as in need of a focal organization to help guide priorities for which vessels in the back-up queue were to pass through before others.

[8] For more on Incident Command Systems, see Journal of Contingencies and Crisis Management (2014).

[9] On-the-ground examples with visual representations of different interconnectivity configurations are found in Roe and Schulman (2016).

"characteristic" configurations than focusing on the variable and visible *shifts* as an indicator of significant operational changes, interinfrastructurally.

To illustrate further, what has been called "emergency response and initial service restoration" not only brings reciprocal and mediated interconnectivity into the mix. It also cannot be assumed that sequential interconnectivity disappears in the process. It reappears, but differently. Restoration of the electric transmission grid, after a disaster, would start with the 500kV lines, then the 230kV, then the 115kV, and so on. We were also told by a statewide emergency manager in the Pacific Northwest that response to a major ice storm consisted of first closing the affected state roads, followed by power companies coming in to move the downed lines, and then crews coming in to remove the fallen trees. In other words, it would also be an error to assume that "immediate response and initial service restoration" is altogether exceptional with respect to interconnectivity: Serial sequences still show up in incident response as they do in pre-incident planning. It's the shifts to new or reconfigured interconnections that matter compared to configurations in base-level interconnections pre-incident.

Control variable shifts with respect to critical interconnectivity. Control variables were defined as actionable real-time features of an infrastructure that can be manipulated to alter the overall state of that infrastructure, such as voltage and frequency controls for an electrical grid or water valves, pipes and pumps to control real-time water flows from dams or other reservoirs.[10]

[10] Control variables are further detailed in Roe and Schulman (2016).

While control variables heuristically identify specific and separate infrastructures, in our framework *system control variables are the critical means for interinfrastructural connectivity*. Control variables overlap when the same waterflows from a dam to the hydropower plant also differently serve as control variables for real-time irrigated agriculture and water treatment plants in between. The overlap of control variables can, however, be problematic in managing shifted interconnectivity even when the control variables seem more separate from each other. Firefighters setting their firebreaks under more accessible rights-of-way, which are the same rights-of-way created for electricity transmission lines, can also create conflict between backfires needed by the firefighters and the voltage and flow paths along the transmission lines. When major wildfires occur near power lines, field crews from a major electric transmission provider are dispatched to coordinate with firefighters over line and safety issues, e.g., shut the line down if backfires were needed in the right-of-way. Another example: Because they share the same waterway, clearing a river passage for marine transport and re-opening a major port are important to both. In other words, the configuration of interconnected control variables need not be that of, say, a designed sequential dependence, as when waterflows are managed so as to manage hydropower's electricity generation and transmission. Undesigned but nevertheless mediated and pooled interconnectivity can well be present (latent as well as manifest) even in pre-disaster conditions.

It is instructive at this point to consider the wider system safety implications of shifting control variable interconnectivity. Take the example of automatic shutoff valve and its role in reconfiguring interconnections. The valve is key in earthquake response because it can adjust or otherwise halt water flows as a system control variable and in so doing change the interconnections of those depending on water in the rest of the system, e.g., the effect of shutting off water for, say, firefighting at the same time (Comfort, 2019). There are occasions, of course, when automatic equipment does not work. One of the first things to happen if external and back-up power fails is for water supply operators to revert, where possible, to manual operations.

Such a shift from automated (electronic, digital) operations to manual, hands-on operations triggered by an incident is often described as reverting to an older practice or earlier technology. From the proposed framework's perspective, however, the shifts from (more) automated to (more) manual operations reflect and recognize that the same system control variables remain important—that doesn't change—and can only remain so through back-up or improvisational efforts like manual response. Even when "shifting to manual operations" with respect to the same system control variable looks like the practice they used to do (under one set of interconnectivity configurations), doing so may not have the same role in another set of interconnectivity configurations. The conceptual and methodological implications are notable, e.g., interinfrastructural safety or societal safety strategies that do not accommodate the shifting role and necessity of manual operations may well not be suitable for real-world policy and management. (For an example of the safety difficulties in clawing back manual operations once they have been automated, see the case material on autonomous marine systems in Utne et al [2019]).

Accordingly, loss of a system control variable—as the loss of the critical means for interconnectivity—can interrupt very visibly interinfrastructural operations, e.g. a stuck drawbridge (depending its position when stuck) can change the configuration of transportation across a river (if stuck open) and vessel travel on the river underneath (if stuck closed). Further, losses trigger the search for substitutional processes and support. The immediate release of government monies and the sharing of more cross-infrastructure data become highly fungible in terms of being single resources with now more uses during emergency response and initial service restoration. In case it needs saying, the addition of new technologies can mean different control variables to be managed interinfrastructurally. Our interviewees from the Pacific Northwest are clear about this. "I'm more concerned about that [cybersecurity related to interdepartmental operations] right now than I am about a big earthquake," said a district infrastructure director.

Last but not least, there are shifts in major inter-organizational relationships affecting infrastructural operations. A defining feature of "longer-term recovery" is the presence of new and shifting political stakeholders and, with them, altered imperatives for ongoing interinfrastructure operations. Hand-shake agreements, in our approach, are reflections of reciprocal interdependencies between managers or operators to help each other out. But "a hand-shake is good for six months or so," an experienced emergency manager phrased it in the Pacific Northwest interviews. So, while it may be fine for immediate post-disaster interconnectivity, reciprocities must be reinforced for longer-term recovery afterwards, including by means of formal, legal contracts.

Emerging or new manifest and latent interconnections (and their different configurations) are critical in defining and identifying on the ground what constitutes "infrastructure recovery." Examples of new issues arising in recovery include getting rid of legacy technologies and facilities or adding new protections with “never-happen-again” regulations. It is easy, in other words, to see what interviewees insist about recovery, “All of this takes time.” From our framework perspective, it is better to say that shifting or emerging interconnectivities extend time and duration as they include new latent-to-manifest interconnections and tensions over managing latency that lead to “it took much more time and money than anyone ever thought.”

Infrastructure Performance Standards. Roe and Schulman (2016) identified the following performance standards to which critical infrastructures managed in real time:

[TABLE 1 HERE]

This earlier 2016 research demonstrated how systemwide management risks and types of uncertainties differ as management performance standards differ.

We saw above that the avoided events standard may be adopted because the precluded events standard is not (any longer) feasible or because conflicting organizational or social priorities have eroded the commitment to that standard. Evidence of other performance standards are also found in the literature. Per Table 1, some dreaded events may be treated as inevitable in infrastructure operations (e.g., earthquakes in Indonesia) or can be compensated for in some major safety improvements afterwards (as after Three-Mile Island). This “compensatory reliability” standard reduces social pressures for a precluded event standard.

Our recent Pacific Northwest research goes further and identifies another performance standard for early post-disaster operations, that of the provision and utilization of "requisite variety." The demand for requisite variety is familiar to experienced emergency managers and infrastructure operators: the need to increase real-time options, strategies and resources so as to better match the requirements of unpredictable or uncontrollable conditions.

Requisite variety is the principle that it takes some complexity to manage complexity (Ashby, 1952; Weick, 1995). If a problem has many variables and can assume a diversity of different conditions or states, it takes a variety of management options to address this complexity and to transform them into a smaller range of managed states. If there are variations in problem inputs, there must be process variety available to managers to cope with the input variance in order to produce managed outputs and outcomes. Having a diversity of resource and strategic options, including being able to assemble, improvise or invent them, is a way to match and manage problem complexity with a variety of capabilities.

Roe and Schulman (2008) found in the transmission grid control center of the California Independent System Operator, a need to improvise and invent options or assemblies of options as part of reliable avoidable event operations, and not just for effective immediate response post-disaster (see also Boin et al, 2016; Frykmer et al, 2018). Requisite variety and the strategy of positive redundancy are frequently coupled. It is common in the high reliability literature to see the use of positive redundancy for handling interruptions in already ongoing operations, e.g., the ability of bringing online a generator when power suddenly fails. That positive redundancy also, however, offers affordances to use generation for new purposes during emergency response.

Let us focus specifically on the role of requisite variety as a performance standard in defining more clearly what is meant currently by immediate emergency response and initial service restoration. What's success in a disaster, we asked emergency managers and staff in our latest Pacific Northwest interviews, and their answer was frequently a version of: "Being here and doing as best as we can, would be considered a win," one infrastructure operator summed up. But the best with respect to what?

Our approach takes that "best" and formalizes it. Effective emergency response and initial service restoration can be redefined as the contingent correspondence of task demands and response capabilities (resources, skills, options, strategies) to meet those demands, even when those capabilities must be invented or fabricated. The term, "contingent," conveys the sense that the conjunction of capabilities and demands is by no means assured through pre-incident mitigations, formal preparedness plans, and other prior organizational arrangements, such as mutual aid agreements. The terms, "match" and "conjunction," represent first and foremost an *interconnection* between demand and capability.

Seeking or inventing requisite variety in matching unpredictable/uncontrollable task demands with contingent resource capabilities is, our framework argues, a strategy and performance standard of interconnectivity that better fits and defines immediate emergency response and initial service restoration. System control variables are an important means of managing shifted interconnectivity configurations so as to create a changing requisite variety match of capabilities and demands.

By way of illustration, several interviewees described the case where an ice storm took out water and communications on one side of a major interstate road in the Pacific Northwest but did not do the same for a city on the opposite side of the interstate. Fortunately, the latter city could serve as a “hub” in transferring emergency water supplies from a third site to the ice-stricken city. The hub also supplied generators to the distressed city, thereby providing electricity for its temporary water supply. As such, this case revolved around improvisational behavior undertaken by at least three entities with respect to their interconnected control variables in the backbone infrastructures of water and electricity.

Not only are major latent interconnectivities often made visible in an incident, so too are real-time improvisations necessitated for the contingent and continuing requisite variety matches around already dynamic system control variables and interconnectivity configurations. For this reason, “What are the things that worked for conditions that you didn’t anticipate?” becomes a prime performance question for possible lessons learned, as one experienced emergency manager put it.

Understandably then, there is a huge diversity in organizational and network formats for addressing real-time matches between contingent task demands and contingent capabilities: task forces, special districts and jurisdictions, dedicated government agencies, designated statewide officers, watersheds and planning regions, coordinators and liaisons, consortia, councils, as well as ad hoc groups formed by operational personnel across the interconnected infrastructures. Such diversity is what is to be expected and must be looked for, given the focus on multiple, shifting configurations of interconnectivity.

The added importance interviewees place on having their own personal and professional contacts and relationships must also be seen as the recognition that prior and formal structures for organizational and network diversity can only go so far, and not far enough when it comes to the search for requisite variety. Network contacts can be drawn from any level in a hierarchical organization—and from inside or outside the formal structures of emergency management. This wider ambit also helps explain how a planner, regulator or agency executive can also be a pre-disaster foundation for cross-organizational contacts and ad hoc group formation post-disaster.

It is, however, majorly important to note that performance standards and effectiveness for interinfrastructure *recovery* over the longer-term differ from meeting just-for-now needs for requisite variety. During recovery, additional stakeholders, objectives and political trade-offs move center-stage, along with an expanded set of community values and policy goals. What this means is that, as one experienced interviewee said, standards for recovery are "difficult because every community is different and their priorities are different". From our perspective, a key indicator that this is in motion is when ongoing efforts lose the interconnected logic and urgency recognized and shared immediately after the disaster.[11] The absence or attenuation of that focus in longer-term recovery is notable, as the interconnectivity configurations become more contentious and "politicized" than those immediately following the disaster.

To summarize in our framework terms, the operations in immediate response and restoration, as distinct from longer-term recovery, differ in their mix of shifts, configurations, control variables and performance standards, with "recovery" exhibiting:

(1) a lack of the logic and urgency evident in decisionmaking immediately after the system failure (more formally, the lack of actionable granularity);

[11] On complications that can occur in response and recovery, see Cedergren et. al. (2018).

(2) new and emerging manifest as well as potential latent interconnectivities not witnessed pre-disaster or immediately after system failure (largely but not exclusively because of the introduction of new stakeholders and problems hitherto in the background); and

(3) systemwide performance standards that differ in kind or degree from those pre-disaster interconnectivities. New systemwide performance standards may even be part of a "new normal" that embraces new social objectives as well as new benchmarks for societal safety.

In short, it may be "the sooner the response, the sooner the recovery," but such adages leave out all the major complications in recovery that differ from immediate response.

With those details and examples in mind, let us turn to the question of "So what?" What purchase does the framework provide for clarifying and differentiating interinfrastructure operations, now and over time?

In answer, those familiar with emergency management literatures will need no reminding as to how important inter-organizational communications and on-the-spot improvisations are to effective management. Each has been treated as key by way of requiring or establishing situational awareness on the ground, before, during and after an incident. But interconnected improvisations and communications are such instrumental factors in shifting infrastructural operations that they need, we believe, greater attention and prominence.

Improvisations

It turns out, we saw above, that some constellations of shifted interconnected infrastructure configurations around control variables under a requisite variety performance standard require processes of improvisations and that these are associated with major changes in interinfrastructure operations.

Improvisations so characteristic of immediate emergency response and initial service restoration are an exemplary case of making use of what is at hand, even if not originally designed so (the aforementioned single-resource/multiple-use feature of interinfrastructural interconnectivity). For that end, past practices that evolved under earlier base-level interconnectivities may be helpfully resurrected for post-disaster improvisational behavior. Personnel in roads and water departments, for example, may be more proficient at improvisation in an emergency because they also work together and improvise at other times, e.g., when road crews regularly pave over sites after water line repairs have been undertaken. But again, past practices are no surety that contingent improvisations post-disaster will be effective for establishing then-and-there requisite variety.

An example helps. Several interviewees described an incident during major Labor Day 2020 wildfires in the Pacific Northwest. Here is how one operations manager in a major energy transmission company described the kind of interconnectivities they faced when its lines and a key substation were threatened:

> When the fire was encroaching upon said substation, we formed up a little team between the utilities and said, "Hey—" . . . "Hey, Forest Service. Hey, firefighters"—the Colorado team, I think, was out there—"What are you doing to prevent this? Because if the fire gets to this substation, about, I would say, a few million folks will be out of power. What are you

> doing to firefight before it hits that substation?" Then they were saying, "We didn't know it was a critical infrastructure. We got these other fires that we're worried—it's more of a priority for us right now."
>
> We said look, "It's gonna impact both the cities of Eugene and Salem if this particular substation goes down." They actually took our advice. We were able to send fire teams out there and, like we said, build those backfires and everything else to kinda burn out the brush and whatnot. We also brought in heavy equipment, bulldozers and whatnot, and built a berm basically around the substation.

These interinfrastructural improvisations on the spot ended up “saving the asset,” which in our framework’s terminology was preventing failure in system control variables interconnected through a shared substation and a nearby telecommunications tower.

Another example is also instructive. An ice storm that shut down electricity to four water treatment plants required the use of back-up generators, but only two were available. This placed priority on continuous diesel supplies, 24/7, for those two generators, and in the words of a Pacific Northwest interviewee, “a lot of our [provider group] members were going to gas stations, filling up with whatever they could find” for that round-the-clock generation. To characterize such improvisations as incidental one-offs or the side-work that mates do for each other is to miss the point from our framework perspective. A workaround improvised within a control room in order to ensure its system operations continue without interruption is not the same as those improvised by two or more backbone infrastructures confronting the loss of systemwide control variables—since the shifting configurations and relevant performance standards differ so (e.g., the former's precluded events standard and the latter's standard of requisite variety).

This means that interconnected improvisations involving shared or overlapping control variables become highly significant when the improvisations establish interconnectivities that both determine and shift the scale(s) of infrastructural operations. Interinfrastructural improvisations might be the only indicator we have that shifted interconnectivities are underway and so too are adjustments in the scope or scale of operation in the backbone infrastructures. Indeed, some improvisations shift key communication patterns (more below).

As there can be no guarantee that improvisations—these impromptu but major interconnections—will be effective, a premium is placed on people whose improvisational skills increase with experience in operations punctuated by interconnectivity shifts. Newer backbone employees and emergency management staff may well not (yet) have the skills. "A lot of our folks don't have that skill set to be able to look at a pressure reading somewhere and determine the level of water [left in an above-ground reservoir]," a water supply infrastructure manager in the Pacific Northwest told us.

"On the fly, we reconfigured our telemetry [with hand-held generators they were able to obtain]," a water treatment plant manager added about another of their many improvisations during a Pacific Northwest incident. More formally, enhancing the requisite variety of options requires people who see problems in terms of processes and requirements beyond pre-existing job descriptions and documented plans. They do this by assuming responsibilities with others beyond their official duties so as to mesh task requirements with resource capabilities, not least via interconnected improvisations. For our Pacific Northwest interviewees, these processes are as real and empirical as bridges and pipes to be retrofitted.

That their improvisational behavior can and is a mode of actual interinfrastructure operations sheds light on the familiar complaint that you can't plan for all the contingencies in a later incident. True, but that isn't the point here. It's not that planning or building in resilience are irrelevant (for more on building-in-resilience, see Bergström, 2018). It's that a plan and a mode of infrastructural operations are not the same thing. That pre-disaster mitigations, like retro-fitting bridges, reduce vulnerabilities and "builds in resilience" in no way displaces the strategic role of improvisation-as-operations, involving specific interconnectivities, control variables and performance standards. There is no workaround for improvisation-as-operations.

Communications in light of improvisations

Much is already known about intra-organizational communications, including but not limited to those within critical infrastructures.[12] Indeed earlier high reliability research highlighted the importance of communications within and between infrastructures for ongoing operations (Roe and Schulman, 2008, 2016, 2018 and Schulman and Roe, 2018). From the perspective of our framework and the prominence it gives to improvisations, a more nuanced role of inter-organizational communications needs to be appreciated.

The Pacific Northwest research interviews underscore differences in configurations of interconnected communications after certain incidents, including but not limited to a system

[12] In fact, wide distribution of information and open channels of communication across organizational departments and hierarchical levels has long been considered a major trait of healthy "safety cultures" in organizations. See, for example, Institute of Nuclear Power Operators (1973).

failure. Some familiar problems were noted, not least of which are persistent difficulties with respect to interoperable communication systems between and among the different agencies, staff and jurisdictions. Interoperability is not guaranteed even under routine conditions, e.g., it has been difficult to keep some of the control room software operating on a daily basis, let alone at more pressing times, we were told.

In framework terms, vertical and horizontal communication of interest are characterized by interconnectivity shifts. One example is particularly notable and complex: the shifts from predominantly one-direction instructions and commands in sequential dependencies of vertical communications to more continuing cross-talk and negotiated agreement in mediated, pooled and reciprocal communication patterns necessary for horizontal micro-coordination of interinfrastructural, often improvisational, restoration. Here communication patterns follow from, rather than determine, the interconnectivity configurations. Nothing again is guaranteed by way of mixes of configurations and patterns of communication to be provided. But shifts can be and are observed, as when the professionals contacted and communicated with in one's network shift pre-disaster, during the disaster, and afterwards.

This means any temptation to impose vertical-dominant communications is to be resisted when shifting interconnectivities demand horizontally-rich communication. No amount of vertical communications, such as through a single Incident Command System or equivalent, can substitute for achieving a high-enough bandwidth of information for close real-time micro-coordination of reciprocal interdependence and interconnected improvisations. The direct-line phone connections to the control room of a major electricity utility from a water utility or a wastewater treatment plant are examples of "pilot-to-pilot" coordination and interdependencies. In important respects, this shifted communication *is* the coordination. The shift in the communication configurations from vertical-sequential to include reciprocal-horizontal is a hugely valuable indicator of changed interconnected configurations and, with them, infrastructural operations.

Against this backdrop, the effectiveness of inter-organizational communication is not a misleading one of vertical *versus* horizontal communications (as if it were a matter of centralization *or* decentralization). That is too formal and incomplete a description of communications, if it implies improvisation is not center-staged. Effective vertical communication, Pacific Northwest interviewees underscored, requires close interactions between and among authorities and staff down to the horizontal granularity of real-time field interactions on-the-fly.

The demand for more granularities can also require more detailed documentation, as do formal processes for seeking US federal emergency assistance or FEMA reimbursement. Some interviewees reported that structure of the Incident Command System enabled informal lateral communications to take place, including with positions outside that structure. Where so, the Incident Command System once activated seems to provide an element of stability to treating interconnected improvisations as a means of providing added options for real-time operations. Other research and cases suggest that the ICS structure might not be as facilitative (GAO [2011] and Renaud [2012).

Conclusion

The refocus proposed in this article asks readers to move beyond conventional terms of infrastructure operations concatenated as: normal or routine operations, sometimes temporarily disrupted and then restored back, at other times tripping over into outright system failure, thereafter responded to urgently as an emergency and eventually to be recovered systemwide, from which a new normal may be evolve. This sequence and the terminology can remain a useful heuristic. However, when the analytic focus shifts to major or systemwide infrastructure risks and uncertainties, more is needed. Our approach is a step in that direction. We focus on infrastructure interconnections to track and describe their temporal operations differently and in the process this yields different policy and management implications.

To summarize, we suggest that interinfrastructure operations can be usefully distinguished by: different shifts and configurations in their interconnectivity, particularly affecting control variables used to manage the infrastructures. An important part of the process is interconnected, improvisational operations during major shocks, and shifting performance standards to which management and operations are directed. Drivers of these shifts in operational states can be physical destruction of assets in emergencies, but other drivers can be major technological changes as well as substantive changes in legislation and regulation. Risks and uncertainties differ significantly across these shifting states. How they play out is an empirical question.

In this perspective, the conceptually most notable feature of system failure in the backbone infrastructures is the reconfiguration of interconnectivities around the systems' control variables and performance standards. This most visibly occurs when surviving and available infrastructural personnel and equipment are reassigned to massive relief and rescue efforts immediately after a catastrophe. Here, disaster interconnectivity reflects prominently the loss of even base-level interconnectivity across infrastructures. This perspective, moreover, underscores when the "first responders" in a disaster are not from emergency management agencies, but are in fact the backbone infrastructure operators and field staff closest to seeing system failure unfold.[13]

What does this mean, policy-wise, for societal (interinfrastructural) safety? One answer is evident when it comes to managing risks and uncertainties. Systematically important banks in a number of countries currently undergo periodic stress tests to assess their reliability under different crisis scenarios. Increasingly the scenarios include those related to global climate change (for a recent description and performance assessment, see Cullen, 2023). If the critical infrastructure sector of banking is critical enough for governments to stress test under various disaster scenarios, so too backbone critical infrastructures should be stress tested for the same or similar scenarios. (This is the case not least because the financial services depend as much on interconnected backbone infrastructures as well.)

Accordingly, the extent to which an Incident Command System (or its equivalent) and Continuity of Operations Plans (COOP or equivalent) can accommodate interconnectivity shifts, not just during but also before and after an incident, becomes a major issue from our framework perspective. That is, interinfrastructural stress testing would have to focus more on real-time processes of interconnected improvisation and communication than on, say, documented emergency plans and succession protocols for stated risks and uncertainties.

[13] On similarities and differences between backbone operators and emergency managers in one case study, see Roe and Schulman (2015).

The framework we have offered is an analytic one that we believe encourages more sharply focused management, as well as regulation and policy applied to infrastructure performance, emergency management and societal safety. In this understanding, societal safety is better thought of as an adverb than as a noun (Ryle, 1949/2002; Oakeshott, 1975). Safety should refer to how operations and specific tasks are conducted and risks prevented or avoided, not simply an inferred overall state of "safety" in between accidents or failures. Large socio-technical systems that perform safely are those that do more than conform behaviors to rules, or craft better management processes, or exhibit specific mind-sets over others. Society mandates that its large socio-technical systems perform safely—even without understanding fully that safety requires managing changes in latent-to-manifest interconnections, control variable uses and performance standards. With these changes, the persistence of prior procedures, processes and mind-sets for system safety may well become problematic (see Teperi et al, 2023).[14] Trying to regulate "safety" as if it were a state or condition obscures on-the-ground complexities, contingencies and improvisations involved in addressing the shifting risks, uncertainties and unknowns for interconnected infrastructure operations across all system states.

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[14] Matters are more complicated when societal safety and societal security are distinguished (Høyland, 2018; Nilsen et al, 2018). The complications grow considerably when the focus is global (e.g., Le Coze, 2018).

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Table 1. A typology of reliability standards across states of infrastructure operation (Roe and Schulman, 2016)

Reliability type	*Dominant infrastructure state(s)*	*Reliability standard*	*Reliability strategy*
Precluded events	Normal operations	Socially unacceptable events must never happen	Technical design, operations within analysis, and precursor resilience
Avoided events	Normal, disruption, restoration	Internally unacceptable events should not happen	Risk-benefit analysis and risk trade-offs
Inevitable events	Disruption, failure	Social acceptance of disruption and failure as unpreventable or inevitable	Insurance, emergency response management, and recovery resilience
Compensable events	Recovery, new normal	Failures forgiven by learning and added capacities for a new normal	Technology updates, procedural revision, and reorganization