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Abstract

Practical, theoretically sound strategies are needed to design recovery strategies that account for heterogeneous users in massively damaged, interdependent infrastructures. This dissertation provides a framework for developing a controller to repair a geographically large interdependent system with many stakeholders that is not suited to straightforward mathematical characterization. The framework employs a satisfactory control approach based on proportional-integral-derivative, or PID, principles, applied to a discrete-time, time-varying system. The proposed framework also combines network science and Systems-Theoretic Process Analysis to design a recovery strategy for interdependent infrastructure.

The combination of network science and Systems-Theoretic Process Analysis are complementary, and novel: Systems-Theoretic Process Analysis frames losses in terms of a system, system components, and component interactions [1]. Network science facilitates the depiction of the system, system components, and component interactions using feature-rich edge lists. Additionally, notion of a controlled process in the Systems-Theoretic Process Analysis fits well with the “resilience curve” ([2]) framing of recovery problems. Accordingly, this dissertation exploits the control and feedback framing to shape transient state characteristics to limit impacts to residents and to respond to new information, constraints, and disturbances.

This proposed framework was applied to a case study in a real interdependent infrastructure system. Goals were set based on real-world policy considerations, and then formalized into formal control rules using Systems-Theoretic Process Analysis. The PID-based controller that was designed using this methodology produced results that are superior to recovery strategies built without feedback. Graphical techniques to visualize controller outputs and refine them were also provided and demonstrated. This latter set of tools acknowledges the need for stakeholder input, particularly in public sector systems. Finally, an adaptation of the Resilience Matrix approach is provided as a monitoring tool during implementation of the recovery framework. The Resilience Matrix can be used to assemble evidence that recovery is or is not meeting decision-maker goals.

The result is a practical and theoretically sound decision support methodology that accounts for key locations, proximities, alternatives, interactions, and sources that constrain system users (the problem structure), as well as individual features and “system properties downscaled” to the component level. This framework is designed to be interoperable with common data formats and asset management systems, and can be integrated into a live work-planning application. This work contributes to efforts to support human population resilience by treating peoples’ resilience as a function of infrastructure system resilience.

To Anna

Acknowledgements

Many of us who attend graduate school are far from home. Others have struck out without anywhere else to call home, assembling monastic lives in small rooms and one-bedroom apartments. We may be mean of circumstance and threadbare of safety net. We choose this precarity for many reasons, including the chance for more stable footing a few rungs up on the socio-economic ladder. Those who have already experienced the ganging aft agley of best laid plans are also aware that these chances may not materialize. In the meantime, we hope we are hardy enough and lucky enough to weather any mishaps along the way.

To my lab-mates, advisor, neighbors, babysitters, and favorite therapists: You have been there when I have been sick, injured, frightened, and grieving. You have helped me lift heavy objects and shoulder challenging emotional burdens. I leave this season of my life having healed from harms I could not even name when I began this journey. Everything I have weathered, I have weathered in the shelter of your kindness.

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1 Introduction

Massively damaged interdependent infrastructures are subject to lengthy recoveries. The recovery process itself is complex, and can take months to years to complete when major disaster damage occurs. Factors such as aging infrastructure systems [3], increasing urbanization in high-risk areas [4] and changing climate [5]–[9] increase the risk of massive infrastructure system damage and complicate the reconstruction process.

When the damaged infrastructure is part of a community system, the human impact is significant. Socially vulnerable populations are disproportionately vulnerable [10]–[14]. Inequities also arise throughout other parts of the disaster lifecycle, including emergency response and long-term recovery (see Figure 1). Recovery decisions are therefore of particular importance to socially vulnerable populations because they have fewer resources with which to adapt.

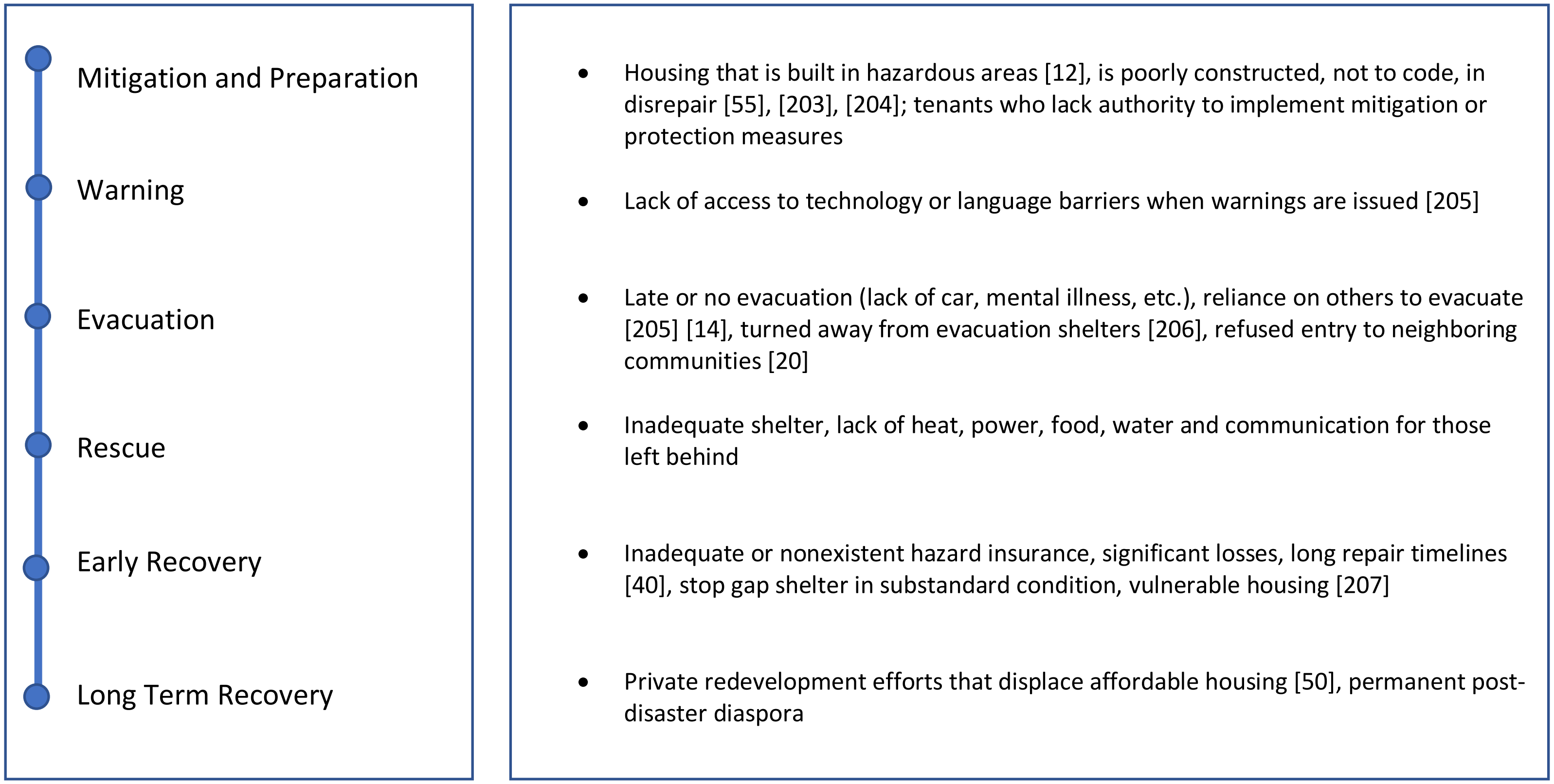


Figure 1. Socially vulnerable communities face infrastructure inequities at all phases of the disaster lifecycle: the natural hazard mitigation, disaster response, and long-term recovery processes. These inequities lead to poor post-disaster outcomes, including during disaster-related displacement.

Among the many challenges faced by socially vulnerable populations (see Table 1) is increased risk of displacement, and a great deal of literature connects this risk qualitatively to infrastructure-related causes. Current estimates suggest that disaster-related displacement, estimated at approximately 24M people in 2016, is approximately four times as common as displacement due to conflict [15]. However, quantitative resilience tools directed at civil infrastructure systems are in their infancy [16], and, in addition, resilience research in this domain is rarely concerned with long-term recovery [17], [18].

Table 1. Recent examples of challenges faced by socially vulnerable populations during the Atlantic hurricane season.

STORM, YEAR, AND EVACUATION/DISPLACEMENT OF SOCIALLY VULNERABLE POPULATIONS
Hurricane Katrina (2005) • "Prisoners were abandoned in their cells without food or water for days as floodwaters rose toward the ceiling [19]." • "Armed with machine guns, Gretna City police officers collaborated with officers from the Jefferson Parish Sheriff's Office and the Crescent City Connection Police Department to block off the Gretna Bridge-the only way out of New Orleans-for at least two days [20]"
Hurricane Ike (2008) • "[H]omeless individuals…told staff members that they were starving and had not eaten in three days. [They] also reported that they were turned away from the designated emergency shelter because they were homeless prior to the storm [21]. "
Hurricane Sandy (2012) • "[M]ost of the New Yorkers still without power and heat 12 days later were people of color living in low-income housing [22]." • "Many [undocumented] immigrants…continued to live in damaged apartments infested with mold and vermin, or otherwise attempted to rebuild their lives without the assistance available to other victims [23]." • 2017 Update: "The city's public housing is in a particularly [perilous state] – of the 33 apartment towers that required repair work on crippled heating and lighting systems, only one property has completed work [24]."
Louisiana Floods (2016) • "Most of the 150,000 homes flooded were rendered uninhabitable…[and] many homes affordable for ELI [extremely low income] renters [were] destroyed by the floods [25]."
Hurricane Harvey (2017) • "[F]amilies who evacuated their homes to escape Hurricane Harvey and are now getting eviction notices [26]."

Given the increased risk of extreme events over the lifetime of infrastructure systems with multidecade life spans, techniques that can handle massive damage and heterogeneities in user populations are broadly valuable. Fortunately, there are promising modeling tools that move beyond GIS natural hazard overlays and spreadsheets and are suitable for providing quantitative decision support for the complex problem of recovery when faced with major infrastructure damage [17]. These tools must be developed in such a way that the metrics, models, and outputs are simple, well-documented, multihazard, of appropriate spatial and temporal resolution, and adaptable to changing circumstances [17], [27]. Tools should also work with existing data wherever possible and must be flexible with respect to handling missing data. Lastly, new tools should run on widely available hardware and software. The latter explicitly acknowledges that both computational resources and electricity may be limited during large-scale infrastructure system recovery.

1.1 Purpose and Scope

The research objective of this dissertation is to address the need for a practical, rational, quantitative approach to resilience goal-setting, strategy planning, and outcome assessment during long-term recovery. To achieve this objective, this dissertation describes and applies a method based on Systems-Theoretic Process Analysis (STPA) and proportional-integral-derivative (PID) network control. These methods are applied to the design of recovery strategies in massively damaged interdependent infrastructure, and to show how feedback can be used to improve recovery outcomes. This top-down, goal-based approach is structured, providing a transparent and defensible decision-making process.

Challenges to achieving this research include:

- It is difficult to monitor interventions in complex systems: uncertain causality and sensor limitations are two examples among many common monitoring challenges.
- Solutions in this space must accommodate the need to set complicated recovery goals and incorporate multiple stakeholders.
- Legal, regulatory, and policy constraints must be considered alongside financial ones.
- Decision-makers also need to be able to account for other entities with co-located assets, political jurisdictions, and new disturbances that can arise before recovery is complete.
- Iteration to check solutions with experts and stakeholders becomes important, and therefore, so do visual methods to facilitate this type of engagement.

With a growing body of research about what can go wrong during a recovery, it is essential that we develop engineering techniques to support the decision making process. Modern automatic control seeks to correct deviation from a desired value, oftentimes using feedback to do so more effectively. In closed-loop control, feedback serves to check progress, and checking progress is essential for goal-based resilience assessment during recovery. Second, feedback can be used to refine the recovery trajectory, that is, the manner of recovery, limiting the impact of a months-to-years-long process over time for system users. Feedbacks corresponding to critical system properties affect users' ability to adapt. Incorporating feedback into the recovery process is an important key to improving the effectiveness of recovery strategies.

1.2 Contributions and Organization

This dissertation provides a framework for developing a controller to repair a geographically large interdependent system with many stakeholders that is not suited to straightforward mathematical characterization. For this problem, a satisfactory control approach was selected to accommodate the many irresolvable data uncertainties and dynamic features inherent in this problem domain. Examples of data uncertainties include the actual state of a repair corridor, which is a network segment that can include underground, co-located, undocumented utilities. Examples of dynamic features include weather and resource related interruptions, new disturbances, and population adaptations that render recovery goals obsolete or at cross-purposes.

Satisfactory control is an advance over practice, where ad hoc approaches informed by funding and personnel availability are the norm. This is also a different, and arguably more suitable, tack than recent interdependent infrastructure recovery research, which ranges from manual or permutations-based approaches [28], to various exact and metaheuristic optimization approaches [29] to this problem. The former is unwieldy; the latter elides the importance of the uncertainties and dynamic features just described.

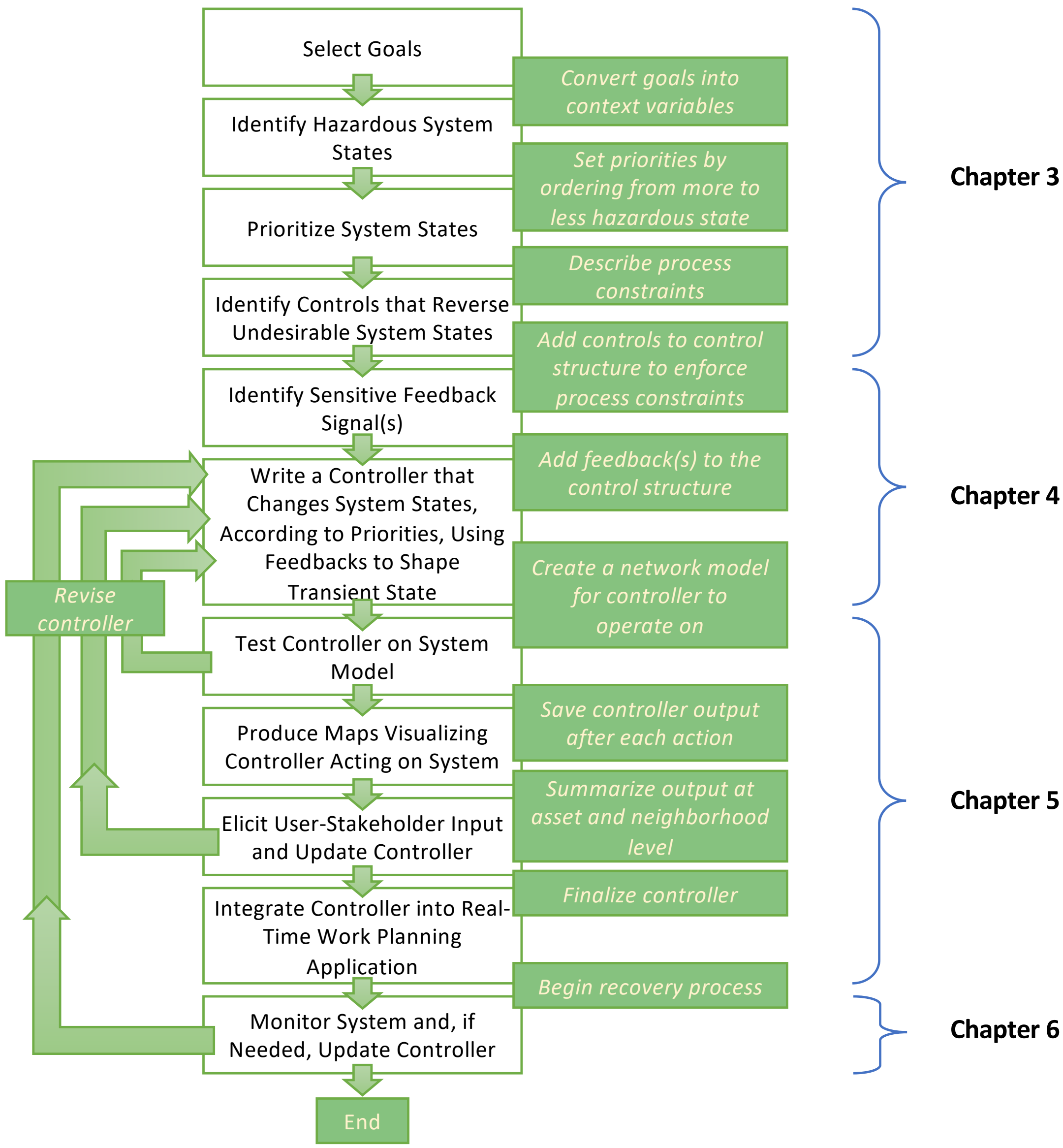


Figure 2. Chapters 3-6 describe a framework that devises, refines, and implements a recovery strategy using a controller that enforces recovery process goals on the interdependent infrastructure system.

The proposed framework, shown in Figure 2**Error! Reference source not found.**, combines network science and STPA to design a recovery strategy for interdependent infrastructure. The combination of network science and STPA are complementary, and novel: STPA frames losses in terms of a system, system components, and component interactions [1]. Network science facilitates the depiction of the system, system components, and component interactions (using feature-rich edge lists). This combination is also theoretically sound because the literature shows that effective recoveries need to be able to consider the system, its components, and component interactions. Additionally, STPA's notion of a controlled process fits well with the "resilience curve" ([2]) framing of recovery problems, and suggests there is an opportunity to use control techniques to improve outcomes with respect to goals. The concept of feedback, as implemented here using a system attribute (delay), helps practitioners and policy makers connect repairs, which must always occur at the component level, to system recovery goals.

STPA is extended to transform goals initially articulated in the language of law and policy into graded categories of desirable and undesirable system states that can be used programmatically. In a novel application, STPA is also used to design the architecture for the recovery framework (Chapter 3). In order to apply STPA to an already-damaged system, this approach extends STPA from simply identifying unsafe (or non-resilient) states to developing graded categories of unacceptable states to capture a notion of system states' relative contribution to system losses (Chapters 3 and 4).

For the purposes of demonstration, this framework is also applied to a case study in a real interdependent infrastructure system. In Chapter 4, STPA is combined with network science to produce a recovery model for a small U.S. city (Charlottesville, VA). The selected recovery problem uses STPA to consider detailed geospatial data and equity considerations (Chapter 5).

Further, the controller is intended to be calibrated by domain experts and adjusted iteratively with input from decision makers and users (Chapter 5). Stakeholder review is necessary for both completeness and legitimacy in systems with heterogenous users, including public sector infrastructure. The calibration process is illustrated using details from case studies of recent disasters. The review and refinement process is conducted using graphical techniques to visualize controller outputs. These techniques originate from the field of GIS-based stakeholder engagement. Effective practice for using the graphical review approach with a subject expert and stakeholders is summarized in Section 5.4.

Lastly, we introduce a complementary monitoring and assessment tool in Chapter 6 to alert decision makers when emerging issues, such as new adaptations by users, require an adjustment to controller rules. This tool is an extension of the well-documented Resilience Matrix (RM) approach [30], [31]. The assessments provided by the tool are tailored to the system recovery goals and track recovery outcomes across multiple management domains. The RM approach provides either confirmatory evidence that recovery is on track, or indicates problems that may require updates to the controller rules or direct action to the decision maker in the wider policy and economic context.

The result is a methodology that accounts for key locations, proximities, alternatives, interactions, and sources that constrain system users (the problem structure), as well as individual features and “downscaled” system properties as they present at the component level. Furthermore, the PID-based controller that is designed using this methodology produces results that are superior to recovery strategies built without feedback. This is a theoretically sound and practical method to manage complexity in the recovery process. To the author's knowledge, this is the first time PID control has been applied to recovery in geographically large complex systems, as well as the first time STPA has been combined with geospatial network science. Validation and limitations are discussed in Chapter 7.

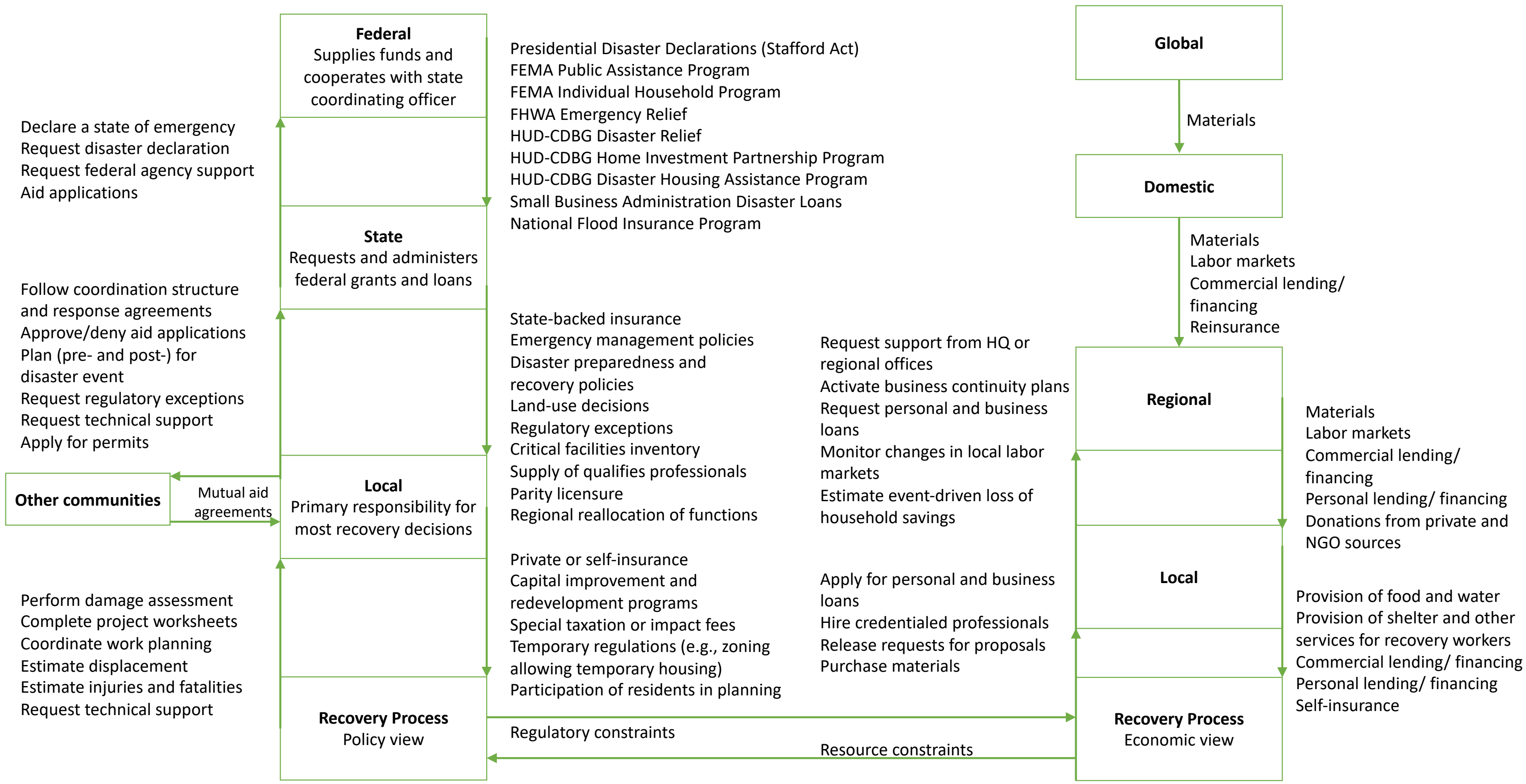


Figure 3. An economic and policy view of the infrastructure recovery process in the United States. From [32], [33], [34], [35], [36], [27], [37], [38]

1.3 Key Terms

This dissertation considers at length both natural disasters and engineering techniques adapted from safety engineering. These fields sometimes use similar terminology, albeit with different, disciplinary-specific meanings. In order to reduce confusion, the definitions used in this dissertation are provided here.

Disasters: Events such as floods, wildfires, and earthquakes interacting with people and the built environment. [36]

Hazards: System states that, in the worst case, can cause a loss. Hazards can arise from components or interactions between components. [1]

Natural Hazards: Natural geophysical events, such as flood, wildfires, and earthquakes, that arise from and are shaped by location. [11]

Resilience: The ability to prepare, plan for, absorb, recover from, and adapt to adverse events. [13]

Safety engineering: Engineering to avoid causing specified losses. [1]

2 Literature Review

This chapter provides an overview of the literature from disciplines that have been synthesized to create this new approach to interdependent infrastructure recovery. The first section reviews the role of damage to interdependent infrastructure systems in community recovery. This is followed by a section discussing recovery through the lens of interdependent infrastructure, including recent examples of interdependent infrastructure recovery models. Next, the advantages of using geospatial network science to depict the interdependent infrastructure model is described. This is followed by a summary of literature concerning the advantages of our selected control approach. The final next section describes literature concerning a particular technique that is used throughout this dissertation, Systems-Theoretic Process Analysis.

2.1 Resilience and Recovery in Interdependent Infrastructure Systems

Table 2 identifies community infrastructure systems according to humanitarian, emergency management, and resilience standard-setting sources.

Table 2. Human-infrastructure interdependencies. Marked boxes indicate that the reference considers the infrastructure system.

Reference	Infrastructure System						
	Building Stock	Transportation	Water/Wastewater / Stormwater	Electricity	Oil & Gas	Telecom	Other
Anzellini et al. (2017)	✓						Infrastructure (non-specific)
Kromm and Sturgis (2008)	✓		✓	✓			Health care
United Nations Office for the Coordination of Humanitarian Affairs (2004) & Tajgman (2010)	✓	✓		✓			Infrastructure (non-specific)
Federal Emergency Management Agency (2017)	✓	✓	✓	✓	✓	✓	Critical infrastructure systems
Federal Emergency Management Agency (2018)	✓	✓	✓	✓	✓	✓	Parks, recreational facilities, other
Federal Emergency Management Agency (2012)	✓	✓	✓	✓	✓	✓	HVAC. Temporary alternatives: generators, water bladders
Federal Emergency Management Agency (2008)	✓	✓		✓	✓	✓	Public health services
Department of Homeland Security (2016)	✓	✓	✓	✓	✓	✓	Financial systems, health and social services, natural and cultural resources
National Institute of Standards and Technology (2016)	✓	✓	✓	✓	✓	✓	

2.1.1 Practical impediment to recovery #1: Infrastructure-related household characteristics

Predictors of protracted displacement include being a renter, being carless, and having limited household wealth. The infrastructure systems directly relevant to these concerns are building stock, especially housing, without which people are less likely to return [46], and the modes of the community's transportation system. Displacement risk for renters arises when damaged rental properties are repurposed or take longer to rebuild than other building types [47]; when entire neighborhoods are redeveloped [48]–[50]; due to housing shortages from competition with recovery and humanitarian workers [51]; and due to policy-related issues such as slower timelines for rental rebuilding programs compared to homeowner assistance [40], [52]. Low-income, low-wealth households are at risk of displacement both because income is predictive of housing damage [49] and because disaster-induced damage to lower-income homes or rental units is much likelier to result in financial ruin for the household [53], both of which can be impediments to return [40].

Carless populations that have evacuated are at risk of displacement because they may not be able return unassisted over long distances [54], [55], cannot easily travel between temporary and permanent housing to make repairs [56], or recognize, using information sources such as transit agency customer trip planning tools, that it is not feasible to resume employment or carry out household recovery tasks given lengthy detours and service interruptions at home. Disaster damaged infrastructure also exacerbates vulnerable groups' pre-disaster mobility challenges, which are a function of demographic factors such as socioeconomic status, racial or ethnic group, gender, age, and family composition [57]–[59]. Carless populations are common among the elderly, disabled, low-income households, young adults, and, in large cities with good transit, much of the general population. The latter is true even in countries like the US where vehicle ownership is high.

2.1.2 Practical impediment to recovery #2: Damaged infrastructure systems important for daily life

Key infrastructure systems enabling the livelihoods of residents supports activities such as education, commerce, and movement within the community. These systems include lifelines (e.g., water, electricity and other utilities), public facilities such as schools, housing, telecom, and transportation systems. In addition to housing-related displacement, displacement risks to business owners involve both residential (home-based businesses and customers; [Laczko and Aghazarm, 2009; Marshall and Schrank, 2014]) and non-residential buildings [61] such as those zoned for commercial and industrial purposes. Businesses particularly vulnerable to failure are small businesses with local markets, located outside downtown commercial districts [32]. Localized damage to a neighborhood can completely disrupt the activities of both the business owner and customer base.

Displacement risk related to transportation system damage results from the transportation system's lifeline role and its role in residents' daily mobility needs [62]. Limited functionality, long detours, and service interruptions impact commerce, education, and workforce participation [63], [64]. Transportation system damage can also impede recovery and humanitarian efforts [65].

Telecommunications, which are highly interdependent with transportation systems, also influence displacement risk. Events affecting transportation systems (and, likely, other infrastructure systems) require people to adapt through greater-than-usual use of communications systems [66]–[69]. Damage to the latter can therefore impair a household's ability to adapt to infrastructure damage during recovery. Examples where households can use telecom to adapt to community infrastructure damage include trip planning, taking online courses rather than attending class in person, maintaining a web-based customer network, teleworking, and scheduling deliveries rather than traveling.

2.1.3 Practical impediment to recovery #3: Damaged infrastructure systems regarded as important for evacuation

The transportation system predominates over other infrastructure systems as important for re-entry of displaced populations. Appropriate modes of transportation for re-entry, including transit options such as trains and buses, must be available [54], [70], travel times must be reasonable [71], and communication infrastructure must be available to facilitate notification of and communication between returning populations [72]. Socially vulnerable populations may have additional or different infrastructure needs than other populations [73]. If return is authorized and returning populations include pedestrians, authorities must designate appropriate access for foot traffic and other active transportation [20].

During re-entry, damage and problems such as inundation, erosion, scour, washouts and debris affecting infrastructure system components such as roads, rail, bridges, signals and co-located utilities must be repaired or managed through traffic plans [55]. Building infrastructure such as depots must be functional and accessible, and designated shelters should be clearly identified. Regarding the latter, displaced populations can be difficult to locate and quantify, but designated shelters could influence infrastructure system repair priorities depending on the estimated number, location, and identity of evacuees [74], in addition to modal restrictions or family size-related vehicle capacity requirements. Lastly, fuel infrastructure is an important constraint [75].

2.1.4 Summary of practical impediments to recovery: Infrastructure systems needed to consider reconstruction's impact on population displacement

Based on the review of multidisciplinary displacement literature in this section, the six infrastructure systems relevant to displacement are *building stock, transportation systems, water/wastewater/stormwater, electricity, oil and gas, and telecommunications*. In particular, residential building stock and transportation systems are not readily substitutable with stopgap measures.

2.2 Interdependency Types During Recovery

This section describes important interdependency types for recovery. As mentioned in the previous section, the most efficient reconstruction strategies exploit infrastructure interdependencies, types of which are defined in Table 3. This is because restoring function to an infrastructure system includes restoring systems on which it is dependent:

- *Operational interdependencies* are infrastructure systems that need to be functioning for an infrastructure system of interest to be functioning.
- *Restoration interdependencies* concern effective coordination and sequencing of reconstruction activities within the recovery environment [76], [77].

For an overview of other operational interdependency classification frameworks, see the survey by Ouyang (2014).

Table 3. Operational and restoration interdependencies.

Reference	Interdependency	Definition
Rinaldi et al. (2001)	Physical	The states of interdependent infrastructure systems are dependent on one another's material outputs
	Geographic	An environmental event affects the states of all infrastructure systems in a given geography
	Cyber (alias: Information)	The state of the infrastructure system is dependent on the information system transmitting commands from computerized control systems
	Logical	The states of interdependent infrastructure systems are dependent on one another through a causal mechanism not addressed above
Sharkey et al. (2016)	Traditional precedence	A restoration task in one infrastructure system cannot begin until restoration task in another infrastructure system is completed
	Effectiveness precedence	A not-yet-completed restoration task in one infrastructure system causes less effective execution of a restoration task in another infrastructure system
	Options precedence	A restoration task in one infrastructure system can be begin after a restoration task in one of several possible infrastructure systems is completed
	Time-sensitive options	If an infrastructure system restoration task is not completed by a certain time, a task in another infrastructure system must be completed instead
	Competition for resources	Restoration tasks in multiple infrastructure systems are competing for the same, limited resources

Restoration interdependencies as defined in Table 3 will vary by event and location. They are revealed during the damage assessment and work planning processes. For brevity's sake, they are not further discussed here.

Operational interdependencies between pairs of infrastructure systems are summarized in Table 4 from several sources [27], [79], [80]. The degree of coupling between each pair (H=high, M=medium, or L=low), is also indicated, describing the level of dependency between the two as in Pederson et al. (2006). "High" indicates an infrastructure system is unlikely to return to full (or safe) operation without the other system in the pair. "Low" indicates that one system is likely to retain full or partial operability, at least temporarily, without the other. "Medium" lies between the two.

Table 4. Operational interdependency matrix.

Infrastructure System	**Building Stock**	**Transportation**	**Water/Waste/ Storm**	**Electricity**	**Oil & Gas**	**Telecom**
Building Stock	--	H	H	H	H	H
Transportation	M	--	M	H	H	H
Water/Waste/Storm	H	H	--	H	M	H
Electricity	M	H	L	--	M	H
Oil & Gas	M	H	L	L	--	H
Telecom	M	H	L	H	L	--

For each pair, the degree of coupling is not necessarily symmetrical; for example, water/wastewater/infrastructure is more dependent on electricity than the reverse. Data availability and data-sharing considerations are a real challenge to modelers interested in representing interdependencies. Real world models will likely need to incorporate a combination of real interdependency data and semi-quantitative interdependency estimates elicited from domain experts. For a notional example where a model represents interdependencies using link weights on a continuous 0-1 scale are assigned within a network model, semi-quantitative assignments might look something like: H=1, M=0.5, L=0.1.

2.2.1 Interdependent Infrastructure Model Types used in Recovery Modeling

This section describes modeling approaches that can represent interdependencies within CISs. Network models are particularly well-suited for displaying and describing interdependencies. In addition, workflows exist to, for example, translate municipal GIS data to graph networks using packages such a *shp2graph* or *networkx* from R and Python, respectively [81], [82]. Previous authors have classified CIS modeling techniques in a variety of ways (see, e.g., Rinaldi, [2004]) but for brevity, see Ouyang, (2014), which is briefly summarized below.

1) **Empirical**. Methodology-independent, quantitative analyses of disasters using historical data or data generated through expert elicitation.

2) **Agent-based.** Bottom-up modeling where infrastructure assets and their rule-based behavior are treated as components of a system, clarifying interdependencies and revealing system behavior that may not be apparent at the component level.

3) **System dynamics.** Top-down modeling of stocks, flows and feedbacks within a system. Feedbacks can include infrastructure interdependencies. Stocks represent state or quantities which change over time through flows between stocks.

4) **Economic theory.** Input-Output, Computable General Equilibrium models, and potentially others where infrastructure is treated as an "intermediate good" that facilitates interaction between producers and consumers.

5) **Network-based.** Graph-based models of infrastructure systems described using nodes for individual assets and links to show physical, geographic, cyber and logical interdependencies within and between one or more infrastructure systems.

6) **Other approaches**. Other graph theory-based methods (such as Bayesian networks and petri-nets) and non-graph methods (such as control theory approaches) not described above.

2.2.2 Recent Recovery Models

Only one model in this group included both housing and roads, Franchin and Cavalieri (2015). Their research team is interested in recovery from seismic events from the structural engineering perspective. Their network-based model also considers many of the key utilities that make returning to a residence attractive. A scorecard (Table 5) compares the reviewed models and discussion follows.

Table 5. CIS model evaluation criteria used for this study. Check mark indicates the presence of element in the CIS model. The score awards a single point for each of H, M, and check mark and serves as a relative ranking of the highly relevant papers surveyed here.

	Appropriate Infrastructure		Geospatial Details			Spatial Scales			Agents		Political and Funding		Evolution and Uncertainty		Score
Reference	Primary	Interdependent	Infrastructure location	Topography	Hazard Proximity	Community	Neighborhood	Housing Unit	Decision Makers	Residents	Jurisdiction	Funding	Uncertainty and Probability	Dynamic	Count
Bristow, 2019	H	H	✓		✓	✓	✓	✓	✓	✓			✓	✓	11
Franchin and Cavalieri, 2015	H	H	✓	✓	✓	✓	✓	✓		✓			✓	✓	11
Lin and Wang, 2017	L	L	✓	✓	✓			✓		✓	✓	✓	✓	✓	9
Bhamidipati et al., 2016	M	L	✓	✓	✓	✓	✓		✓			✓		✓	9
Paredes and Dueñas-Osorio, 2015	M	L	✓	✓	✓	✓			✓			✓	✓	✓	9
Peeta and Zhang, 2014	M	M	✓			✓			✓	✓	✓	✓		✓	9
Bhatia et al., 2020	L	M	✓		✓	✓			✓		✓		✓	✓	8
Val et al., 2014	M	L	✓	✓	✓	✓							✓	✓	7
Hwang et al., 2016	M	M			✓	✓			✓				✓	✓	7
Argyroudis et al., 2015	M	M	✓	✓	✓	✓							✓		7
Park et al., 2014	H	H				✓			✓	✓				✓	6
Bristow and Hay, 2016	L	L			✓	✓			✓				✓	✓	5
Ouyang, 2017	M	L	✓		✓	✓			✓						5
Chang et al., 2014	M	L			✓	✓			✓					✓	5
Sharkey et al., 2015	M	M				✓			✓		✓			✓	6

Appropriate Infrastructure

The surveyed CIS models did not include all or even most of the primary and secondary infrastructure identified as critical for considering population displacement. Only two models in this group included both housing and roads. Franchin and Cavalieri [83] are interested in recovery from seismic events and come from the structural engineering perspective. Their network-based model also considers many of the key utilities that make returning to a residence attractive. Bristow [28] is interested in recovery assessment from the perspective of restoration of building services, and merges a GIS asset model with interdependency tables and damage data for a portion of an urban area.

Geospatial details. The models do not typically make note of which infrastructure components are damaged, which poses obvious difficulties for communicating damage and performance. This also limits the ability to categorize infrastructure components according to recovery funding eligibility, which is closely related to asset type and asset ownership. Four papers mention funding [84]–[87], however, except for Bhamidipati et al. [84], the CIS modelers reviewed do not specifically consider the critical role of funding constraints in recovery sequencing.

Spatial scales. The models in this selection consider recovery at the community level, but most do not consider the more granular neighborhood and structure-level scales at which people organize their households and local social networks. Notable exceptions are Franchin and

Cavalieri [83], [28], and Bhamidipati et al. [84], who consider neighborhoods, and Lin and Wang [85], who consider individual structures. Other important spatial delineations, such as jurisdictions across which decision makers may need to collaborate, are also generally absent, although Lin and Wang [85] and Peeta and Zhang [86] do mention this issue.

Decision makers and other stakeholders. While most of the models reviewed here mention decision makers at least once, only five papers [28], [83], [85], [86], [88], mention residents or community members. Field crews or other workers are not discussed, neglecting the potential use of CIS models in work planning. It should be noted that three of the four papers referring to community members or residents are interested in CIS recovery from the perspective of structures or facilities, an emphasis which the other models generally lack.

Political and funding environments. Rigorous consideration of political jurisdictions, and how they interact with funding streams and recovery responsibilities, is lacking in these papers. The exception is [89], which models CIS recovery under various levels of decentralized decision-making. The major finding of their paper is that lessened effectiveness of recovery efforts due to decentralization can be mitigated through information-sharing [89].

Evolution and uncertainty. Nearly all models in this group consider the evolution of the system over time. Although they and the other modelers neglect discussion of information-related infrastructure uncertainties, [85] are the most comprehensive in their description and handling of information uncertainties in their model:

- Interdependency Uncertainties: Operational dependencies on utilities are modeled as binary on/off and are prerequisites for moving out of certain damage categories
- Damage Assessment Uncertainties: Building damage is classified into discrete categories (green/yellow/red tags). Utility damage is approximated using empirical and analytically
- Reconstruction Timeline Uncertainties: Probabilistic modeling of the return of individual components and the full portfolio to full function
- Population Dynamics Uncertainties: Modelers note that uncertainties in population changes impact whether building portfolio recovery occurs

However, in all models, practical issues such as data consistency, security, standards, and interoperability are not discussed.

Additional considerations. These gaps suggest a need for improved communication between the structural engineering and infrastructure systems communities in matters of modeling recovery. Transportation systems are missing from many of the CIS models, which is a fatal flaw for any study interested in population displacement, which is fundamentally a human mobility problem. To achieve actionable decision support, CIS modeling teams with experts from both disciplines may be a particularly fruitful avenue of collaboration.

2.3 Geospatial Network Science to Model Interdependent Infrastructure Systems

GIS is important but not sufficient to model the recovery process. GIS is growing in popularity as an infrastructure asset management solution and has been used in resilience projects for community infrastructure subsystems such as roads [90], transit networks [91], [92], building stock [93], and water/wastewater infrastructure [94]. In various CPS resilience applications, asset management itself is the resilience contribution [95], and asset management databases are also fundamental to other resilience goals such as cyber-security [96] and reliability [97].

GIS is also useful to create visualizations and spatial analyses. Domains that use GIS in these ways include natural hazard mitigation and environmental planning: selecting wind farm sites using Multicriteria Decision Science [98], identifying assets vulnerable to sea level rise [99], understanding public use of forest road networks on public lands [100], and citizen science applications [101], among others. However, GIS lacks network analysis' ability to examine connectivity, structure, and other system-level attributes.

Geospatial graphs retain the advantages of a GIS while adding the essential ability to use graph theory to account for interdependencies during recovery planning and reconstruction. Leveraging interdependencies is an important key to effective recovery strategy development [28], [102], [103] and reconstruction [76]. Network analysis is able to represent interdependencies through edge lists, and is a popular approach to understanding complex physical systems such as civil infrastructure systems (CIS) [78]. A recent network optimization approach [29] in the infrastructure recovery space uses sophisticated metaheuristic and network-based measures, but their use of the latter relies heavily on definitions of centrality measures from social networks rather than identifying and exploiting the centrality measures best-suited to represent service provision in infrastructure systems, and furthermore does not connect infrastructure system structure to user heterogeneities. Another recent model uses delay as an important resilience indicator [104].

2.4 Satisfactory Control of Interdependent Infrastructure Systems

Disciplinary studies and patents describe numerous controllers designed and implemented for complex, networked infrastructure. Controllers that are resilient to disruption are particularly of interest. Recent examples of resilient controllers include controllers designed for cyber-physical systems (CPS) such that, alongside the primary objective, the controller provides incident detection [105], automatic incident response [106], and adaptive control that returns the system to stability after attacks [107]. Some approaches can detect or handle both cyber and physical faults [108]. Resilient controllers appear to be most common in cybersecurity and adjacent disciplines.

During recovery, the attempt to return the system to full performance after encountering a disturbance is consistent with definitions of engineering system resilience [16], [109]. The return to full performance after encountering a disturbance also describes the behavior and purpose of controllers. However, the same data problems, uncertain dynamic features, and complexity that render recovery of the system challenging to solve heuristically by decision-makers make it difficult to represent mathematically through such forms as state-space representations. A closed-form mathematical representation is necessary for designing an optimal control scheme. Therefore, this system is not well-suited to optimal control.

However, aspects of this system that are critical for users and highly responsive to repair actions are observable. Important observable characteristics include system properties that are problematic with respect to goals, such as damaged critical infrastructure components. Sensitive system properties can be selected to provide feedback for a closed-loop control system. Even where optimal control is not possible, PID controllers are well-known to provide satisfactory control [110]. These common controllers have historically been used in the majority of industrial control systems [111], [112].

2.5 Systems-Theoretic Process Analysis of Interdependent Infrastructure Systems

2.5.1 Definition of STPA

Systems Theoretic Process Analysis (STPA) is a hazard analysis technique for engineered systems, summarized here based on [1]. A distinction in nomenclature must be made here: In disaster management, a hazard refers to the disaster itself, such as a flood hazard. In safety engineering, a hazard is an undesired behavior in the engineered system that can lead to a loss. Because we are adapting a safety engineering technique, the latter terminology is used in this chapter. Where floods or other disasters are discussed, the phrase “natural hazard” is used.

STPA defines the source of hazards as both undesired component interactions and component failures. According to this model, accidents result when accumulated hazards cause system failures during either normal operations or in response to external disturbances [113]. Accidents are system failures that cause losses, and engineers prevent system failures by eliminating hazards. Hazards are eliminated systematically by controlling component behavior such that only nonhazardous behavior is permitted. Therefore, any relevant hazards and constraints must be identified for each component as well as their interactions.

Appropriate constraints are identified in STPA using a top-down approach, which is conceptually appropriate for the objective of achieving good *system* performance by enforcing appropriate *component* behavior. This hierarchical model of interactions is two-way. High-level system behavior is considered a consequence of lower-level components and interactions. In turn, lower-level components and interactions are affected by control actions or commands. Lower-level behavior is then reported upwards in the hierarchy through feedbacks.

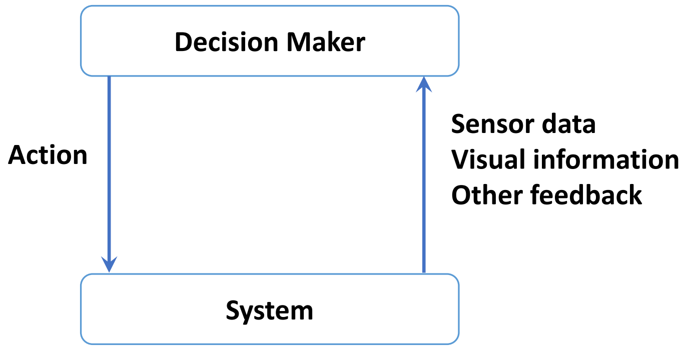


Figure 4. A simple, high-level control structure is sufficient to begin the STPA analysis, which adds detail and controllers as control actions that can cause recovery problems are identified.

This model of interaction is the initial control structure such as that shown in Figure 4, from which control actions that cause recovery problems can be identified and to which additional controllers can be added. Note that in the safety engineering literature on STPA [1], [114]–[117], a control action that can result in unacceptable behavior is typically referred to as an *unsafe* control action, or sometimes a *hazardous* control action. This dissertation intentionally uses the term "recovery problem" because not all actions that are detrimental to resilience or recovery are necessarily unsafe in the standard definition. Controllers must address the cause of control actions that cause recovery problems. Control actions that cause problems result from factors such as inconsistencies between the human or automated controller's process models and how the process actually works, missing or inadequate feedbacks, component failures, and inadequate control inputs [114].

2.5.2 Extensions and Novel Applications of STPA to Analyze Interdependent Infrastructure Recovery

STPA is used extensively in the remainder of this dissertation. Extensions and novel applications of STPA are employed. These extensions and novel applications combine STPA with many of the other engineering techniques described above:

1. Rather than using STPA to analyze an existing or planned system, we are designing a new system to deal with an emerging problem from the ground up (Chapter 3).
2. Rather than using STPA to prevent losses, we are a walking the system back from losses that have already occurred, with a desire to be able to identify highly effective courses of action. This requires an adjustment from simply identifying unsafe (or non-resilient) states to developing graded categories of unacceptable states to capture some notion of system states' relative contribution to system losses (Chapters 3 and 4). This approach can potentially also be applied to problems like system retrofits and system restoration projects.
3. We show how to combine STPA with network science to handle systems with interdependent infrastructure (Chapter 4).
4. We apply STPA to a problem involving geospatial characteristics and equity considerations (Chapter 5).
5. We combine the essential review and refinement process of STPA with stakeholder engagement tools, which is necessary for both completeness and legitimacy in systems with heterogenous users, including public sector infrastructure (Chapter 5).

6. We introduce a complementary monitoring and assessment tool to alert decision makers when new adaptations by user require an adjustment to controller rules (Chapter 6).

As we will show in subsequent chapters, these applications and extensions of STPA render the complex system recovery problem more tractable.

3 Extending STPA for Recovery Strategy Design

3.1 Overview

In this section, we are interested in modifying STPA to identify a sequence of control actions that result in high system-level resilience in a damaged system, with the aim of reversing system-level hazards. This method produces an architecture that enforces process constraints on the interdependent infrastructure recovery, which is used in subsequent chapters. In a departure from previous applications of this method [114], [118], we are not interested in *preventing* system-level hazards, since those are already present when a complex system is substantially damaged. However, modifications must be made for STPA to handle multi-objective decision-making in massively damaged interdependent systems. These modifications allow us to render the interdependent infrastructure recovery problem more tractable by leveraging STPA's ability to analyze and improve systems experiencing problems with components and due to component interactions.

First, rather than eliminating hazards using control actions, we are reversing hazards that have already resulted in substantial losses. These hazards are caused by nonfunctional assets due to either direct damage or damage to an infrastructure service the asset depends upon. Therefore, in addition to the best available data for the system model, a thorough damage assessment, such as the type need to apply for FHWA or FEMA repair funds in the US, is needed.

It is also the case that priorities are different during different phases of the disaster lifecycle (e.g., Faturechi and Miller-Hooks, 2015), and depend on decision-maker goals. A simple example of a goal set for the long-term recovery phase is to return to full function of the system by repairing each asset or replacing it in kind (other examples of goals include “build back better”). Therefore, rather than the typical STPA approach that uses a single set of goals for a single process – normal, safe functioning of the system – this modification of STPA recognizes that goals must be tailored to each phase of the disaster lifecycle and particular problems facing users of the system.

Further, the hazard elimination process will be extensive and time-consuming in the recovery environment, and cannot be represented as near-instantaneous and simultaneous application of a control actions. Repair time and sequencing become important. Sequencing influences factors important to public policy such as efficiency and fairness, and decision-makers will be responsible for setting goals commensurate with these objectives. In addition, managing information uncertainties becomes necessary, since major increases in estimated repair time for an asset may change the preferred sequence of events. However, goals must be achieved within constraints, since the process may be partially or wholly prescribed due to both policy and feasibility considerations, for both individual assets and for the system as a whole. Policy constraints may align with or exist in addition to stakeholder concerns. Engagement of the latter is an important related topic described in more detail in, e.g., [119].

Therefore, STPA is used here to design controllers that restore performance by repairing assets in a sequence that reflects recovery process goals within the given constraints. This means that the desirability of potential reconstruction sequences must be quantified along dimensions that correspond to recovery process goals (see the example in Section 3.3). Hazards to the physical system (i.e., damage) can then be eliminated, and recovery process hazards, such as inefficient actions, can be avoided as well. The presence of damage, importance of sequencing, and need to consider reconstruction timelines differs from a typical use of STPA, where controllers are identified and deployed to prevent hazards during normal functioning.

In addition, while one hazard may be eliminated through one or more potential control actions, another hazard may not have any obvious control action. This latter case may arise when decision makers are faced with serious tradeoffs between, for example, short-term functional and long-term resilience goals for a single asset. A control action on one asset may also impact other assets. For example, relocation of one asset to an available location reduces the number of locations available for other assets to be relocated. When a potential control action impacts other assets, tradeoffs must also be evaluated for their impact on the rest of the asset catalogue. The simple case is a long-term recovery with a repair-or-replace-in-kind goal, where the only control action is “repair asset.” STPA can also be extended to cases with more control action options (such as hardening or relocation). For simplicity, only one control action, which most closely resembles typical use of STPA, is illustrated in the example case.

Lastly, resource constraints further curtail options, lengthen the restoration process, and impair attempts to sequence repairs efficiently for strategic gains in performance. Resource constraints are a major consideration in real systems and cannot be neglected. To acknowledge real constraints and to avoid longer reconstruction times due to lack of coordination [120], work is not initiated for an asset until resources (materials, staff, site plans, etc.) are available. A designed recovery strategy therefore dynamically updates the recovery sequence, retaining rules about priority but omitting assets that are not yet resourced. The sequence is populated by previously-omitted assets as resources become available. This is in contrast to safety analysis in STPA, where appropriate control actions must be supplied in a timely manner to meet system requirements before the system can be used. As such, this modification of STPA can also be used for policy analysis, where differences in the resource-constrained and unconstrained version of the same strategy can be used to reveal problems in the availability and timing of funds.

3.2 Background

A civil infrastructure system recovery process led by a full-time recovery manager at the local government level (e.g., town, city, village) was selected to demonstrate the concept of recovery strategy design. Of interest is the long-term recovery process with widespread infrastructure damage and population displacement and other disruptions in system use due to a major disaster. Recovery goals in this scenario are related to both community resilience through return to full mobility and access to infrastructure services, and infrastructure recovery. The human and infrastructure goals are framed as coupled. This is a specific hypothetical case; in other systems where return migration is less desirable to residents, such as the irradiated case described in [121], other goals will be pertinent.

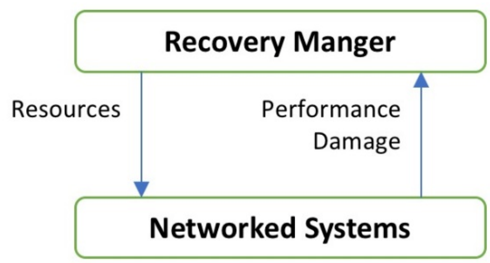


Figure 5. High-level control structure for the recovery process

Recovery managers' decisions clearly impact the habitability of the community, and their responsibility to the public, including socially vulnerable groups, is spelled out in guidance documents (e.g., Department of Homeland Security, 2018). However, resilience-related concerns remain: guidelines for recovery tend to be general, powerful interests have priorities that can compete with the need to address infrastructure related to resident displacement, and regulations, permits and other safeguards are sometimes waived or neglected in the name of expediting the recovery process. A number of causal factors that could impede the efforts of recovery managers are summarized in control block diagram format in Figure 6.

A recovery process led by a full-time recovery manager is chosen because it is in alignment with recent FEMA guidance in the United States [37] and replaces decentralized coordination and communication between entities involved in long-term recovery with a more centralized process. The recovery manager is responsible for executing the recovery plan, coordinating across different levels of government, securing funding, and communicating with the public. At a high level, a recovery manager interacts with the network of infrastructure systems within their jurisdiction through the complex, often lengthy recovery process summarized in the control block in Figure 5.

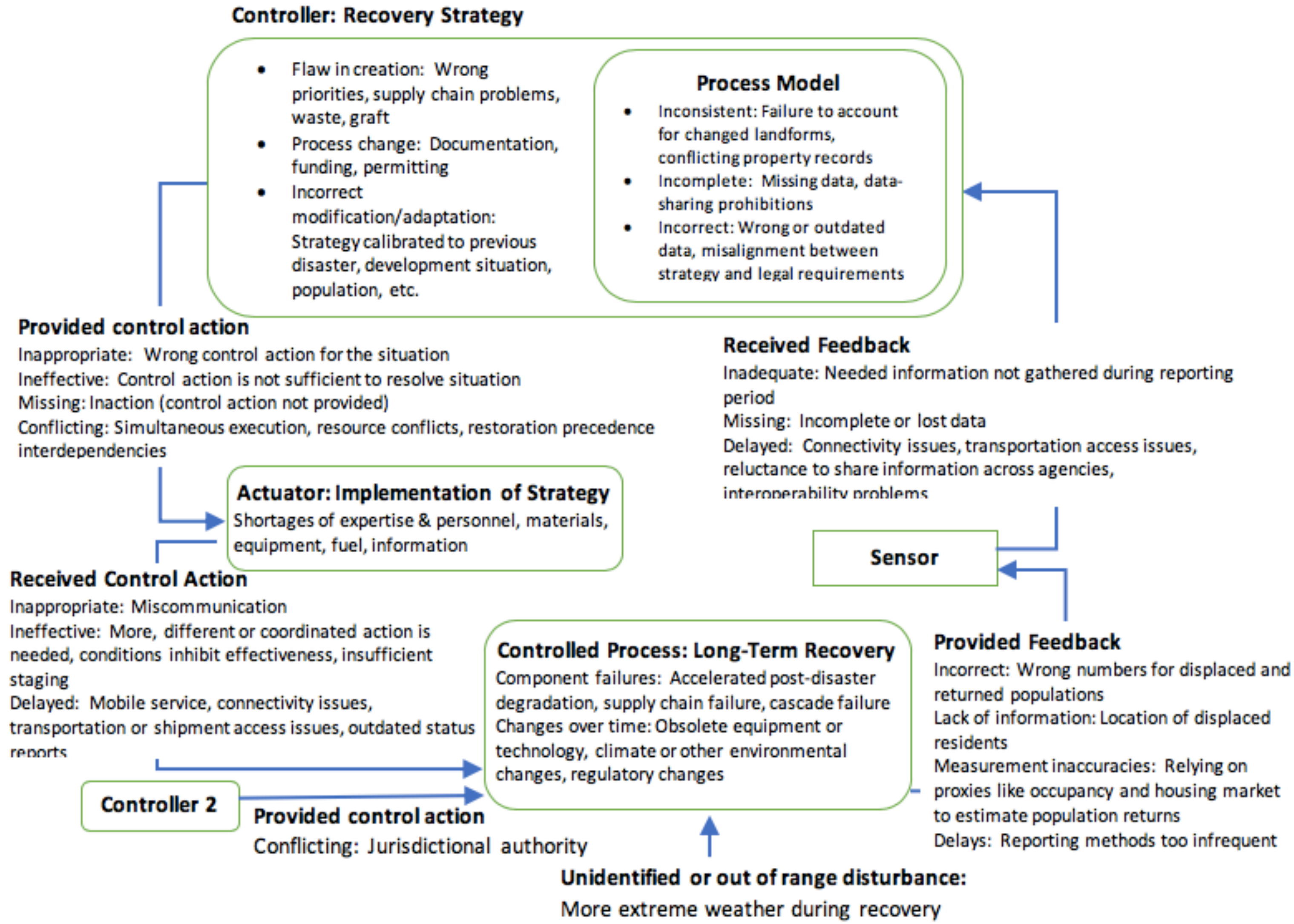


Figure 6. Causal factors to generate causal scenarios associated with safety constraints. Extreme weather event recovery example.

We apply STPA to the recovery process to render it more tractable, using STPA to enforce goals in this complex, dynamic system. In the next section, the control structure necessary to advance from the qualitative goal of resilience to concrete recovery strategy designs and daily work-planning process is outlined. This is achieved through a structured process of abstraction and hierarchical representation

3.3 Technical Approach

3.3.1 System level hazards and accidents

STPA begins with the analysis of system-level accidents and hazards, usually focusing on accidents involving loss of life or injury, but the method extends to other losses [114]. This paper adjusts the nomenclature from “accident” to “recovery problem” (see Table 6). A hazard is a system state that could have a range of consequences, including a loss (see Table 7). With respect to resilience, the recovery problem considered here is the set of situations that delay or prevent the return of displaced residents and impede resumption of daily activities, with attention to the difficulties faced by socially vulnerable populations. Losses related to displacement and mobility were summarized based on [17].

Table 6. System-level recovery problems

Number	System Recovery Problem
A-1	Users cannot access the system
A-2	Users cannot execute necessary functions
A-3	User experience is unsafe

Table 6 contains system-level accidents or recovery problems, and since we are interested in how impacts to infrastructure map to users, those accidents are framed in terms of user experience (UX) rather than networked infrastructure metrics. People-centered quantitative resilience metrics have been developed elsewhere, but they consider community resilience to be distinct from the built environment (e.g., Cimellaro et al., 2016), or they describe community resilience as a function of the built environment, but only qualitatively describe performance goals (e.g., National Institute of Standards and Technology, 2016). As this example progresses, we illustrate how STPA can be used to advance from qualitative descriptions of resilience goals to quantitative networked infrastructure metrics (see Section 3.3.2).

Table 7. System hazards (system states that could lead to accidents)

Number	System Hazard Description
H-1	Destroyed system is not repaired
H-2	Condition of system does not meet standards in time
H-3	Performance of system is unacceptable for too long
H-4	Capacity of system does not meet demand
H-5	Access to system is inadequate

Table 7 lists high level hazards that can result in the recovery problems listed in Table 6. Inadequate access could include problems such as poor design, inadequate spatial or temporal coverage, lack of reliability, etc. Figure 5 shows the high-level control structure for centralized decision-making and resource allocation. The recovery manager is shown acting directly on the networked systems and obtaining necessary feedback. STPA leverages the concepts of abstraction and hierarchical representation to handle complexity, so this minimal level of detail is sufficient to begin the analysis.

3.3.2 Initial control structure

The controller is the recovery process, and associated control actions involve repair of damaged components. Available control actions are those that operate along five dimensions of resilience that are selected for their relevance to the recovery problems identified in Table 6: performance, time, a network importance measure that is sensitive to interdependencies [102], geographically diffuse vulnerable populations, and geographically concentrated vulnerable neighborhoods.

Possible control actions are devised using context variables along those five resilience dimensions. For example, a possible context for the repair of a system component by the recovery strategy, is that:

- Performance is unacceptable,
- Time out of service is unacceptable,

- The diffuse measure of vulnerable populations is critical,
- The concentrated measure of vulnerable populations is critical, and
- The importance to the network is critical.

Repairing a component in this context is the most effective action with respect to the stated resilience goals. Conversely, failing to repair components in this context is the most hazardous resilience action. Table 8 identifies contexts under which the control action “repair component” shifts the system away from system hazards that, in turn, can result in the recovery problems listed in Table 6.

For simplicity, the possible values for each variable are binary True/False values. Table 8 contains only physically meaningful combinations of hazardous states for the control action. Table 8 is also ordered and according to effectiveness, where leftmost contexts are more effective and rightmost are less effective. To facilitate discussion, decision regimes are grouped roughly according to performance and time values. Within regimes, green shading indicates approximately equally effective contexts for the control action to occur.

Table 8. Context table for "repair component" control action

Abbr.	Variable	Value	R1	R2			R3			R4	R5 (Monitor)								R6 (Capital Improvement)						
Q	Performance	Unacceptable	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T							
t	Time out of service	Unacceptable	T	T	T	T	T	T	T	T															
Crit.	Vulnerable pop.	Critical	T	T		T		T			T	T		T			T		T	T		T			T
	Neighborhood	Critical	T		T	T			T		T		T		T		T		T		T	T		T	
	Network	Critical	T	T	T		T				T	T	T			T			T	T	T		T		

The control action sequence is then ordered according to priority, progressing sequentially from more effective to less effective contexts (from left to right) in order to resolve hazardous states effectively. Regime 1 are high-priority hazards where damage includes multiple interdependent systems affecting many users, including vulnerable groups, some of which are spatially distributed and some of which are spatially diffuse. Regimes 2-4 correspond to performance that is unacceptable for some dimensions, but not all. Regime 5 is where time-out-of-service benchmarks have not been exceeded, perhaps due to mechanisms that support graceful failure such as system redundancies, alternatives, and stop gaps. Regime 6 is where baseline performance has been restored (or was never disrupted) and non-critical activities such as capital improvement projects and other economic development initiatives become appropriate.

3.3.3 Resilience constraints

It is now possible to consider recovery strategy design in more detail. To enforce the sequential progression we have identified, we use the context table to derive constraints on control actions. In an actual recovery scenario, issues such as logical precedence [76], [77], shortages of licensed professionals, and other resource constraints may impede the selection of the most desirable control actions in a given situation, however, it is still important that we be able to distinguish between control actions that provide greater or lesser incremental movement toward safe states so that we can select effective options.

Table 9. Constraints derived from control actions in Regime 1.

Resilience Constraint	Description
RC-1	RM must not divert resources to systems without impaired performance [H-1, H-2, H-3]
RC-2	RM must initiate repairs on systems exceeding time-out-of-service benchmarks [H-1, H-2, H-3]
RC-3	RM must give the highest priority to repairs on which many other systems depend [H-3, H-4]
RC-4	RM must not choose repairs that result in drastically different recovery profiles for different users [H-4, H-5]
RC-5	RM must consider efficient work planning by initiating repairs on horizontally and vertically adjacent systems wherever practical [H-1, H-2, H-3, H-4, H-5]

In this example, RC-3 and RC-5 indicate that some type of geospatial representation of the system is necessary. In addition, RC-4 indicates the need to consider and compare user experiences as the system is migrated back toward safety. These additional details can be immediately added to the control structure as two models that interact with each other and provide the necessary feedback to the RM. This progressive addition of detail is illustrated in Figure 7 and Figure 8. The exact mechanism can be specified later in the development process.

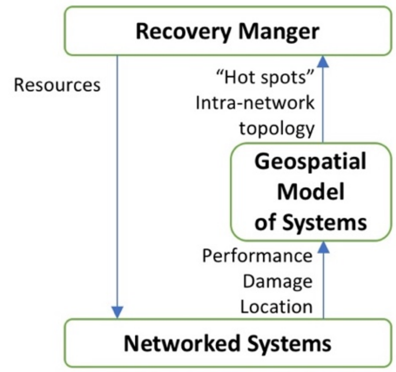


Figure 7. Revised control structure with spatial representation added.

Additional necessary feedbacks can be identified by developing causal scenarios corresponding to the safety constraints. Causal scenarios can be identified using resources such as academic literature, case studies, effective practice, expert experience, and judgement. A control structure such as provided in Figure 6 can be a useful template on which to record the relevant causal factors. Table 10 illustrates a selection of causal scenarios broadly relevant to networked systems.

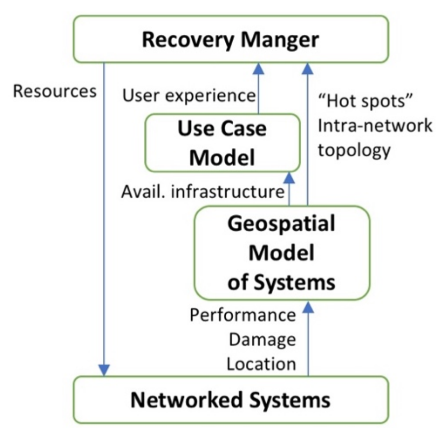


Figure 8. Revised control structure with user experience feedbacks added.

Table 10. Safety constraints associated with widespread damage scenario.

Safety Constraint	Causal scenario(s) that violate safety constraint
SC-1	S-1.1. Performance information is not provided S-1.2. Performance information is not a decision criterion S-1.3. Performance information is delayed
SC-2	S-2.1. Time-out-of-service benchmarks were not set S-2.2. Time-out-of-service is not provided S-2.3. Time-out-of-service is not a decision criterion
SC-3	S-3.1. Interdependency information is not provided S-3.2. Network importance measures are not a decision criterion S-3.3. Rules of thumb are used instead of network importance measures S-3.4. Geospatial proximity is considered an adequate measure of network importance [124]
SC-4	S-4.1. User experience under recovery scenarios is not tested S-4.2. An "average" or other statistical representation of use that does not adequately represent the spectrum of user experiences is used S-4.3. Important or protected classes of user groups are not considered
SC-5	S-5.1. Geospatial data is not provided S-5.2. Appropriate site construction planning expertise is not used

Conflicts between the safety constraints listed in Table 10 must also be identified. Table 11 presents conflicting safety constraints side-by-side. The current control structure has no way to resolve potential conflicts between high impact control actions and the need to reduce differential recovery experiences for users (C-1). It is also not possible to evaluate and compare geospatial versus other aspects of network interdependencies, because the latter are not yet identified (C-2).

Table 11. Unresolved conflicts between safety constraints

Conflict No.	Conflict description	
C-1	SC-3. RM must give the highest priority to repairs on which many other systems depend	SC-4. RM must not choose repairs that result in drastically different recovery profiles for different users
C-2	SC-3. RM must give the highest priority to repairs on which many other systems depend	SC-5. RM must consider efficient work planning by initiating repairs on horizontally and vertically adjacent systems wherever practical

It may be possible to effectively resolve C-1 and C-2 in a number of ways. C-1 indicates the possibility that control actions with high system impact may disadvantage certain user groups (for example, because they rely on impaired portions of the systems which are not yet under repair). The RM could opt to generate a rule stating that impaired performance (A-2) is better than complete lack of system access (A-1) and control actions mitigating A-1 are to be prioritized over A-2. Toward that end, more detailed metrics are provided by the use case model that was added to the revised control structure as shown in Figure 9.

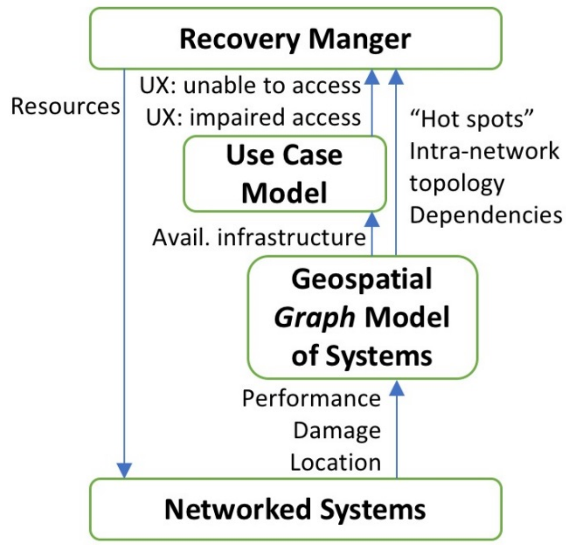


Figure 9. Revised control structure with additional UX metrics and improved representation of spatial and non-spatial network interdependencies.

Figure 9 also provides new feedback allowing identification of network dependencies, however, C-2 is a more complex problem. Practitioners have commented to the authors that work planning is particularly challenging in long-term recovery. The long-term recovery process contributes to conditions that lead to attrition of professionals, including those with irreplaceable institutional knowledge, because the role of decision makers is inherently multi-objective, involves unclear lines of authority outside established chains of command, and is subject to funding and political pressures.

Table 12. Unsafe control actions for the daily work planning coordination process

Control action	Not providing causes hazard	Providing causes hazard	Too early, too late, wrong order	Stopped to soon, applied to long
RM issues priorities for integration into the work plan	UCA-1: Priorities are selected but not received by cooperating entities UCA-2: New priorities are not established when new constraints (resources, policies, etc.) arise	UCA-3: Priorities are selected that do not meet resilience requirements UCA-4: Selected priorities are not feasible given available resources UCA-5: The ordering of intended versus executed priorities is inconsistent (e.g. versioning)	UCA-6: Priorities are communicated too late after being set UCA-7: Priorities are established before sufficient information is available UCA-8: Priorities are selected without appropriate outside input UCA-9: Cooperating entities do not adhere to selected priorities	UCA-10: Recovery is abandoned before adequate performance is restored

It becomes clear that in addition to needing a mechanism for flagging the potential need to repair less-essential systems to 1) allow access or 2) reduce re-work, the decision architecture will have to accommodate significant coordination between teams, some of which will potentially include contractors and outside entities. Even before the characteristics of an actual disaster event or damage assessment has been made, safety constraints on unsafe control actions that can occur in coordination process can prompt development of the necessary communication and coordination pathways to achieve resilience goals. Practitioner examples of coordination mechanisms from various domains include fusion centers and the incident command system, but something similar does not yet exist for long-term recovery.

The unsafe control actions applicable to the daily work planning process itself (Table 12) are not all addressed by the existing control structure. From the perspective of data management, it is expedient to use the existing control structure depicted in Figure 9, which already includes a system representation that could be used in GIS-enabled work planning, to provide safety constraints for coordination. This new detail is added to the control structure and depicted in Figure 10.

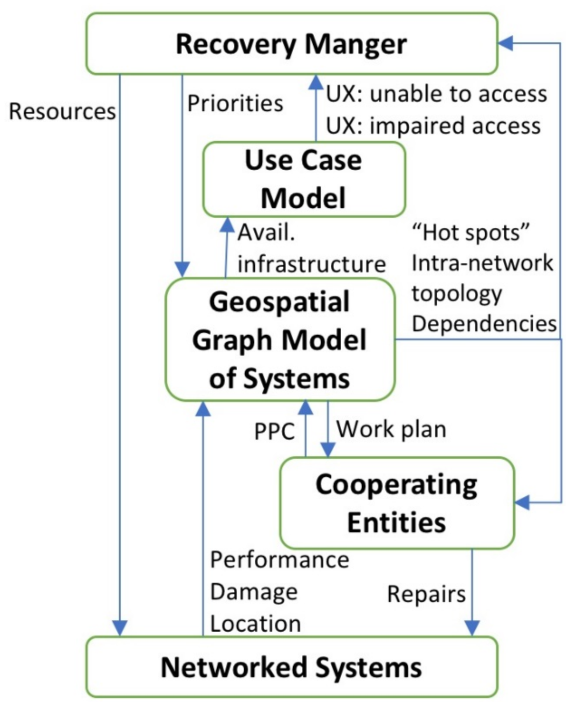


Figure 10. Revised control structure with additional work planning and coordination detail.

The completed control structure is sufficient to begin producing the controller that enforces the goal-based constraints on the recovery process, and to define the controller outputs. We have established in this chapter that the controller needs to operate on a network representation of the infrastructure system, and moves from high-hazard states to low hazard-states. Outputs must include a depiction of the system after each repair action, and the edge (a segment on the transportation network with co-located utilities) that is repaired at each repair action. These initial elements of the controller are shown below in Pseudo-Code Snippet 1.

Pseudo-Code Snippet 1. Produce an updated system representation and list of repaired edges after each repair action.

Input: Damaged Graph, *G*, with *n* damaged edges, and *m* priority regimes
Output:
1. Graph with new repair (each action), $\{G_{repair\_action\_1}, G_{repair\_action\_2}, \ldots, G_{repair\_action\_n}\}$
2. Edge order, $\{e_{repair\_action\_1}, e_{repair\_action\_2}, \ldots, e_{repair\_action\_n}\}$

While any($E(G)_{damaged}$) = TRUE
    Choose $E(G)_{damaged}$ & m_{max} -> $E(G)_{candidate}$

⋮

3.4 Summary

This chapter represents resilient recovery as a system control problem, using system theoretic analysis techniques capable of translating goals initially articulated in the language of law and policy into descriptions of desirable and undesirable system states. In the example application, metrics are devised to highlight the needs of various user populations (that is, residents), some of whom may be particularly vulnerable. Further, all hazards are defined in such a way as to acknowledge recovery challenges commonly faced by the most vulnerable populations in the system. Effective control of the system necessitates identification and representation of a control structure, which we have shown. The control structure can also be viewed as a technique for identifying high-level architecture requirements for a system model. The system model shown here is suitable for coordinated multi-agency recovery efforts.

4 Combining STPA and PID network control

4.1 Overview

This chapter describes the combination of STPA and PID network control within a recovery model. This PID-inspired controller is the part of the architecture, sketched out in the previous chapter, that is responsible for implementing the designed recovery strategy. The controller operates on a network model of the infrastructure system, which is described in more detail in the next chapter. The recovery strategy is built using the network model of the infrastructure system, the details of which were determined using STPA, as described in the previous chapter.

This network model is combined with a PID controller that enforces a formalized version of the system goals. Here, PID control principles employ key decision variables to design an empirical, stepwise recovery curve that reduces the impact of damage over time during recovery. The controller acts on the model to produce a recovery strategy. The recovery model therefore consists of both the infrastructure system model and the controller. Figure 11 depicts the infrastructure system model and the controller within a notional decision support tool during long-term recovery.

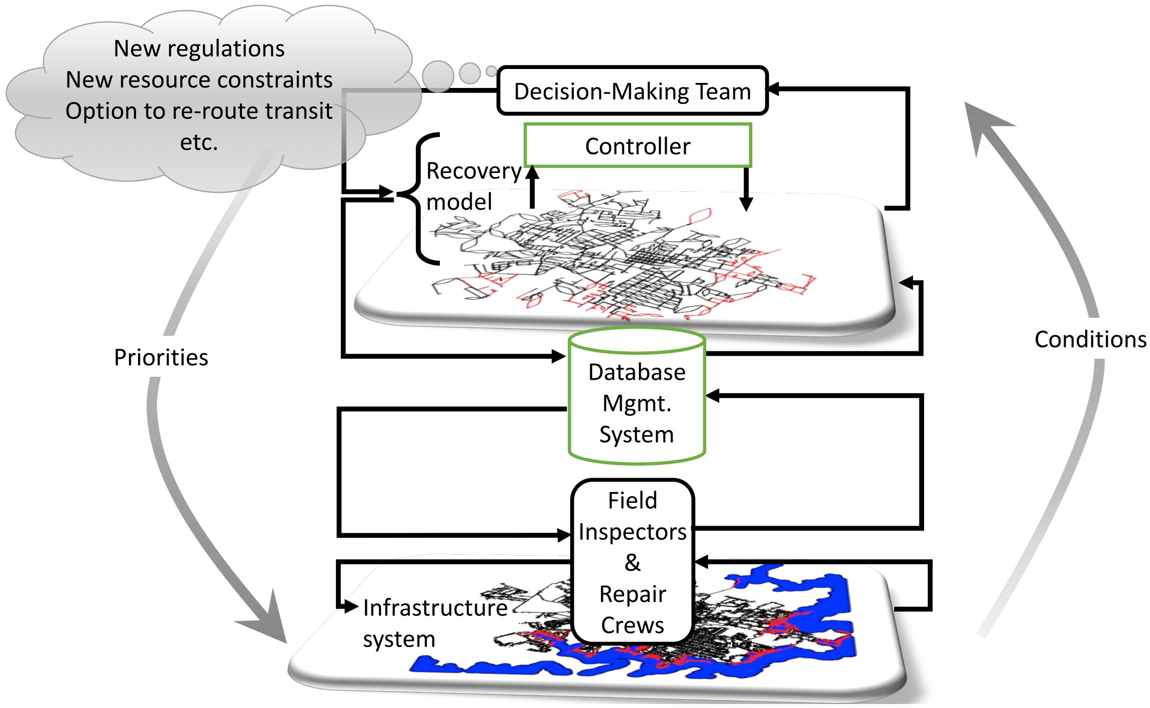


Figure 11. Long-term recovery from an event is facilitated by a decision support system that contains a controller and a system model. Upward f acing arrows indicate uptake of information and downward facing arrows indicate communicated actions.

Due to both the problem structure (first introduced in Chapter 1, Section 1.2) and spatial variation of population needs, corridor repairs may have vastly different impacts on recovery goals. As Ayyub points out [125], infrastructure resilience impacts are generally uncertain between the times of destruction and reconstruction. Furthermore, users typically cannot access a system component or service until reconstruction is complete. Therefore, step functions for individual infrastructure elements, or in this case, corridors with co-located assets, are preferred in the absence of data supporting other curve shapes.

In multi-step cases where more than one corridor is damaged, it is possible to order the rectangular steps to minimize cumulative impacts over the course of system recovery. However, even when selected goals remain appropriate for the system, the ideal order of steps varies depending on system changes. Acknowledging the potential of new disruptions, new constraints, and new information to arise, we adapt the principles of PID to the rectangular reconstruction steps to accomplish recovery ordering. The controller described in this chapter is therefore constructed using each of a proportional, integral and derivative components, adapted to a discrete-time, time-varying system, where performance improvements are represented as non-uniform rectangular steps.

4.2 Background

In the previous chapter, STPA was used primarily for sketching out the architecture of a recovery decision support model. STPA is now used in this chapter as an intermediate step for formalizing recovery goals in that model. Researchers will find STPA is suited to the intermediate step of defining system states that correspond to system goals using natural language.

Systems-Theoretic Process Analysis (STPA) uses context tables to define key system states. Context variables are the subset of process variables and values that need to be controlled to achieve system goals [118]. STPA also includes some notion of feedback.

Context variables come directly for the resilience literature already summarized above. In sum, quantitative resilience benchmarks typically involve a dimension of performance and a dimension of time [30], [125]–[129]. Anywhere more than one infrastructure asset is under consideration, such as in system-level assessments of resilience, a third dimension is needed to represent criticality (the importance of components of the system). The concept of criticality is well-known in physical and cyber infrastructure domains such as natural hazard mitigation, climate adaptation, and incident response, where practitioners use this concept to guide resource allocation. The formalization of the key contexts is described below.

Feedback selection is also described in the subsequent sections. Selection criteria include the following: Feedback should be selected based on the nature of the problem, which in this case, involves reconstruction and mobility. Feedback must be accessible to the controller designer and meaningful to the system users. Effective feedbacks will reflect system properties rather than component properties, because we are seeking to reverse system-level hazard states. Sensitive feedbacks are preferred.

4.3 Technical Approach

The recovery strategy is built using a model of the infrastructure system. The controller acts on the model to produce a recovery strategy. The recovery model therefore consists of both the infrastructure system model and the controller. Figure 11 depicts the infrastructure system model and the controller within a notional decision support tool during long-term recovery.

4.3.1 Recovery Model Function Description

The controller produces the recovery strategy by setting a repair order for the corridors. Corridors are ordered first by priority regime, which is defined using system states that map to recovery goals (Section 4.3.5). Within the priority regimes, there are opportunities to influence the trajectory of the performance recovery curve, and the controller performs this additional task by using appropriate feedbacks (Sections 4.3.3 and 4.3.4). The controller borrows from the principles of PID controllers to construct a performance recovery curve that, within the priority regimes, minimizes the impact to residents over the recovery duration.

The controller output must also be reviewed by appropriate stakeholders involved in recovery decisions. This process is described in the context of an actual recovery case study (Section 5). The review and refinement process is conducted using graphical techniques to visualize controller outputs. These techniques originate from the field of GIS-based stakeholder engagement. Effective practice for using the graphical review approach with a subject expert and stakeholders is summarized in Section 5.4. Once the controller has been reviewed and finalized, the controller-produced strategy is designed to be robust to construction interruptions.

4.3.2 Infrastructure Model Architecture

This approach to recovery modeling requires a network representation of the infrastructure system. A model concerned with practical impediments to return for the purposes of occupation or repair of private residences by owners and resumption of daily life requires, at minimum, the location and condition of the transportation network and condition of building infrastructure. GIS feature attributes from point-type features and vertices on polylines become node data in the network representation. GIS feature attributes from polyline segments become edge data in the network representation. The data requirements for a case study are listed in Table 13.

Table 13. Minimum data for recovery strategy design model.

Variable	Edge Data	Node data
Infrastructure feature attributes from asset management databases	Location (per lane) Direction Length Type Owner/jurisdiction	Location Type Population served or occupancy Owner/jurisdiction
Performance	Binary representation indicating damage/undamaged	Binary representation indicating damage/undamaged, or Red/Yellow/Green tag
Time out of service	Construction estimate	Construction estimate
Network importance	Use statistics for transportation links (e.g., annual daily traffic)	Service-provision type centrality score
Geographically diffuse vulnerable populations	All transportation modes included (walking, transit, paratransit)	Identification of schools, group homes, day centers, etc.
Geographically concentrated vulnerable populations	–	Census data (e.g., in the US, Social Vulnerability Index at the Census Block Group level)
Delay estimate	Length, or speed limit, or average speed for mode	–

Well-known uncertainties related to infrastructure include lack of or conflicting knowledge about the configuration, placement and sometimes even the existence of components due to factors such as data-sharing restrictions, missing data and non-digital data (e.g., Halfawy and Eng, 2008). Improvements in integrated asset management are necessary to resolve these issues [131], as are increases in post-disaster data-sharing and communication [89]. These gaps, and disagreement on which infrastructure and other systems and processes to focus on for disaster resilience, present difficulties with respect to establishing appropriate pre-disaster baselines [132], and hinder resilience assessment and recovery strategy design.

Missing infrastructure data and limits to data sharing are also sources of interdependency uncertainty. Even with complete asset catalogs of all infrastructure systems, however, interdependencies may be unclear or difficult to identify, for example, in chains of influence where the interdependencies are several steps removed [80]. Further, multiple types of interdependencies may be necessary for analysis, but could be ill-suited to representation in the same modeling framework. Pre-packaged albeit data-intensive methods are available to specify interdependencies (e.g., Klein et al., 2008) or to link infrastructure through market interactions (e.g. Zhang and Peeta, 2011). There is also evidence that Boolean specification of the presence of an interdependency is sufficient for some CIS recovery modeling applications [135], but models considering capacity and demand or analogous concepts have wider applicability. Methods focusing on geographic interdependencies (proximity and access) neglect other types of interdependencies (e.g., Ramachandran et al., 2015), but can be useful with respect to work planning.

This infrastructure model cannot resolve all these information uncertainties and simply focuses on representing the system using the best available data publicly available and readily cleaned using standard methods. Demonstrating the ubiquitous challenges in obtaining complete data, in the case study community, other linear-type assets (water and wastewater, gas) were listed as available by request, but were not included since the data owners did not respond. In this particular recovery problem, knowledge about the placement of other assets is helpful but not essential for initial recovery strategy development.

Even where digitized transportation network and building infrastructure data are not available, infrastructure location (buildings) and length (transportation network) can be estimated. One common approach uses human mobility data (e.g., [137]–[140]). These alternative sources of infrastructure data make the network model of the infrastructure system model transferable to locations where mobile trace data is available.

Infrastructure data is also used to produce construction duration estimates, which are notoriously uncertain, particularly in a post-disaster scenario. Construction duration estimates are necessary because construction duration is used to approximate the system response time (i.e., transient state) in the controller, described below. We assume that construction duration is proportional to the length of the network corridor. This is obviously a very simplified estimation procedure, but it is consistent with preliminary cost estimation procedures used in projects ranging from damage assessments and capital improvement projects (e.g., [141]) and is considered essential for distinguishing between projects in infrastructure networks. Linear quantity estimates are therefore familiar and readily available. Estimates are typically refined further during detailed site inspections, providing the unique project detail necessary for more accurate quantity-based estimation [142].

4.3.3 Controller Architecture

The proposed approach to recovery modeling also requires a closed-loop controller. The recovery controller is designed to repair the infrastructure system in series by corridor, in an order consistent with the decision makers' articulation of priorities and goals, with input from other stakeholders. After the initial implementation, review and refinement of the controller is then used to identify problems with goal implementation, explore reconstruction where multiple reconstruction teams are available, and explore controller variations that accommodate compromises and tradeoffs (Section 5.4).

The initial controller is therefore modeling the coordinated actions of a site repair team performing reconstruction in a sequence of corridors. As described above, the infrastructure system is represented by a graph network containing the feature attributes of the infrastructure components within each corridor. A desirable controller builds a repair sequence that produces satisfactory system performance compared to other possible repair sequences at each time point, and over the course of the recovery, as illustrated in Figure 12.

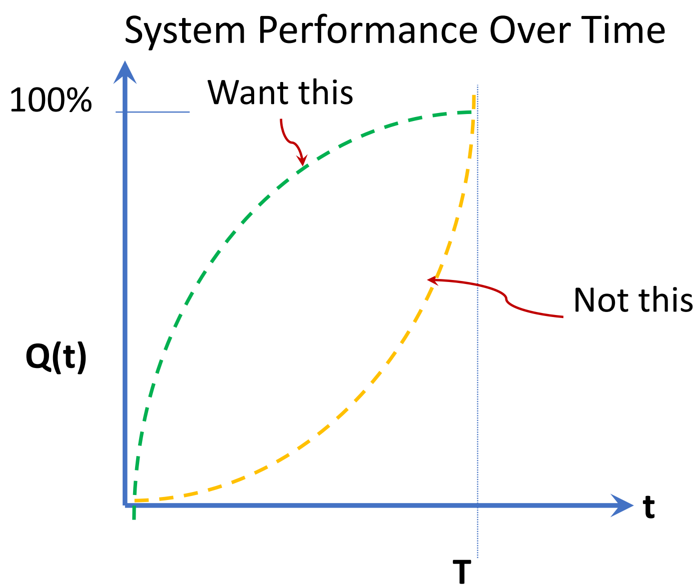


Figure 12. Preferred and unsatisfactory recovery curves produced from the same criticality system states, but with repairs occurring in opposite order.

This is a system where undershooting the set point (the recovery goal) is more of a problem than overshoot. Undershooting is failure to recover fully. In a recovery scenario without sufficient reconstruction activity, some damage will remain or increase due to additional degradation. Overshooting is continuing unnecessary activity after reconstruction is complete, but unlike pneumatic or electrical controllers, reconstruction crews notice when they have finished a corridor and stop. Therefore, the challenge is to build a reconstruction curve that aggressively reduces impediments to returning displaced residents.

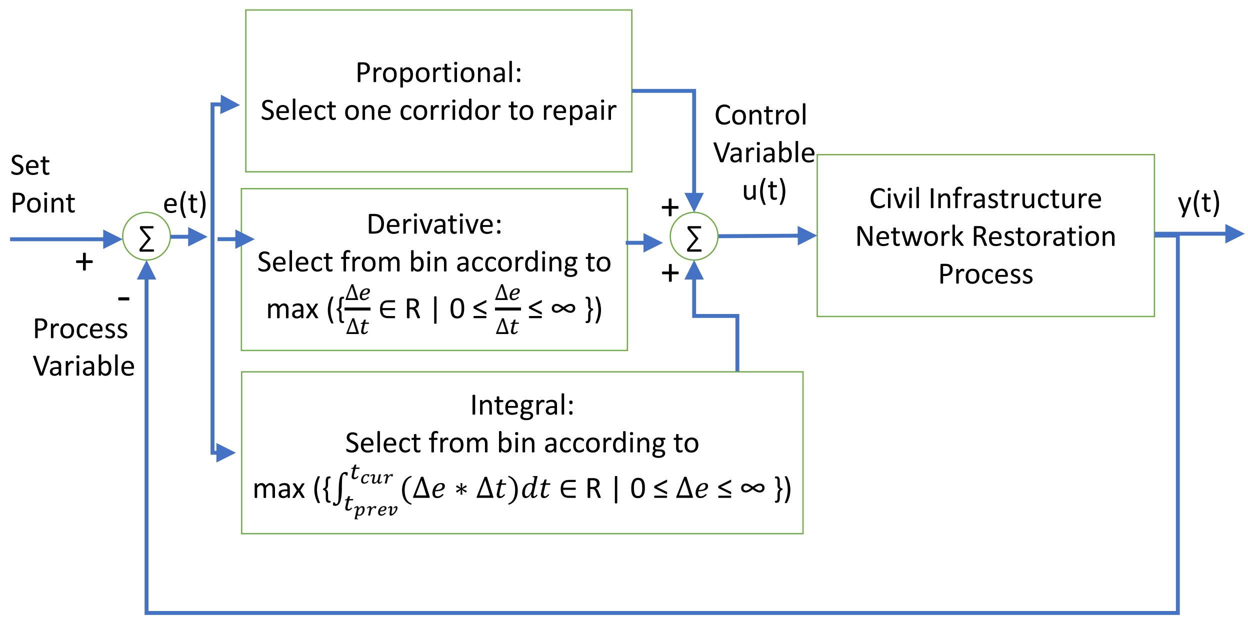


Figure 13. The PID-based controller selects the corridor with the maximum error to repair time ratio, and in the case of ties, chooses the corridor that is the fastest to repair. This controller also moves sequentially through the criticality regimes.

A controller that uses infrastructure damage data and infrastructure system properties to develop a recovery strategy is shown in Figure 13. The proportional element of a PID controller initiates a correction (recovery) when there is a difference between the set point (recovery goal) and the process variable (system performance). The derivative part of a PID controller predicts the error in the future based on the current tangent slope of the error curve. The integral part of a PID controller produces changes to the control output at a rate proportional to accumulated error over time. The objective of the integral action is fast response.

Here, when two or more corridors within the same regime have equal error-to-response time ratios, the PID controller selects the smaller area under the delay-distance curve to produce the preferred recovery curve shown in Figure 12. Therefore, for two corridors with identical error-to-response time ratios, the faster fix according to estimated construction time is given priority. Error detection and selection is therefore quite important to controller performance. Selection of the error, used in the feedback, is discussed below.

4.3.4 Selecting Feedback

Feedback should be selected based on the nature of the problem, which in this case, involves reconstruction and mobility. Feedback must be accessible to the controller designer and meaningful to the system users. Sensitive feedbacks are preferred.

4.3.4.1 The Controller Design Perspective

We have several options for the error signal. One option is to simply use the remaining corridor repairs, $e_{corridor}$, as the error signal. Reducing $e_{corridor}$ produces a stepwise descent of one critical, damaged corridor per repair action. This finding implies that all corridors are equally attractive. Another error signal that is both appropriate for this problem and readily estimated by the data already required for the infrastructure model is the estimated delay, posed to system users attempting to travel within the system, caused by the damaged corridor e_{delay}. In the problem considered here, a corridor's contribution to mobility is measured as the delay that would be caused to an individual at an end of a corridor seeking any other location within the system if that corridor were to be removed. Assuming two-way roads or other modes, this delay is also equivalent to the delay posed by travelers trying to reach that corridor.

The feedback $e_{corridor}$ can range from zero to some finite number, while e_{delay} can range from zero to infinity (due to unreachable points in the damaged network). The potential performance improvement per repair action given by e_{delay} is therefore also much greater than that given by $e_{corridor}$. Therefore, e_{delay} is much more promising for distinguishing between corridors that may be vastly different in terms of their ability to drive large reductions in delay time. This signal is also important because the recovery strategy in the example problem needs to consider mobility, which is a system property rather than a corridor property.

In a larger network, researchers or practitioners may choose to reduce the computational burden of estimating delays by reducing the number of destinations to those actually visited by someone living near that location before the event, if that information is available. Another option is to restrict destinations to those within a limited time or distance radius, but while each of these options can reduce the computational burden, it is not recommended because radius restrictions require additional data and require assumptions about post-disaster adaptive behavior.

Delay is estimated as follows. First, travel time is estimated using Dijkstra's algorithm applied to the undamaged transportation network sub-graph. This travel time is the baseline. Dijkstra's algorithm estimates the shortest path, and where no path exists, produces an infinite travel time. The algorithm is appropriate for this type for infrastructure network model, which is a directed cyclic graph with no negative cycles. There may be more than one shortest path, but since only travel time is captured, differences in path do not a pose a problem for comparison between travel times in the damaged and undamaged network.

In the current formulation, delay is computed by baseline travel time from a corridor in the undamaged system compared to the system with that corridor removed. Although outside the scope of this paper, analysis showed that this approach drove delay to zero more quickly than assessing mobility after each repair. The former also has the advantage of being computable ahead of the damage event. Multiple travel modes can be accommodated in this formulation. Larger delays are considered greater impacts, and infinite delays have the most impact.

4.3.4.2 The User Perspective

Delay is a metric with clear meaning to users, and is a long-standing metric in transportation economics. Delay has also been used as performance indicator in some resilience studies, such as [104]. In a heterogeneous population, it may be justifiable to assign delay of the same duration different economic values depending on socioeconomic characteristics. However, this approach does require additional data beyond what is proposed here. A more straightforward approach to using delay as a feedback is simply to assume that infinite delay is infinitely costly. This assumption implies that infinitely costly trips are impossible for all populations.

Provided all transportation modes are accounted for, this assumption is robust to population heterogeneities. As discussed in more detail elsewhere, impossible travel is also a key indicator for the duration of population displacement [17] in massively damaged civil infrastructure system. Lastly, infinite delays are useful for many other problems where user-facing system metrics are important. Examples pertinent to both public and private systems include infinite time to receive a product and infinite time to access a resource.

4.3.5 Formalizing Goals

System goals must be formalized to be used by the controller. This requires analytical judgement. Goals initially articulated in the language of law and policy are converted by the analyst into descriptions of desirable and undesirable system states. Without a formal description, it is impossible to automate the recovery design.

This conversion will be imperfect, which necessitates the review and iteration described in following the case study. Analysis that incorporates or quantifies natural language variables is an ongoing topic of both decision and design research, starting with work such as [143] and continuing through present with the recognition that interpretation has downstream effects on requirements, architecture, and outputs (e.g., [116], [144], [145]).

4.3.5.1 From Goals to Natural Language Descriptions of System States

The quantitative version of system goals must be highly tailored to the questions of interest. Specifically, system states, with cutoffs that determine whether the system state is acceptable or unacceptable, must be selected to match system goals. System states and cutoffs will potentially change over time for a single complex system, and will certainly vary depending on the problem and type of system. Therefore, system states are not standardized; however, it is possible to take a systematic approach to identifying appropriate system states. For this problem, a set of system states and cutoffs are needed to assess progress toward the goal of displaced, socially vulnerable populations regaining access to pre-event routes, transportation modes, and destinations.

These are resilience goals, and an intermediate step before defining them quantitatively is to define system states corresponding to the system goals using natural language. Referring to the literature, we describe resilience within a community's infrastructure system using dimensions of performance, time, and criticality. Quantitative resilience benchmarks typically involve a dimension of performance and a dimension of time [30], [125]–[129]. Anywhere more than one infrastructure asset is under consideration, such as in system-level assessments of resilience, a third dimension is needed to represent criticality (the importance of components of the system). The concept of criticality is well-known in physical and cyber infrastructure domains such as natural hazard mitigation, climate adaptation, and incident response, where practitioners use this concept to guide resource allocation.

Researchers will find top-down, system theoretic approaches (e.g., Leveson, 2012) are suited to the intermediate step of defining system states that correspond to system goals using natural language. For example, Systems-Theoretic Process Analysis (STPA) uses context tables to define key system states, where context variables are the subset of process variables and values that need to be controlled to achieve system goals [118]. Table 14 shows individual contexts for this problem, which are defined as having hazardous or effective characteristics with respect to achieving the system-level resilience goals in the dimensions of performance, time, and criticality. Criticality is divided into three categories in Table 14: Network importance, and two measures of social vulnerability.

Table 14. Context variables and characteristics with respect to system-level goals. The three criticality-based criteria include a network centrality measure and two social vulnerability metrics.

Category	Context Variables	Hazardous/Effective	Goal
Inclusion Criterion	Performance	Does/Does not	Achieve or exceed baseline
Inclusion Criterion	Time out of service	Does not/Does	Meet or exceed benchmark
Criticality Criterion	Network importance	Does not/Does	Meet or exceed benchmark
Criticality Criterion	Geographically diffuse vulnerable populations	Do not/Do	Have service restored
Criticality Criterion	Vulnerable neighborhoods	Do not/Do	Have service restored

STPA is typically used by system safety engineers, but we assert that it also handles resilience goals in this damaged, dynamic system and recovery process. Given that restoration decisions are made for individual assets within a system, system-level states are defined at the system level, and then downscaled and attributed at the asset level. For more details on STPA, readers are directed to (Leveson, 2012).

4.3.5.2 From Natural Language Descriptions of System States to Formal Descriptions of System States

Formal descriptions of system states are shaped by both the goals and the choice of system representation. In this example, a network representation is selected, since the subject of the inquiry is complex networked systems. More details on the network representation are provided in the next section. In this section, formal descriptions of system states are selected for five resilience dimensions. Each node in the infrastructure network has feature attributes with quantitative scores for all five resilience indices.

The performance state variable is binary and represents damaged or undamaged assets. In a real system, damage severity often coincides with the location of vulnerable populations for many natural hazards [11].

The time out of service state variable is also binary. For convenience, it is assumed to exceed the acceptable time in all cases where the performance state variable is damaged. This assumption differs from a real system, where it is possible that performance is unacceptable while time out of service is still acceptable due to workarounds or stop-gaps.

The geographically diffuse vulnerable populations state variable and the vulnerable neighborhoods state variable can each take values in an interval of the form $[0,1] \in \mathbb{R}$. The vulnerable neighborhoods state variable relates demography to geography through analyses such as that which produces the U.S. Social Vulnerability Index (SoVI) (Cutter et al., 2003). The geographically diffuse vulnerable populations state variable simulates the identification of buildings such as schools, group homes, and elder care facilities that are known to community leaders such as emergency managers.

The network importance state variable can take values in an interval of the form $[0,1] \in \mathbb{R}$. The goals of this state variable are to distinguish between nodes providing more or less service to other nodes within the system. This variable is computed from the structure of the network itself. Centrality scores that account for system-wide rather than solely local features are appropriate for this problem. To demonstrate importance estimates, a measure of transportation node importance was computed structurally using the HITS hub score [146]. The "hub" concept aligns well with the need to depict service provision. The completed controller (introduced in Chapter 3) is described below in Pseudo-Code Snippet 2.

Pseudo-Code Snippet 2. The initial controller design uses feedback to shape the transient state of the recovery curve to minimize accumulated delay to socially vulnerable residents during recovery.

Input: Damaged Graph, G, with n damaged edges, and m priority regimes
Output:

1. Graph with new repair (each action), $\{G_{repair\_action\_1}, G_{repair\_action\_2}, \ldots, G_{repair\_action\_n}\}$
2. Edge order, $\{e_{repair\_action\_1}, e_{repair\_action\_2}, \ldots, e_{repair\_action\_n}\}$
3. Delay reductions due to recovery actions $\{d_{reduction\_1}, d_{reduction\_2} \ldots, d_{reduction\_n}\}$

While any($E(G)_{damaged}$) = TRUE
    Choose $E(G)_{damaged}$ & m_{max} -> $E(G)_{candidate}$
    Choose $E(G)_{candidate}$ & $max\left(\frac{delay\ reducton}{repair\ time}\right)$ -> $E(G)_{fix\_set}$
    Choose $E(G)_{fix\_set}$ & $min\ (delay\ reduction \times repair\ time)$ -> $E(G)_{fix}$
    Repair $E(G)_{fix}$ in G_{repair_action}, and save G_{repair_action} for next step
    Store e_{repair_action}
    Store length of e_{repair_action} (proxy for repair time)
    Store $delay\ reduction \times repair\ time \times population\ affected$
    If some edges are still damaged, next
    else stop
end

4.4 Summary

This chapter introduced a control theoretic approach to producing an infrastructure recovery strategy that is capable of accounting for heterogeneous user needs in a geospatially distributed network. The preliminary transformation of policy requirements into formal control rules is demonstrated. The controller is constructed using PID control principles, adapted to a discrete-time, time-varying system, where performance improvements are represented as non-uniform rectangular steps. A case study using this framework is presented in the next chapter. Validation and limitations are discussed in Chapter 7.

5 Case Study

5.1 Overview

This framework describes the use of a controller that generates recovery strategies for a case study. The architecture, controller, and interdependent infrastructure models described in the previous two chapters are produced and employed in the case study. This recovery framework is applied to an infrastructure recovery simulation of a real system with simulated damage.

5.2 Background

Recovery strategies, like resilience assessment techniques, must be developed in response to particular goals at a particular location. If calibrated across natural hazards, strategies can potentially be multi-hazard, but to begin, consider a particular disaster. Consider the following type of recovery scenario, system, and goals.

Disasters occur periodically that result in massive infrastructure damage and widespread protracted population displacement. Examples include Hurricane Katrina, where damaged infrastructure and floodwaters meant that many Gulf Coast residents, including nearly the whole city of New Orleans, which numbered approximately 400,000, was displaced [147]. More recently, the combined damage from Hurricanes Irma and Maria caused enough infrastructure damage to produce, among other effects, a total blackout and displacement of nearly 500,000 of the over 3 million residents of the island of Puerto Rico [148].

One recovery goal might be to repair conditions sufficiently to allow return, rebuilding, and the resumption of daily activities. Unavailability of necessary infrastructure – particularly transportation networks - is an important practical impediment to return and rebuilding, and the right to return is an internationally recognized right [41]. Typical considerations in such a situation include what to rebuild first given available resources, and how to comply with resilience, inclusive design, and civil rights imperatives [72], [149] for a recovery that avoids disparate impact and prioritizes vulnerable residents.

To build the recovery strategy corresponding with these goals, we must:

- Make high-level decisions about model architecture
- Select available, appropriate feedbacks for the controller

  Formalize the goals so they can be used with the controller and infrastructure system model

This chapter uses the STPA-designed control structure devised in previous chapters and proceeds with implementation, testing, and refinement for a particular interdependent infrastructure system and goals. Once the initial controller is constructed, suboptimal outcomes and potential solutions can be identified. Various stakeholders may be involved in the review of a controller concerned with public sector assets, and as such, a graphical review method is proposed and described.

Since an effective recovery strategy benefits from detailed local knowledge (see Section 5.4), as does the complementary monitoring approach introduced in Chapter 6, the local community was selected for this case study. The City of Charlottesville, VA, contains a state university and the university health system, which are the major employers. It is a demographically diverse community with approximately 47,000 residents and features cultural places of significance including a UNESCO World Heritage Site. According to the most recent Emergency Operations Plan for the community [150], floods pose the highest risk of natural hazards, followed by winter storms. This small city has limited emergency management staff and some digitized infrastructure data. However, this approach is physically scalable to communities or groups of communities with more assets. This approach is also scalable to situations where infrastructure data is not digitized but where human mobility data can be used to estimate infrastructure type and location, as noted briefly above in Section 4.3.2.

Readers will also note that the natural hazard and damage model are simple. The purpose of this chapter is not to illustrate state-of-the-art natural hazard and infrastructure damage models, but to show how the proposed framework works with common data management systems and formats. An important area of future work is to evaluate the framework's usefulness for hazard mitigation and climate adaptation planning, incorporating new natural hazard maps that make use of climate scenarios, including for the riverine-type flooding considered here [151].

5.3 Technical Approach

This section describes the infrastructure recovery simulation applied to a real system with simulated damage. The simulation consists of an infrastructure system model, a hazard model, a damage model, a reconstruction model, and recovery controllers. With respect to controllers, we compare P, PD, and PID. Details for each model follow. Model information uncertainties are also described, and, where possible reduced.

5.3.1 Infrastructure Model

Roads were sourced from the City of Charlottesville GIS website and are also available as TIGER lines files from US Census. Available features needed for this work were side of the street and street name. This particular community did not include speed limit data, and annual daily traffic (ADT) was incomplete, so for the purposes of demonstrating the decision support framework, 35 mph was chosen for all streets and ADT was assumed identical. To demonstrate delay estimates using justifiable variations in the features, road length was computed during the transformation to network graph. ADT for the full set of roads would improve the results of the latter.

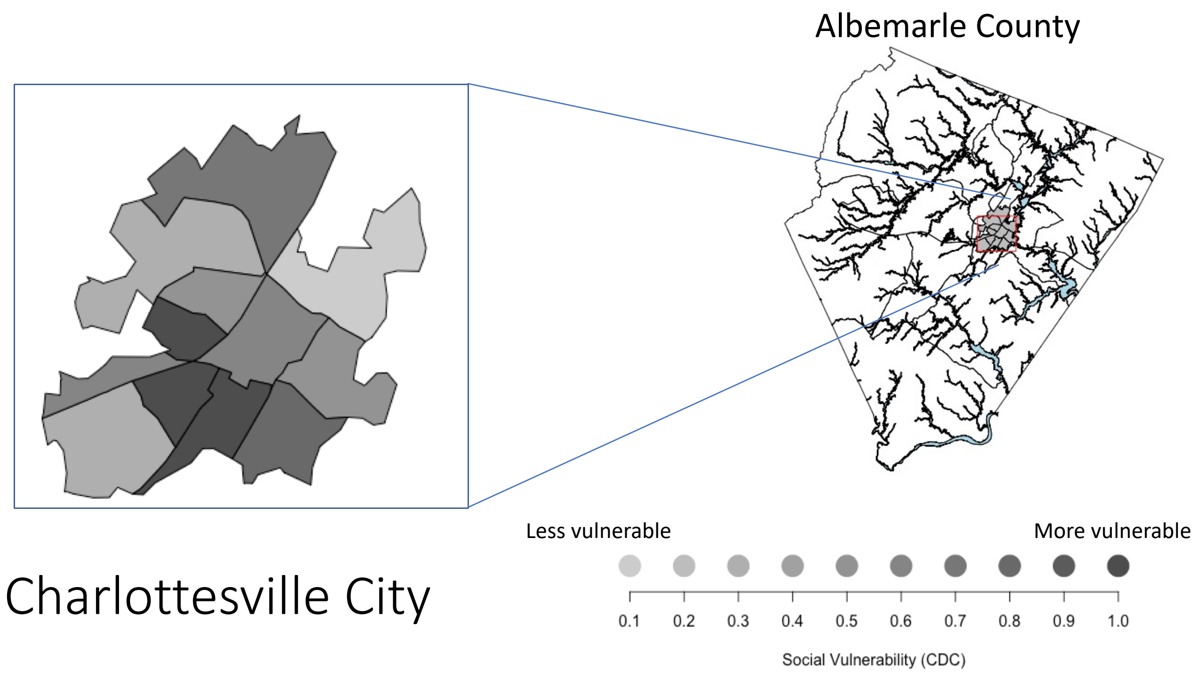


Figure 14. CDC SVI indices at the Census tract level were assigned to infrastructure elements to differentiate user needs in the system following a flood event [152], [153].

Simple topological corrections to the roadway were made programmatically using the GIS tool GRASS. Topological corrections included ensuring nodes at intersections, snapping disconnected roadway lines, and removing duplicates. Peripheral parts of the road network that could not be topologically corrected with these tools or by inspection were discarded for the purposes of this exercise.

Buildings were also from the city GIS website. Each structure becomes a node in the resulting network using the suggested method. Building type was predominantly residential, both owner-occupied and rental. Known utility buildings, such as water and wastewater treatment plant, are outside the spatial area under consideration. Available features needed for this work includes street name and number and affected population. Number of floors and occupancy were not available. Neighborhood population is therefore distributed equally to each structure. If floors and occupancy are available, population estimation approaches such as that outlined in [154] are more accurate.

Since this approach is modeling a simulated disaster that has already occurred, the CDC SVI index, which identifies vulnerabilities during recovery was selected instead of Cutter's SoVI, which identifies overall multihazard vulnerability. Cutter's SoVI, which focuses on vulnerability due to hazard and demographic risk, is a more appropriate choice for modeling mitigation and adaptation prioritization prior to an event or for multihazard planning. Two CDC SVI indices, which are both continuous variables which ranged from 0 to 1, were applied to the structures within each Census tract. The two indices were overall tract summary ranking and housing type and transportation ranking.

Overall Social Vulnerability in the populations affected by simulated flood damage ranged from a high of 0.91 to a low of 0.08. Transportation and Housing Vulnerability ranged from 1.0 (the most vulnerable score) to 0.14. The two types of vulnerability are highly correlated, at 0.86. None of the damaged nodes were highly critical. For the preliminary control rule, edge repair order is determined by: $max(sum(f(u)+f(v))$. In this rule formulation, f is the count of instances meeting any of the three criticality benchmarks (see Table 14) and u and v are adjacent nodes. For instance, a node associated with one structure that meets all three benchmarks receives a score of 3. Delay estimates are used to break ties, as explained previously.

5.3.2 Flood Model

The natural disaster input is a simple approximation of a major flood. Water resources are from the FEMA's National Flood Hazard Layer. Data was obtained for the Rivanna River, which borders the city. A simple buffer extending the 0.02% recurrence interval event was used to create a rough approximation of a major flood event. The buffer is 250 US survey feet. This approximation of a major flood, while not a hydrological flood model, allows the recovery controller to be demonstrated on a significant amount of infrastructure damage in a populated location vulnerable to a natural hazard.

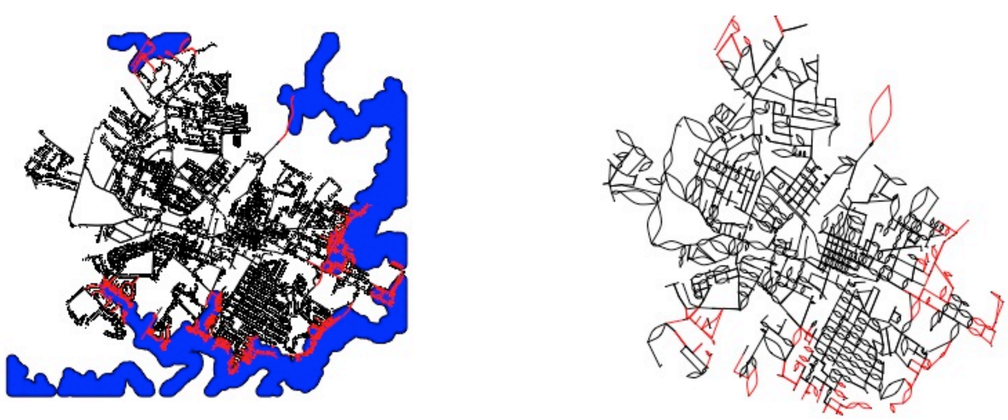


Figure 15. The leftmost image shows the infrastructure system and simulated flood. On the right, the damaged infrastructure system is transformed into a graph for analysis.

5.3.3 Damage Model

Following an event causing massive damage, the state of repair and level of infrastructure functioning may be unclear [65], especially at the beginning of the damage assessment process. (For a conceptually related damage assessment strategy which balances the needs of various community groups, please see Balcik [2017].) Damage assessment can include in-person inspections by trained professionals and through citizen reporting mechanisms [156]–[158], which can be complemented by drone- or satellite-assisted methods [159], [160]. However, assessment can be overly subjective and benefits from standardization [161].

In the case study model, the damage model is simple for the purposes of demonstration. The flooded area was used to assign damage to the infrastructure system. The damage classification variable is binary: damaged or undamaged. Following [125], damaged corridors are treated as completely inoperable until reconstruction occurs. Infrastructure elements within or crossing the boundary of the flood area are counted as damaged. Damage within a corridor remains until it is repaired by the controller. For simplicity, repair duration and cost are both assumed to be proportional to the length of the corridor (see the next section). Depending on the modeler's needs and available data, it is also possible to use HAZUS damage models [162], field damage estimates, and formal construction estimates. While not shown here, new damage can be applied to the system in the case of additional disturbances during recovery.

Table 15. A summary of the damage model, applied to the infrastructure model, is broken down by neighborhood.

Neighborhood	Population	Approx. Population Affected by Damage	Overall Social Vuln.	Transport and Housing Vuln.	No. of Roads Damaged	Distance Damaged (miles)	Pct. of Mileage Damaged	No. Buildings Damaged
Ridge Street	4080	941	0.89	0.98	39	3.5	22.3	187
Belmont	4517	740	0.66	0.89	62	4.6	19.8	251
Martha Jefferson	2565	715	0.43	0.74	63	6.5	36.7	254
Redfields and Sherwood Manor	5614	419	0.21	0.31	14	1.7	37.6	22
Fifeville	4053	261	0.91	0.75	16	1.8	14.8	61
Barracks Rugby and Venable	4567	94	0.23	0.57	17	2.4	9	17
Rose Hill	2867	0	0.45	0.57	0	0	0	0
North Downtown	3210	0	0.50	0.85	0	0	0	0
10th & Page	5481	0	0.83	1.00	0	0	0	0
Jefferson Park Ave.	3656	0	0.55	0.71	0	0	0	0
Greenbrier	4189	0	0.59	0.76	0	0	0	0
Locust Grove	2243	--	0.08	0.14	2	0.9	--	1
City-wide	47042	3170	0.55	0.71	213	21.4	13.8%	793

For the case study, approximately 800 structures and 21 miles of roadway were damaged within the community's neighborhoods (defined by cross-referencing US Census Tracts with neighborhood maps). Table 15 summarizes the damage. This damage results in delays to travelers compared to travel time in the baseline (the undamaged system).

During baseline, the average shortest path from each node that will be damaged by the flood event to the other nodes in the network requires a travel time of approximately 87 hours. All

1170 nodes are reachable by all other nodes during baseline. After damage occurs, shortest path analysis reveals that 52% of trips become longer than at baseline for the damaged nodes. 29.7% of trips that were possible at baseline become impossible altogether. An average of 349 trips become impossible for each damaged node. None of the damaged nodes have fewer than 237 impossible trips, and 6 nodes are cut off entirely from the network.

5.4 Controller Review and Iteration

Once the initial controller is developed, controller results are produced and examined. The purpose of inspection is to reveal issues that are inconsistent with system goals. For simplicity, during controller review and iteration, no resource constraints or additional disruptions are modeled. After finalization, the same controller can quickly update the strategy when the system faces changes in resource availability or additional disturbances from the same type of natural hazard. If the recovery goals are the same, the controller can also be reviewed and calibrated to handle additional hazard types.

A graphical method for inspection is used for the review process. Reviewers are needed to identify adjustments explored in this section:

- Controller rules may need to be reframed if the controller does not adequately meet decision maker goals (analyst and decision maker)
- Model parameters and inputs may require common-sense adjustments (analyst)
- Stakeholders may provide new information about ground truth or user needs

- Stakeholder requirements and resource availability may necessitate compromises in the controller design.

5.4.1 Initial PID Formulation

The controller repairs the damage in the infrastructure system, moving from high-criticality corridors to lower criticality corridors (Table 8, page 45). As expected, the PID controller results in fewer impacts to residents than the P controller, that is, as the area under the curve for impossible trips over the recovery period (impact area). This area is approximated by finite sum in discrete time.

$$A_{Impact} = population\ at\ damaged\ origin\ nodes\ \times\ \#\ of\ impossible\ trips \times\ reconstruction\ duration$$

The PID controller performs similarly to the PD controller for this particular problem and set of damages. The improvement between the best-performing PID and next-best PI may appear minor (0.1% change in impact area), but if infinite delays are infinitely costly and the ability for system users to adapt is considered crucial in a system that is under repair, these small improvements become important.

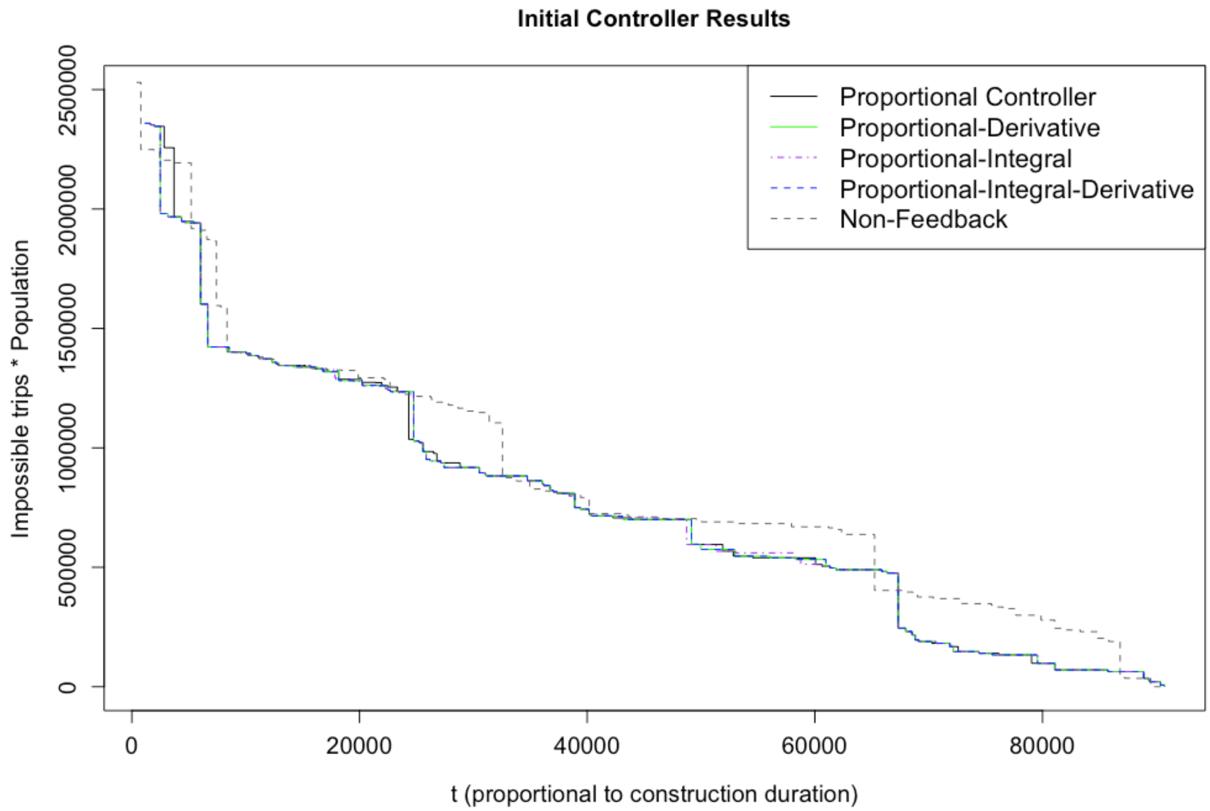


Figure 16. The three controllers (P, PD, and PID) produce a repaired system in the same time, but PID results in the fewest impossible trips over the recovery period. A non-feedback approach performs poorly compared to all feedback approaches.

Any of the feedback approaches (P, PD, PID) perform better than a controller without feedback, with an improvement of greater than 12% (Table 16). The non-feedback controller shown here uses the same location-based social vulnerability data and network importance measures, but without the delay estimates. This represents an intermediate point of performance between the PID controller and a purely GIS-based approach that does not consider network connectivity at all, nor feedback. Non-feedback approaches to recovery strategy design are inferior.

Table 16. Feedback-based recovery strategies perform better than non-feedback strategies based on the impact of impossible trips.

Controller	Impact Area	Improvement over non-feedback
Non-feedback	7.70E+10	--
P	6.71E+10	12.9%
PI	6.67E+10	13.4%
PD	6.72E+10	12.7%
PID	6.67E+10	13.5%

5.4.2 Graphical Method for Geospatial Control Rule Refinement

The initial results must be further reviewed to ensure that recovery rules are producing the expected and desired results. To facilitate review, we recommend outputs be depicted in time-lapsed recovery animations in a map format with accompanying descriptions. Freeze frames from the animation are shown in Figure 17. This approach to reviewing the controller is recommended because map-based review is consistent with public engagement in the natural hazard mitigation and environmental planning domains: selecting wind farm sites using Multicriteria Decision Science [98], identifying assets vulnerable to sea level rise [99], understanding public use of forest road networks on public lands [100], and citizen science applications [101], among others.

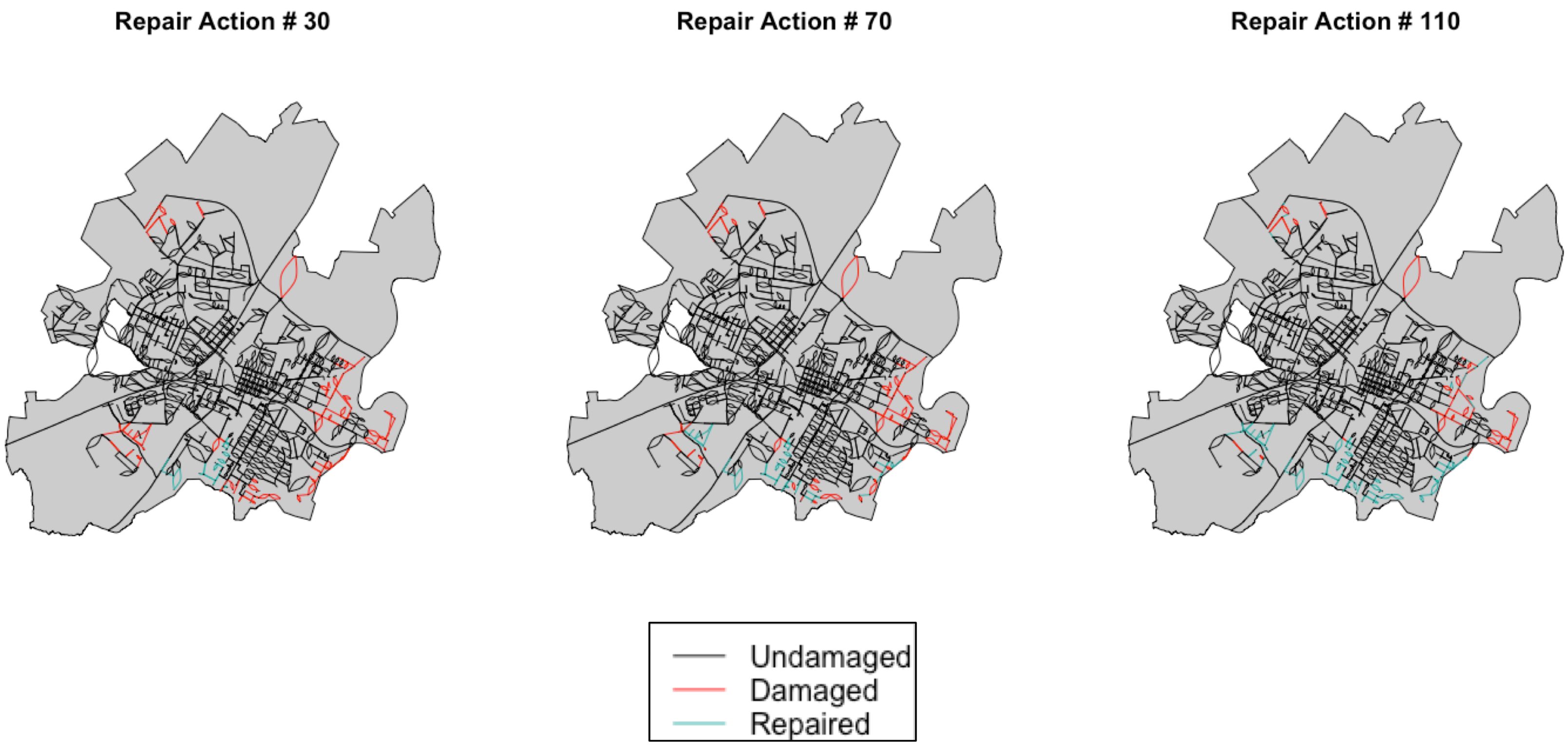


Figure 17. The controller can be induced to produce a graphical output of its progress in a familiar map format. The output can then be inspected for consistency with desired results. Controller outputs at three points in the recovery process (early, middle, and late) are shown here. Undamaged, damaged, and repaired edges are depicted.

The format is designed to be familiar based on its similarity to mapping apps accessible to mobile device users. Without using familiar formats, outputs from complex systems models are not always legible to stakeholders who may hold critical domain expertise but are unfamiliar with the modeling approach. The graphical output is a review tool for rapid prototyping and revision of control rules that respond to disturbances and operate at the system level.

5.4.3 Domain Review

Once the initial control rules have been established, missing or conflicting rules must be identified. Domain experts should be consulted at this step. In this example, one appropriate domain expert is a local emergency management professional. The domain expert should be familiar with both the system and with past recovery problems relevant to the system recovery goals. In this case, recovery problems are those that impede mobility and access within the system. Academic case studies, periodicals, and law suits are possible sources of historical recovery problems in community infrastructure systems. The domain expert examines the controller output to determine whether any of these historical recovery problems are present. The presence of recovery problems indicate that missing or conflicting controller rules are present

By reviewing historical recovery problems, two new recovery problems unaddressed by the controller are identified. The first is isolation of socially vulnerable populations because of access limitations to neighborhoods that are less vulnerable, illustrated in Figure 18. At three points in the recovery process (early, middle, and late) residents in a more vulnerable neighborhood are cut off from a common route to a major employer, which is located in a less vulnerable neighborhod. This mobility impediment could impair the economic recovery of the community.

A similar historical example is the shutdown of subway service after Superstorm Sandy resulting in school dropouts [63], and, likely, other challenges with respect to livelihood. This problem can be addressed by adjusting the controller to allow repair of corridors where only one node of the corridor segment, rather than both, qualifies for membership in the current priority regime. It could also potentially be addressed through an interleaving strategy, described in Section 5.5.

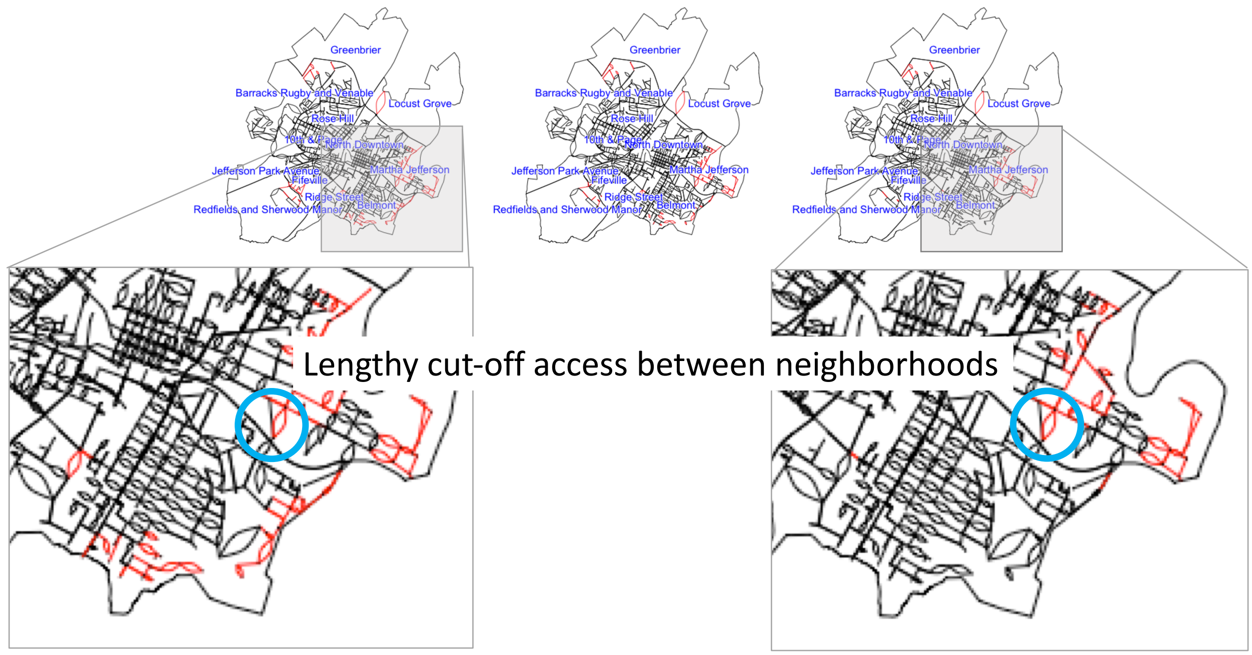


Figure 18. Domain expert review of the controller output can check for known historical recovery problems like long-term access problems between neighborhoods. In this case, residents are cut off from a major employer. Controller rules are then reframed to avoid these problems.

A second potential problem regards reconstruction efficiency and the availability of staging locations. If damage greatly impedes movement through much of the network by repair crews, it may be important to address corridors by neighborhood in the network science sense of the term, that is, corridors with adjacent nodes. The alternative is wasted time where lengthy detours, debris clearing or other activities must precede reconstruction. While significant access problems to the damaged sites do not appear to be a major problem for this particular disaster simulation, where damage is concentrated around part of the periphery of the community, the control rule can be developed and left in reserve for a disaster with different damage patterns.

5.4.4 Analyst Review

Both in initial model development and periodically thereafter, domain experts should work with network analysts and user groups at this point to refine inputs and cutoffs. With regards to inputs, new data may become available or emergent justifications for using different currently available data may arise. Additionally, inspection of model outputs by domain experts and user groups (in this case, community advocates) can reveal problematic outputs.

The following descriptive hypothetical illustrates how adjustments could occur. Statistics are based on the current model construction: The initial cutoff parameters were 0.8, 0.8 and 0.7 for the two social vulnerability metrics and the network criticality metric, respectively. The analyst notes the two social vulnerability metrics are highly correlated at 0.89, and considers replacing one or both to be more assured of capturing different dimensions of vulnerability. The domain expert agrees to keep the existing metrics that pertains to housing type and transportation. The domain expert replaces the second metric with another available metric that concerns household composition and disability, is much less correlated with the first metric, and is a better match for the social science on mobility (summarized in [17]. Parameter cutoffs can be adjusted as well.

5.4.5 Stakeholder Review

User input must also be solicited. Effective practice is briefly summarized here. Participation should be solicited early in the recovery planning process, and web-based options are more likely to reach children and young adults than traditional in-person engagement. Empirical studies suggest participatory GIS with a professional co-located to support stakeholders results in more and higher quality data collection than without a facilitator. The viability of participatory GIS is not limited to developed countries [163]. A specific use of participatory GIS relevant to this research is collecting stakeholder input about important indices of performance and weights to develop a geospatial multi-criteria decision model [164].

It is of particular importance to gather stakeholder input when the analysis and decision making team are serving heterogeneous system user populations. Stakeholder input can be used to close gaps in data and ground truth that existing data streams may miss [165]. Stakeholders that are active contributors tend to make the most contributions and theirs are high-quality contributions, so these stakeholders are worth recruiting and retaining [166].

Regarding the social vulnerability data, community representatives might note that the cutoff for the new household composition variable neglects several group homes that are housing vulnerable population in otherwise well-resourced neighborhoods, or that an important transportation route or mode has been omitted. The analysis team can then agree to appropriate adjustments in a documented and standardized fashion. [165] reports that local governments are more comfortable using stakeholder contributions that have been reported following standards and conventions.

5.5 Discussion

This section discusses the use of the controller after the review and refinement process. First, the impact of interactions between goals and changing resources is described using an example. Finalization of the controller following stakeholder input is also described. Lastly, integration and operation of the controller within a decision support tool like that depicted earlier in Figure 11 is discussed.

5.5.1 Exploring Varied Goals and Resource Changes

The initial controller repairs damaged corridors in series and according to priority constraints. The decision-maker may be interested in exploring additional objectives within these constraints, or may be interested in loosening the constraints somewhat to accommodate other objectives. Compromises and tradeoffs abound in public-facing and public-owned infrastructure. Topics for exploration include:

- Management of resource fluctuations that sometimes allow additional teams to work in parallel
- How to schedule parallel teams so they are fully occupied and finish at approximately the same time
- Interleaving strategies, in cases of abundant resources, so that all or several priority regimes are finished at the same time without violating the disparate impact constraints

Now that a controller has been built empirically, it can be approximated and adjusted analytically to explore these additional objectives. The controller is built to produce a high initial slope for each criticality regime, front-loading major improvements that are quick, and leveling off with smaller improvements that take longer to achieve. This high initial response and near-asymptotic approach to full function can be described using an exponential response curve, as shown in Figure 19. In this figure, the reader will note that the two regimes are approximated by identical output curves.

The geometric aspect of this finite approximation of PID control is not novel. The novelty lies in the framing of interdependent infrastructure recovery as the transient state of a controlled process, which offers 1) the opportunity to shape transient state characteristics to limit impacts to residents and 2) the ability to respond to new information, constraints, and disturbances. This approach produces meaningful improvements for returning and in-place residents who are conducting their own recovery activities at the household level. Ad hoc approaches, and even geospatial overlays that do not incorporate feedback, cannot yield better results, lack transparency, and do not provide the same flexibility to handle changing circumstances.

This estimate addresses the decision-maker questions introduced in this section in the following ways. First, should a decision-maker have enough funding to address both regimes, this can be done in series (with the first regime prioritized) or in parallel. If done in parallel, the two teams will be able to finish at roughly the same time. This information can be used for work planning.

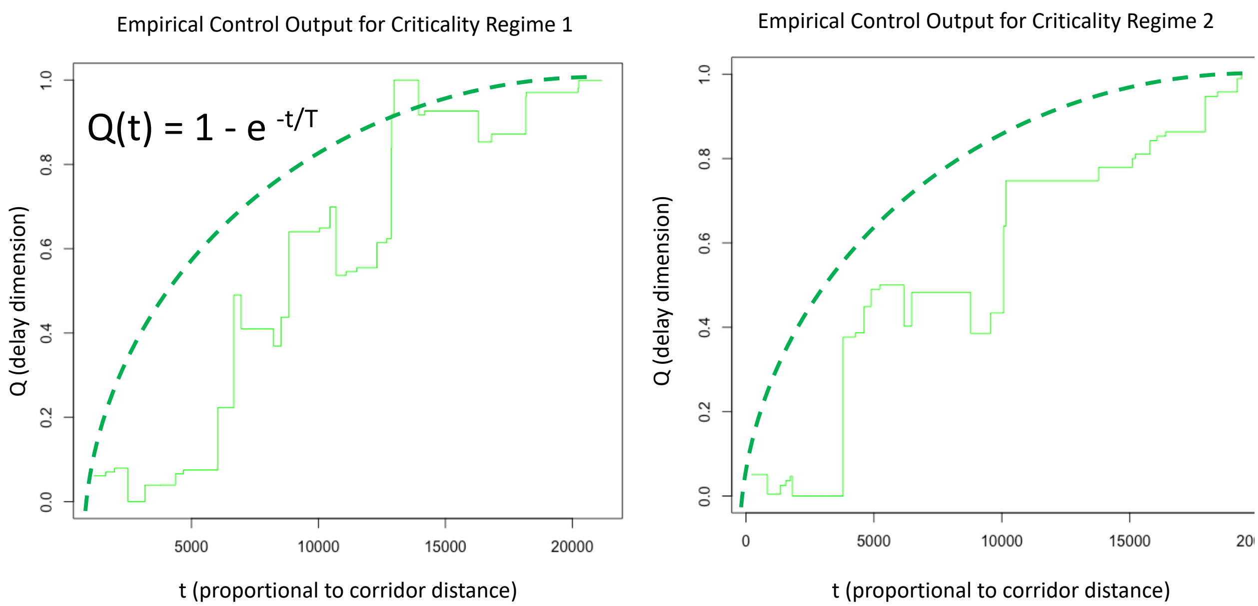


Figure 19. The analytical approximation of the empirical controller's output for two of the criticality regimes is the same exponential response curve.

Another option a decision-maker may wish to explore is interleaving the two regimes. For the example above, this will result in (approximately) alternating corridors in the first and second regime. The total repair time will then become the sum of the two individual repair times. Therefore, the duration to completion for the first regime and second regime will be twice as long.

However, the decision-maker is still able to make the argument that socially vulnerable populations were given a high priority, while also addressing the needs of the populations in the next-most critical regime. In this public sector example, this can be interpreted as balancing equity and equality between residents in the two criticality regimes. When completed in series, though the *duration of completion* for the second regime is longer, the *ending time* for the second regime will stay the same. Consider an example with two adjacent priority regimes, each of arbitrary reconstruction time to verify this point. The two interleaved regimes, with the durations $duration_1$ and $duration_2$ respectively, still require the same total work hours ($duration_{total} = duration_1 + duration_2$). Therefore, the end time for the interleaved regimes is the same as the end time of lowest priority regime in the set of regimes being interleaved.

5.5.2 Finalizing the Controller

These and other approaches involving two or more regimes may be explored until effective and politically feasible options are identified. The analyst's responsibility is to support the decision-maker in exploring modifications to the initial controller. For regimes without identical response curves due to longer reconstruction times, scaling factors are needed to explore parallelization and interleaving. Ultimately, the final controller will reflect decision-maker and user values. User input and formal approval processes, including voting, are desirable and may sometimes be required.

5.5.3 Proposed Use of the Controller Within A Decision Support Tool

Although disruptions, interruptions, and new constraints are not considered during controller design, the finalized controller is capable of handling these when integrated into the proposed decision support system first introduced in Figure 11. This new information must be ingested by the system. In the case of extended reconstruction timelines, field crews or the decision maker can make updates, which may change reconstruction priorities. Edges that do not have the appropriate staff, materials or other resources available can be screened out by the decision-maker. New damage can also be ingested: With the advent of a new disaster before reconstruction is complete, damage assessment must again take place, which will produce a new recovery strategy. In the case of construction interruptions due to resource constraints or weather, reconstruction can simply resume once the interruption is finished with no change in priorities. The appropriate locations for this new information to be ingested by the controller are identified in Pseudo-Code Snippet 3.

Pseudo-Code Snippet 3. Locations in the designed controller where disturbances and resource constraints that affect the recovery sequence can be ingested.

Input: Damaged Graph, *G*, with *n* damaged edges, and *m* priority regimes
Output:

1. Graph with new repair (each action), $\{G_{repair\_action\_1}, G_{repair\_action\_2}, \ldots, G_{repair\_action\_n}\}$
2. Edge order, $\{e_{repair\_action\_1}, e_{repair\_action\_2}, \ldots, e_{repair\_action\_n}\}$
3. Delay reductions due to recovery actions $\{d_{reduction\_1}, d_{reduction\_2} \ldots, d_{reduction\_n}\}$

While any($E(G)_{damaged}$) = TRUE ← Screen out features that do not yet have resources available
    Choose $E(G)_{damaged}$ & m_{max} -> $E(G)_{candidate}$
    Choose $E(G)_{candidate}$ & $max\left(\frac{delay\ reducton}{repair\ time}\right)$ -> $E(G)_{fix\_set}$
    Choose $E(G)_{fix\_set}$ & $min\ (delay\ reduction \times repair\ time)$ -> $E(G)_{fix}$
    Repair $E(G)_{fix}$ in G_{repair_action}, and save G_{repair_action} for next step ← Ingest new disturbances
    Store e_{repair_action}
    Store length of e_{repair_action} (proxy for repair time)
    Store $delay\ reduction \times repair\ time \times population\ affected$
    If some edges are still damaged, next
    else stop
end

5.6 Summary

This chapter has introduced a control theoretic approach to producing an infrastructure recovery strategy that is capable of accounting for heterogeneous user needs in a geospatially distributed network. The preliminary transformation of policy requirements into formal control rules is demonstrated. The controller is constructed using PID control principles. The PID controller shows significant performance improvements over a controller implementation that does not use feedback. Feedback works best when it reflects key system-level properties rather than component-level properties. The controller and accompanying infrastructure model can be produced using open-source software and low cost hardware. A graphical method to review the output of preliminary control rules is also presented.

The controller is intended to be calibrated by domain experts and adjusted iteratively with input from decision makers and users. Stakeholder input and approval is particularly important where decision makers differ from users, where users are heterogeneous, and where buy-in and legitimacy are important, such as with public sector assets. We also provide high-level details for integrating the finalized controller with daily work planning. To the author's knowledge, this is the first time PID control concepts have been applied to recovery in geographically large complex systems. This work contributes to efforts to support human population resilience by treating peoples' resilience as a function of infrastructure system resilience.

6 Monitoring the Recovery Strategy with Multi-Criteria Assessment

This chapter describes the resilience matrix (RM) approach as adapted to the problem of recovery. The RM complements the STPA-based recovery framework by providing rich information about several management domains that affect the course of recovery. This additional information is intended to mitigate some of the difficulty involved in monitoring interventions in complex systems.

The RM assessment can be used directly by the decision-maker, or to identify emergent problems with the control rules. With respect to the former, the RM is able to include information about economic and policy factors that are outside the controller's ability to change, but on which the decision-maker may be able to take direct action. Direct actions include requests for additional funding or technical support from another level of government. The RM can also be used to identify supporting or contradictory evidence that the controller rules are resulting in the desired outcomes. Examples of supporting and contradictory evidence, and their implications for the controller rules, are considered in Section 6.2.7.

The RM approach can also be as a recovery assessment tool independently of the STPA-based recovery model. This decoupling of the RM from the recovery model is useful in cases where 6.data limitations or other resource constraints do not allow production of the recovery model proposed in previous chapters. To show how the RM can work with the recovery model, the following RM example considers the same issue as the case study introduced earlier.

6.1 Background

The Population Resilience Matrix is resilience decision-support tool that jointly considers infrastructure reconstruction and the return of displaced populations. The method for assessing infrastructure-dependent population resilience is an adaptation of the Resilience Matrix (RM), an existing assessment framework developed by Linkov et al. (2013) and expanded in research such as Fox-Lent, Bates, & Linkov (2015) and Fox-Lent & Linkov (2018). The goal of the resulting Population Resilience Matrix (PRM) is two-fold: to explicitly account for human reliance on the infrastructure system during recovery and reconstruction; and to structure that knowledge in a way that it can be used to reduce the duration of displacement across affected geographies and demographic groups within the community. To the author's knowledge, this is the first resilience decision-support matrix that takes a systems approach to population displacement in the context of infrastructure recovery.

6.2 Technical Approach

As originally conceived by Linkov et al. (2013), the RM (Figure 20) organizes system capabilities in the physical, information, cognitive and social domains (based on Alberts, Hayes, & Stenbit, 2003) over the temporal phases of a disaster (prepare, absorb, recover and adapt), as defined by the National Academy of Science (2012). Users assess a community and its critical functions by scoring different capabilities of the system that are relevant to maintaining those functions during a disaster, resulting in an overview of anticipated or actual strengths and weaknesses.

The RM is versatile in that the scale at which it is applied and metrics that are used to populate it are not fixed, but rather, can be tailored to specific contexts.

The RM approach is an attractive method for organizing community goals and metrics related to long-term recovery in part because it is feasible to concisely summarize varied information associated with the recovery process. Complexities associated with recovery stem from such issues as:

- The spatial scale and number of components (i.e., infrastructure assets and owners) in a community infrastructure system;
- The challenges in identifying and quantifying interdependencies between system components [80], [167]–[169]; and
- The logistics and communication complexities arising over time during the recovery process [77], [89].

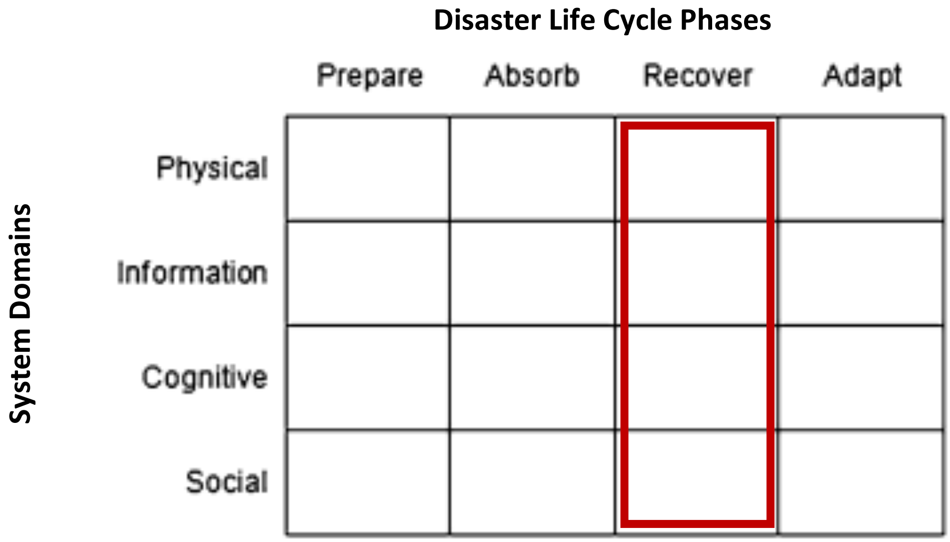


Figure 20. Resilience matrix (RM) concept, excerpted from Fox-Lent et al. (2015). Red indicates the area of focus for this study.

6.2.1 Resilience Matrix Framework for Population Resilience Assessment

Here, we present an adapted RM framework, hereafter Population Resilience Matrix (PRM), that is tailored to the nexus of infrastructure systems and displacement and serves as a method for organizing community goals and evaluating progress toward those goals. The PRM framework is a 4 x N matrix (

Table 17): the infrastructure subsystems that are relevant to population recovery (columns) and major decision and management domains (rows, identical to Figure 20 except “cognitive” is reframed as “project management”). Local community leadership select the infrastructure subsystems to evaluate. One or more performance metrics need to be assigned to each cell of the PRM as a basis for evaluation, a process we explore in Section 6.2.5. We also propose the use of weights to indicate, for example, where funding has been secured and how important the infrastructure subsystem is at a given point in the recovery process in order to prioritize action. Weighting is described in Section 6.2.4. Finally, the use of the PRM at a check point during the recovery process is demonstrated in Section 6.2.6. 6.2.6

The PRM should be employed in either or both pre-disaster recovery planning and during the actual post-disaster recovery process to assess the state of each infrastructure-domain component of the community using selected performance measures. The intention is to generate a sketch-level summary of current conditions and priorities and bring clarity to a complex infrastructure system with multiple asset owners taking multiple coordinated recovery roles. Comparing assessments for different subsets of a community or different points in time during recovery can provide additional insight into how recovery is progressing and about remaining needs and priorities.

Table 17. PRM framework intended to support population resilience (specifically, the return of displaced populations and resumption of daily activities) during recovery. Headings indicate (from left to right), multi-modal transportation infrastructure; commercial, residential and municipal buildings; water and wastewater pipes, mains and treatment facilities; electrical utilities, telecommunications (telephone, internet, cell towers, etc.); and oil and gas infrastructure.

Recovery Progress - Neighborhood or Community							
	Weights						
Weights		**Transport**	**Building**	**W/WW**	**Electric**	**Telecom**	**Oil/Gas**
	Physical						
	Social						
	Information						
	Project Mgmt.						

6.2.2 Define System Boundaries and Threats

The PRM approach is primarily intended for use at the local level, with the two proposed levels of aggregation: the community scale and smaller local political or jurisdictional boundaries such as neighborhoods or public works maintenance regions, although it is potentially scalable. The community- and neighborhood-scale PRM is well-suited to supporting recovery efforts because post-disaster leadership resides with local government and is administered through positions such as the local disaster recovery manager (US). Metrics should be selected to match the jurisdiction or other boundary at which the assessment is conducted. In terms of the source of displacement, we envision natural disasters that damage infrastructure however, with some modification, the approach could also be used to consider other types of displacement, such as displacement due to conflict.

6.2.3 Identify Critical Infrastructure Functions

Identifying which infrastructures are most critical for population recovery is crucial for meaningful assessment and will vary for locales and segments of the population. The PRM approach is flexible to different contexts; the critical infrastructures under assessment and metrics for assessing their quality are chosen by the assessor. Work in the safety and security domain in the last several decades along with much of the work in hazard mitigation and vulnerability assessment provide useful foundations for resilience and recovery analysis. Resources such as Emergency Operations Plans and Threat and Hazard Identification and Risk Assessment documents can help guide assessors in selecting critical infrastructure functions for the long-term recovery process.

With respect to metrics for the infrastructure systems selected, it is important to carefully consider how they relate to the function the systems provide for the community so that the assessment can truly capture progress toward desired outcomes. For example, if a community sets the goal of equitable recovery, which they define, in part, as avoiding disparate impacts to transit users and automobile drivers, they will develop recovery-oriented resilience metrics for both subsystems. Further discussion of metric development can be found in Section 6.2.5.

6.2.4 Elicit Weights (optional)

We envision different types of weighting schemes that could benefit decision makers in planning or conducting local disaster recovery. A weighting scheme on the critical infrastructure function axis can differentiate resource availability for infrastructure categories, e.g., by estimating unmet funding as a proportion of total funding needs for the current set of recovery tasks related to each critical infrastructure function. A weighting scheme on the decision and management domain axis can distinguish importance in terms of sequencing during the recovery process. For example, early in recovery, information-gathering and physical infrastructure reconstruction may dominate, whereas later in recovery, communication may take an increasingly important role.

The weight selection process must be transparent, defensible, and where appropriate, inclusive of experts and members of the public. Along the decision and management axis, expert elicitation in combination with structured civic engagement is a sensible approach to developing a weighting scheme. Incorporating information from community members that rely on various infrastructures is critical to understanding how infrastructure function supports the resumption of daily activities following a disaster. Along the critical infrastructure function axis, a weighting scheme based on funding availability will generally rely on standard engineering cost estimates produced during damage assessment and the bid process. For further reading, resilience planning initiatives such as those discussed in Miles (2018) are valuable references for goal-setting with respect to restoration of function and acceptable timelines.

6.2.5 Select Metrics and Generate Scores

Users of the PRM select metrics that reflect community priorities and can effectively signal where action is needed. Fox-Lent, Bates, & Linkov (2015) remarks that a number of options are suitable for developing metrics:

- A single quantifiable measure
- Aggregation of multiple quantifiable measures (combined through weighted or unweighted average, maximum, minimum, etc.)
- Qualitative checklist
- In lieu of a natural metric, an expert-generated rating to indicate low or high quality/performance

In the Physical decision and management domain, standard engineering metrics such as level of service will often be suitable for use in this linear scale approach (See several transportation resilience-focused examples in Croope (2010), especially Chapter 5, and Croope & McNeil (2011)). For instance, metrics generated for roads could include level of service metrics where upper and lower bounds are determined using levels of service A and F, respectively. Unknowns should automatically be assigned 0. A major exception to the linear scaling approach is when better information, such as nonlinear depth-damage curves, is readily available. As with other RM applications, the final computation is relayed as a heat map rather than in numerical form to focus attention without pretending at precision.

Standard metrics for the non-physical decision and management domains are less mature. For the purpose of retaining our focus on applying the PRM approach, we limit the discussion of metrics development by noting that non-physical metrics may be developed through a combination of strategies such as referring to effective practice, expert consultation, and community goal-setting. With respect to the latter, community engagement is critical for establishing legitimacy around acceptable bounds of performance. An example is provided in Table 18, below.

Table 18. Selected indicators and scores for migration and displacement resilience during short- and long-term recovery. Evaluated for the study scenario's Martha Jefferson Neighborhood in Charlottesville.

Matrix Position	*Metric Selected*	*Value*	*Source*	*Upper Bound (Acceptable Performance)*	*Lower Bound (Poor Performance)*	*Score (Unweighted)*
Transport-Physical	Neighborhoods or developments isolated by shutdowns and washouts (each mode)	10%	Damage assessment, traffic plans	0% (Possible to travel in/out of any neighborhood)	20%	0.5
Transport-Social	Percent changes in student, disabled, and senior transit use	13%	Transit pass records, passenger count records	5% decrease in population ridership	15%	0.2
Transport-Information	Shutdown, alternatives and restoration information available in community members' languages	Media in 4 out of 5 languages. On time.	Press releases; City website; Tweets; 511	All appropriate media used and languages accommodated within 24 hours of new information	Media release missing in one or more languages; media release later than 48 hours	0.8
Transport-Project Mgmt.	Time to design and implement alternate routes and modes to accommodate service disruption	5.5 days	Public works and public safety	2 days	1 week	0.3
Building-Physical	Percent change in capacity of schools	0% pre-storm capacity (closed)	Damage assessment, occupancy restrictions	90% pre-storm capacity	70% pre-storm capacity	0.0
Building-Social	Percent change in number of dropouts	9.5% increase	School records	5% increase	10% increase	0.1
Building-Information	Percent of homeowners and renters (*compute separately*) aware of residence status and housing alternatives	75% up to date	Maps and clearinghouses for owners, renters and landlords	90% of records up to date	60% of records up to date	0.5
Building-Project Mgmt.	Money disbursed compared to damage sustained	78%	FEMA, SBA, est. private insurance	90%	50%	0.7

W/WW-Physical	Percentage of buildings without working water utilities	8%	Water treatment facility	0%	20%	0.6
W/WW-Social	Rates of waterborne illness and dehydration in non-displaced population	1%		0%	10%	0.9
W/WW-Information	Service status and alternatives availability communicated in community members' languages	Media in all languages and on time	Press releases; tweets	All appropriate media used and languages accommodated within 24 hours of new information	Media release missing in one or more languages; media release later than 48 hours	1.0
W/WW-Project Mgmt.	Percent of residents that can be served by current and alternative supplies	88%		90%	70%	0.9
Electric-Physical	Percent of buildings without power. Compute residential (rental, owner) and commercial separately.	32.5%	Satellite or aerial photos, power utility	5%	60%	0.5
Electric-Social	Level of usage compared to pre-storm baseline	50% decrease	Metered usage	10% decrease	40% decrease	0.0
Electric-Information	Public availability of outage and blackout information	Information missing or outdated for 10% structures	Public-WIFI hotspot map; NASA and other satellite photos	All information current	Information missing or outdated for 20% or more structures	0.5
Electric-Project Mgmt.	Percent of residences and commercial buildings with attached or re-attached meters (compute separately) served by utility and alternative supplies	86% of residences served by utility	Power outage maps, electric utility reports and requests	90% of residences served by utility or city-provided alternative	80% of residences served by utility or city-provided alternative	0.6
Telecom-Physical	Percent of phone landlines, fiber optic, etc. down	11%	Telecom utility	5%	20%	0.4
Telecom-Social	Change in spatial density of phone activity	14% decrease in cell tower activity	Telecom utility	10% decrease in cell tower activity	30% decrease in cell tower activity	0.8

Telecom-Information	Public availability of service outage information	Information missing or outdated for 10% structures	Telecom utility	All information current	Information missing or outdated for 20% or more structures	0.5
Telecom-Project Mgmt.	Completed repairs compared to remaining damage	42.5%	Telecom utility	95% completed	20% completed	0.3
Oil/Gas-Physical	Percent of buildings without service	11%	Heating utility	5%	20%	0.6
Oil/Gas-Social	Gas station waiting time for non-displaced residents	12.5 minutes	City records; social media	10 minutes	35 minutes	0.9
Oil/Gas-Information	Open gas stations with available fuel	All stations in service	Social media, navigation apps	All stations in service	70% reduction in capacity	1.0
Oil/Gas-Project Mgmt.	Percent of residences served by existing and alternative supplies	88% of residences served	O&G utility	90% of residences served by utility or city-provided alternative	80% of residences served by utility or city-provided alternative	0.8

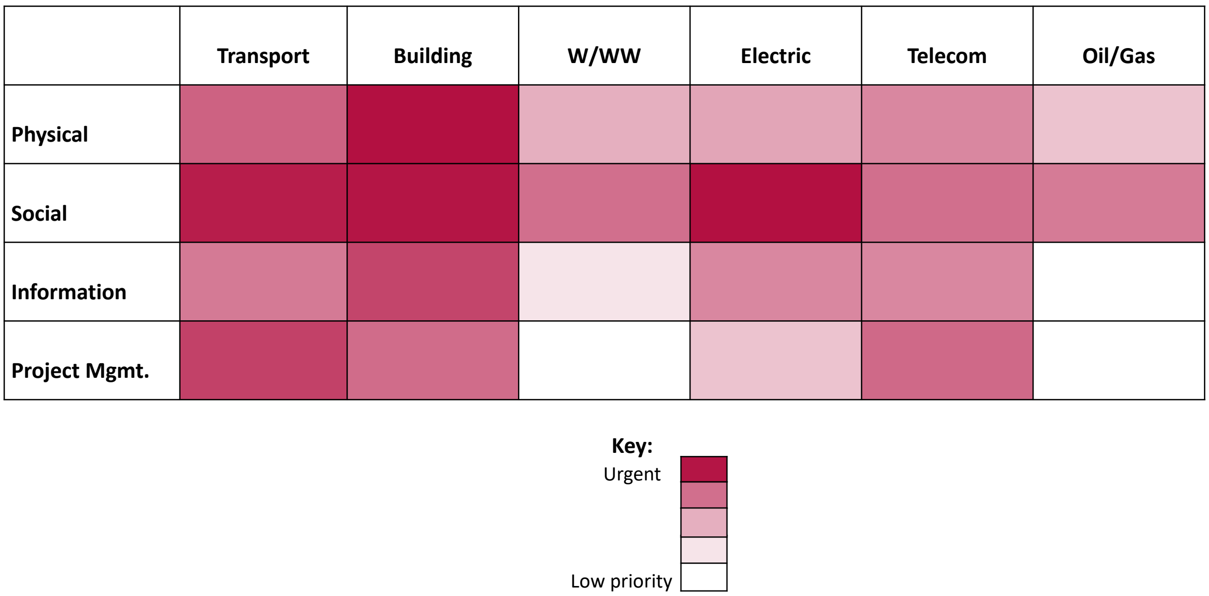
6.2.6 Aggregate Matrices

Within a community, it is likely that a collection of matrices, assessing the same infrastructure functions but representing different spatial scales or jurisdictions, may be needed to inform decision making and facilitate communication. For instance, at least two spatial scales of matrices could be useful in depicting neighborhood-level PRM results and overall community-level PRM results. Other useful spatial breakdowns could include infrastructure maintenance districts within the community. These detailed assessments can then be aggregated spatially or by owner to develop an overall assessment, facilitating reporting to the entities that are responsible for infrastructure (i.e., local, state, federal, private ownership). The PRM approach allows a community to customize information to ensure it is relevant to multiple audiences.

Table 19 provides a graphical summary of the Martha Jefferson neighborhood assessed in Table 18. The PRM applies to the study scenario during the one-month mark after the disaster, once re-entry is officially allowed. The neighborhood contains the affected elementary school and two bus lines. This is the completed version of the matrix that was first introduced in

Table 17.

Table 19. Example of screening-level PRM summary for flood-affected area reported using a heat map color scheme. Deep red indicates areas needing urgent attention from decision makers.



6.2.7 Deciding whether PRM results indicate the need for refinement of controller rules

The first type of insight the PRM can provide does not impact the controller but instead identifies where the decision-maker may be able to take direct action. Consider a controller-driven recovering system, coupled with an unexpected decline in transit ridership metric. The main causal factor is determined to be that rental and public housing are not receiving the same resources as private housing, and insecure housing is affecting renters' ability to participate in the recovery economy (the Building column of the PRM). This is not a corridor reconstruction problem, so it cannot be addressed by the controller. However, this is an economic and policy insight that decision-makers may be able to address directly outside the control structure. These outside economic and policy factors were initially introduced in Chapter 1, Figure 3.

The second type of insight may or may not impact the controller rules. This type of insight uses the PRM to identify supporting or contradictory evidence that the controller rules are resulting in the desired outcomes. Using the PRM to support recovery assessment is important because it is possible, and even likely that some control rule problems will not be identified until the recovery process is initiated, since the review described in Section 5.4 is judgement- and experience-based.

In the case study example introduced in Chapter 5, supporting evidence would show that as repairs are made using the controller-generated recovery strategy, metrics for transportation, housing, and utilities are all improving. The Social row of the PRM management domain is of particular importance for this case study.

Contradictory evidence is less straightforward to evaluate than supporting evidence. Contradictory evidence could show that as repairs are made using the controller-generated recovery strategy, metrics for transportation, housing, and utilities are staying the same, declining, or have mixed signs.

Consider the example of a recovering system, coupled with a declining transit ridership metric (mixed signs). Perhaps the domain review introduced in Chapter 5, Section 5.4.3, missed the first control problem identified in that section: the isolation of socially vulnerable populations from a major employer. A non-exhaustive list of reasons for this contradictory evidence and their resolutions include the following:

1. Nothing is wrong with the control rules. There are system latencies that are inevitable as returning residents initially remain close to home to conduct repairs. Ridership will improve over time.
2. Nothing is wrong with the control rules. However, decision-makers have not communicated sufficiently about reconstruction progress. Prioritize public outreach (the Transport-Information cell of the PRM).
3. Nothing is wrong with the control rules. However, a social media campaign complains that decision-makers have not taken opportunities to re-route transit, change operating schedule, etc., to maximize coverage while reconstruction is ongoing (Transport-Social and Transport-Project Management). Where feasible, implement requested changes.
4. The control rules do not adequately prioritize transit lines. This is the case if transit is missing from the recovery model or the control rules are insufficiently sensitive to transit. Decision-maker and analyst refer to community engagement material previously collected (stakeholder elicitation described in Section 5.4.5), solicit new information if needed, and improve representation or change cutoffs in the recovery model.

5. The control rules did not anticipate an adaptation made by the population. Perhaps non-profit, mutual aid, or private operators offer increasingly popular ridesharing or multimodal options and transit becomes less attractive. Decision-makers evaluate the need to revise control rules to accommodate these adaptations.

To distinguish between the above scenarios, the PRM can and must be used at the Census block, neighborhood, and smaller scales on which the control rules operate. Figure 21 depicts the PRM disaggregated to show both of the neighborhoods involved in this recovery problem. In the case study example, Belmont recovers along the majority of infrastructure systems. However, in the adjacent Martha Jefferson neighborhood, there is still significant disruptions in transportation and other co-located utilities.

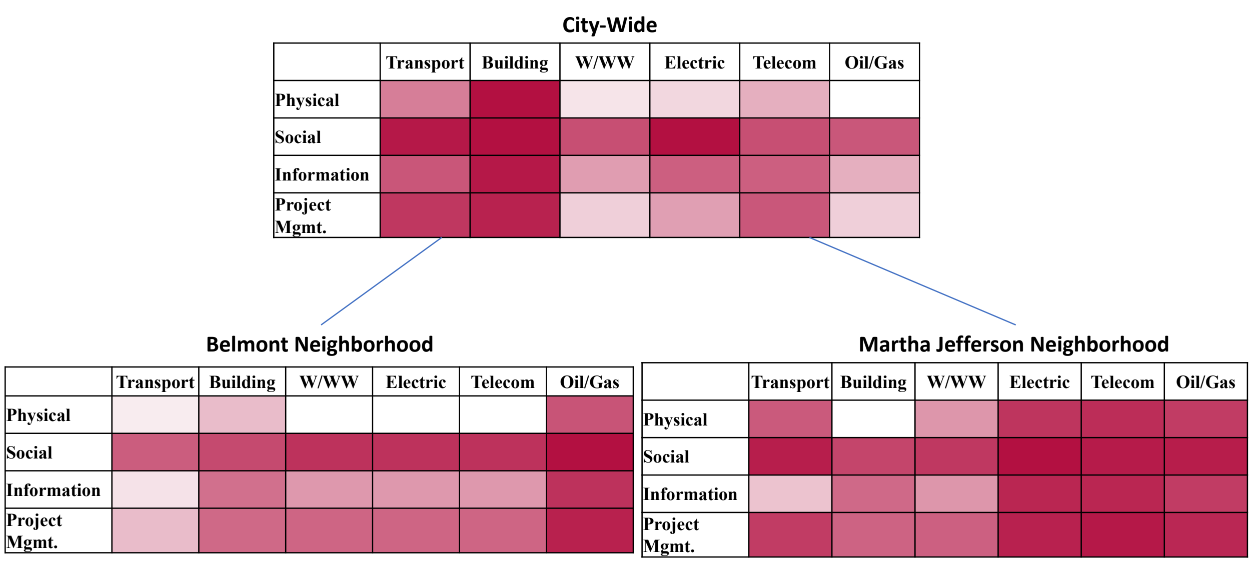


Figure 21. Belmont and Martha Jefferson neighborhoods are recovering at different paces, as expected, but the transportation network problems in Martha Jefferson are affecting residents in Belmont.

Further investigation reveals that one of the closed road segments in Martha Jefferson is Meade Avenue, a key part of Charlottesville Area Transit's Pantops bus route, which provides access to employers and destinations such as retail, offices, and an area hospital. This section of Meade Avenue is also near the cut-off access between neighborhoods identified in Figure 18, Section 5.4.3. In this example, bus service has been suspended on this line. At the same time, it is known that transit is particularly important for carless renters, a demographic particularly vulnerable during evacuation [54], and by extension, during recovery from major community infrastructure damage. This evidence supports the fourth conclusion in the enumerated list above: the current control rules may not adequately prioritize transit lines.

6.3 Summary

This chapter introduced the PRM approach to population resilience during recovery and applied the tool to an extreme flood event. The application example demonstrates the generation and use of event-specific, locally relevant recovery assessment metrics in the PRM. We have demonstrated the utility of the PRM approach for addressing the complicated problem of post-disaster population displacement throughout the infrastructure system reconstruction process. The PRM is an organizing framework and assessment tool that monitors progress towards desired goals across the physical, social, information, and project management domains. The PRM can be used as a monitoring tool for the recovery strategy design framework or independently.

7 Discussion

This chapter discusses model and framework validation and the limitations of this research.

7.1 Overview

This section discusses the validation of the recovery framework in three parts:

- Process validation, considering whether sufficient and appropriate information is evaluated both rationally and with reference to political and jurisdictional considerations, including through stakeholder participation.
- Structural validation, considering formally whether the controller and model behave as expected with respect to recovery goals.
- External validation, considering whether this approach is generalizable to other samples, populations, damage scenarios, and scales. By definition, the effectiveness of a real-world intervention is not fully testable in a research environment, so instead, assessment elements are described.

7.1.1 Process Validation

The scorecard introduced in Chapter 2 summarizes the elements involved in process validation.

The model evaluation criteria from the scorecard are used to evaluate this research (

Table 20). All criteria are met. Validation comments are also reported.

Table 20. Scorecard from Chapter 2 is used to evaluate the case study model.

Model Evaluation Category	Model Evaluation Criterion	Comments
Appropriate Infrastructure	Primary	Includes both residential building stock and transportation systems
	Interdependent	Incorporates into recovery strategy the knowledge that utilities are frequently co-located with transportation network
Geospatial Details	Infrastructure location	Contains component-level detail about linear-type assets
	Topography	Implicitly incorporated in damage assessment. Can be explicitly integrated using a GIS with terrain data.
	Hazard Proximity	Can be integrated into a GIS with hazard data. Contains component-level damage assessment data.
Spatial Scales	Community	The system is depicted at the community level.
	Neighborhood	Neighborhood breakdowns of damage and repair are reported.
	Housing Unit	Contains component-level detail about access and mobility
Stakeholders	Decision Makers	Formalizes the interpretation of recovery goals and policy constraints.
	Residents	Centers the needs of residents for mobility to adapt to damaged systems
Political and Funding	Jurisdiction	Ineligible infrastructure can be screened out by decision maker. Damage and repairs are reported at the neighborhood level.
	Funding	Infrastructure with unavailable funds can be screened out by decision-maker. Recovery strategy is robust to interruptions in funding.
Evolution and Uncertainty	Uncertainty and Probability	New reconstruction duration information and new resource constraints update the recovery strategy.
	Dynamic	The recovery model handles new disturbances and reconstruction interruptions.

7.1.2 Structural Validation

In this section, we consider whether the framework and recovery model behave as expected with respect to strategy design goals. Specifically, we consider:

- Does the controller repair the system?
- Are high priority nodes repaired rapidly?
- Is the repair strategy better than a GIS approach?
- Is the repair strategy better than a network-centrality based approach?
- Is PID better than other feedback approaches?

We assess these validation questions by checking that the model output achieves the intended goals and by comparing the output of the designed strategy to the output under any other strategy. In order to permit a complete evaluation of all possible recovery strategy permutations, a small example problem constructed using the recovery strategy design framework is tested (Figure 22). This example problem consists of 13 nodes and 25 edges, seven of which are damaged. Each corridor contains at least one edge, and seven corridors are damaged, resulting in 7!, or 5040 possible recovery strategies using a permutation-based approach. For simplicity, each corridor is assumed to require the same time for reconstruction and each node has the same population. Criticality is varied randomly, as is the damage distribution. The controller is the same as in the case study.

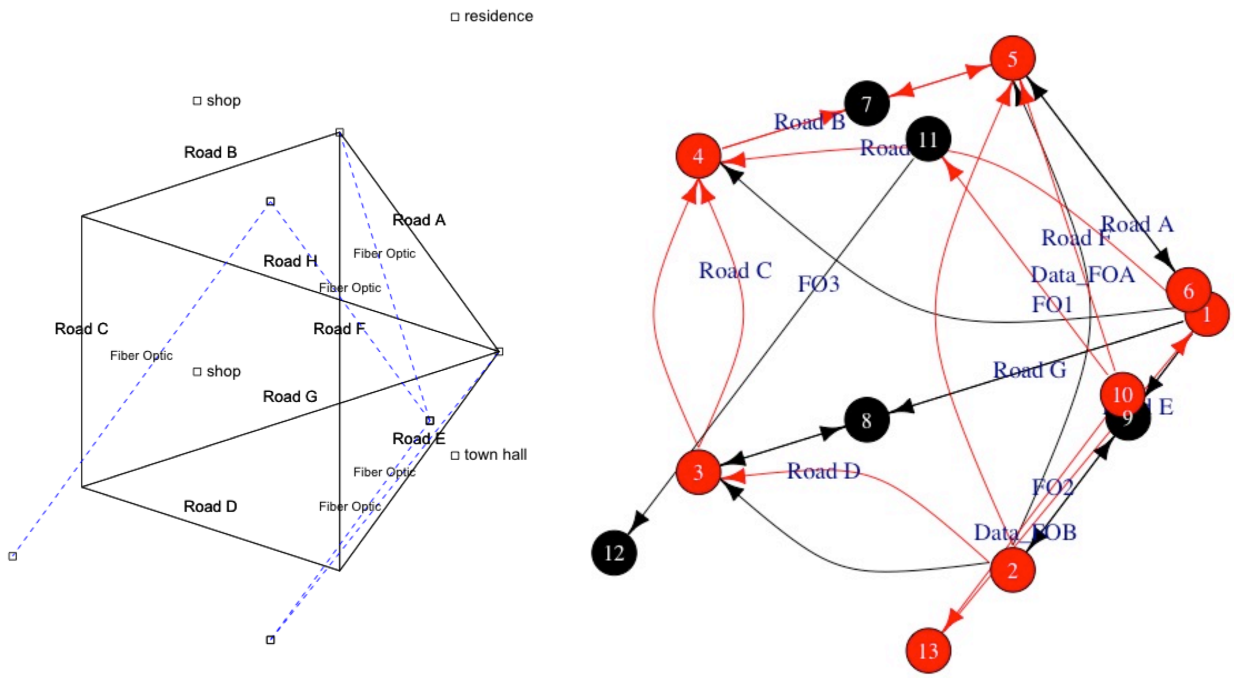


Figure 22. Small example problem with 13 nodes and 25 edges. Nodes 4,7,8 and 9 all meet both social vulnerability criteria and are therefore of particular interest when assessing the recovery strategy. These nodes are discussed more below.

This structural validation step is performed on a small network problem because the computations become unwieldy with the city-sized network. With 172 damaged edges in Chapter 5's case study, the number of permutations is of the order 10^{312}. Therefore, we apply the same control rules to the smaller problem and compare the outcomes to a permutation-based approach.

First, we run the controller on the damaged infrastructure system to determine whether the system is being repaired. The reconstruction results at each time step are recorded. A graphical depiction of the system under repair (Figure 23) shows that at least one edge is repaired per time step, as expected. When an edge is repaired, it transitions from black to red. Once all the incoming edges are repaired, nodes can transition from black to red. At the final time step, all nodes and edges are repaired.

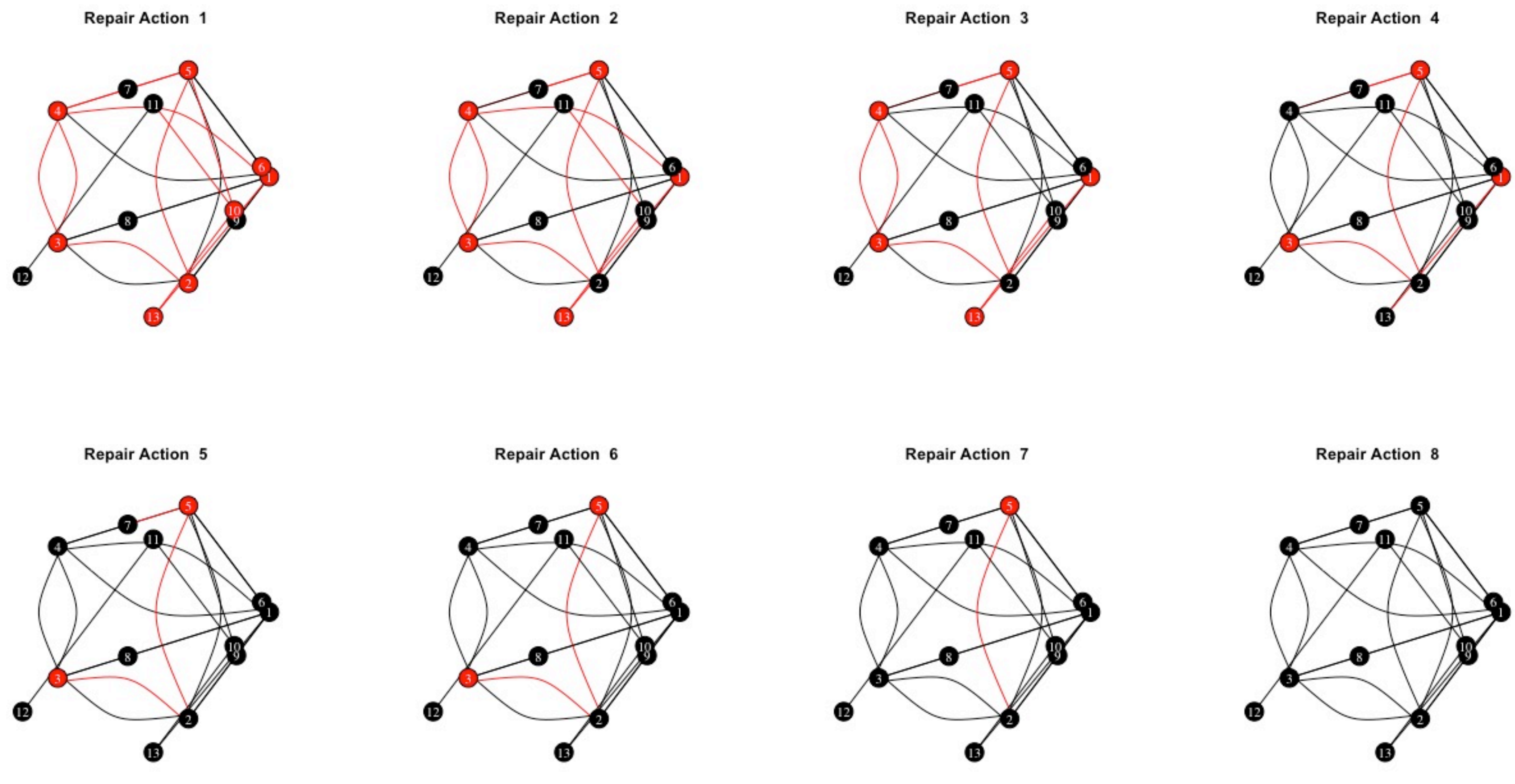


Figure 23. Graphical depiction of controller results for example problem after each repair action. After the first action, one of the seven damaged corridors is repaired, and at the final point, all corridors are repaired.

Then we check the quality of the repair process. We want a designed strategy that performs equal to or better, with respect to the goals, than under any other strategy. With seven damaged edges, there are 5040 possible sequences of corridor repairs for this example problem. The model's response to the designed strategy, namely, faster recovery for nodes with high network importance, high social vulnerability, or both, is as expected.

- At the network level, the designed strategy is completed by time step 7, slightly slower than the average for all permutations of corridor repair, which is time step 6.7 and identical to the median repair time, which is also 7.
- At the network level, the designed strategy is also within the window of the 0.25-0.75 quantiles at each time step, suggesting the designed strategy will not have a significantly different outcome compared to another repair strategy overall or at any time step *for the network as a whole*.
- For nodes that are of high network importance, the designed strategy significantly out-competes other strategies (averaging 4 time steps compared to the mean of 6.7)
- For nodes that are characterized by high diffuse and high localized social vulnerability, the designed strategy significantly out-competes other strategies (averaging 3 time steps compared to the mean of 6.7)

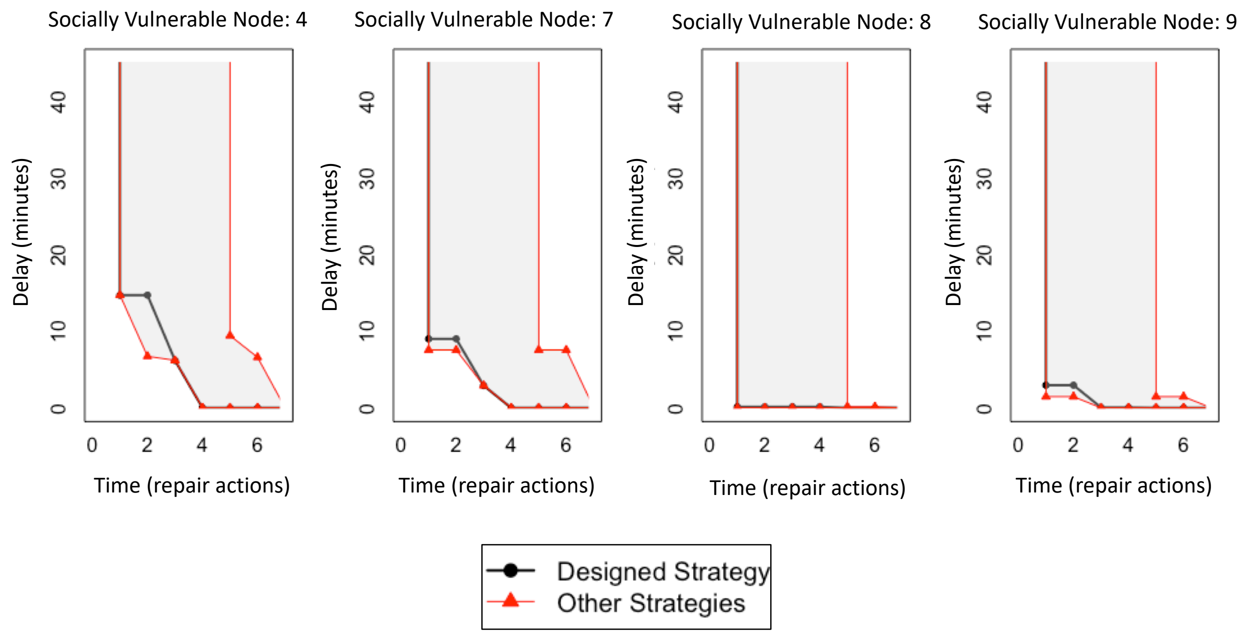


Figure 24. The designed recovery strategy, shown here at several socially vulnerable nodes, is generally equal to or superior to other strategies at the highest vulnerability nodes. Other possible strategies (edge order permutations) are also shown.

More important than the above measure of network restoration, we also check that mobility is restored rapidly for nodes meeting both social vulnerability criteria. Figure 24 depicts the comparison between the designed and other possible strategies. With this small example graph, it is possible to generate strategies consisting of each of the 5040 possible edge permutations. The metric of interest is return to zero delay compared to baseline travel time. The controller-produced recovery strategy results in rapid, monotonic reduction of delays for socially vulnerable populations least able to adapt to damaged infrastructure. The designed recovery strategy reaches zero delay as fast as the fastest strategy. At some earlier time steps, the fastest strategies perform somewhat better than the designed recovery strategy.

This difference in performance between the fastest permutation-generated strategies and the designed recovery strategy is appropriate because of the designed strategy's focus on priority regimes (not individual nodes). The designed recovery strategy seeks a rapid reduction of delay for each priority regime rather than for an individual node. Therefore, at an individual node, a permutations-based approach sometimes finds a better strategy than the designed recovery strategy for that node. When the highest priority regime has only one node, the designed recovery strategy is identical to the best permutation-based strategy for that node. The model's response to the designed strategy is therefore as expected for the delay metric in this small example model.

We also consider PID compared to other controller types. PID is compared to proportional, proportional-integral, and proportional-derivative controller types. Comparisons consider the small example model, already introduced in this section. Results for the example problem show that PID is equal or superior to other control strategies (Figure 25).

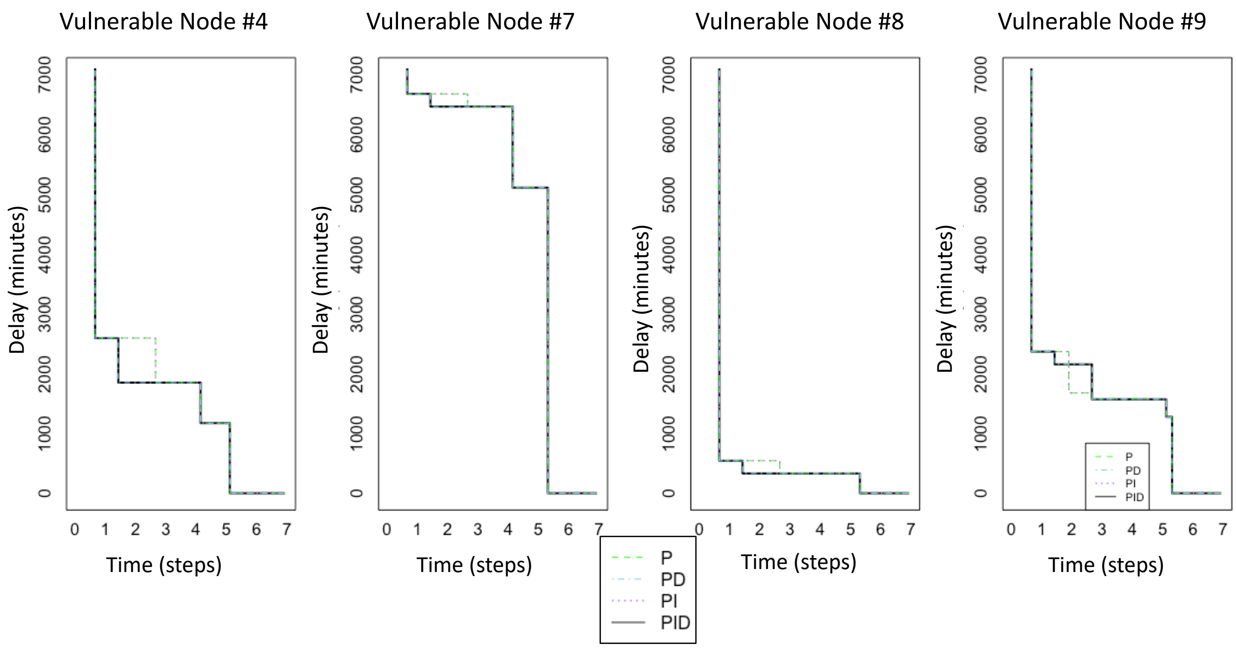


Figure 25. PID results equal or out-perform other controller strategies in the small example problem with several identical-length edges.

In addition, we consider PID compared to control strategies that use fewer context variables. The context variables, first introduced in Chapter 3, are:

- **Q**: Performance is unacceptable,
- **t**: Time out of service is unacceptable,
- **DV**: The diffuse measure of vulnerable populations is critical,
- **SV**: The concentrated measure of vulnerable populations is critical, and
- **NW**: The importance to the network is critical.

The first two variables, *Q* and *t*, are screening variables corresponding to our requirements excerpted from Section 3.3.3:

1. RC-1 RM must not divert resources to systems without impaired performance [H-1, H-2, H-3]
2. RC-2 RM must initiate repairs on systems exceeding time-out-of-service benchmarks [H-1, H-2, H-3]

Since we do not consider it physically meaningful to repair a system that does not have impaired performance, these two requirements are held steady. Variations on the PID controller considering one variable, SV, DV, or NW are examined. Variations considering two variables, SV-DV, NW-SV, and NW-DV are also examined.

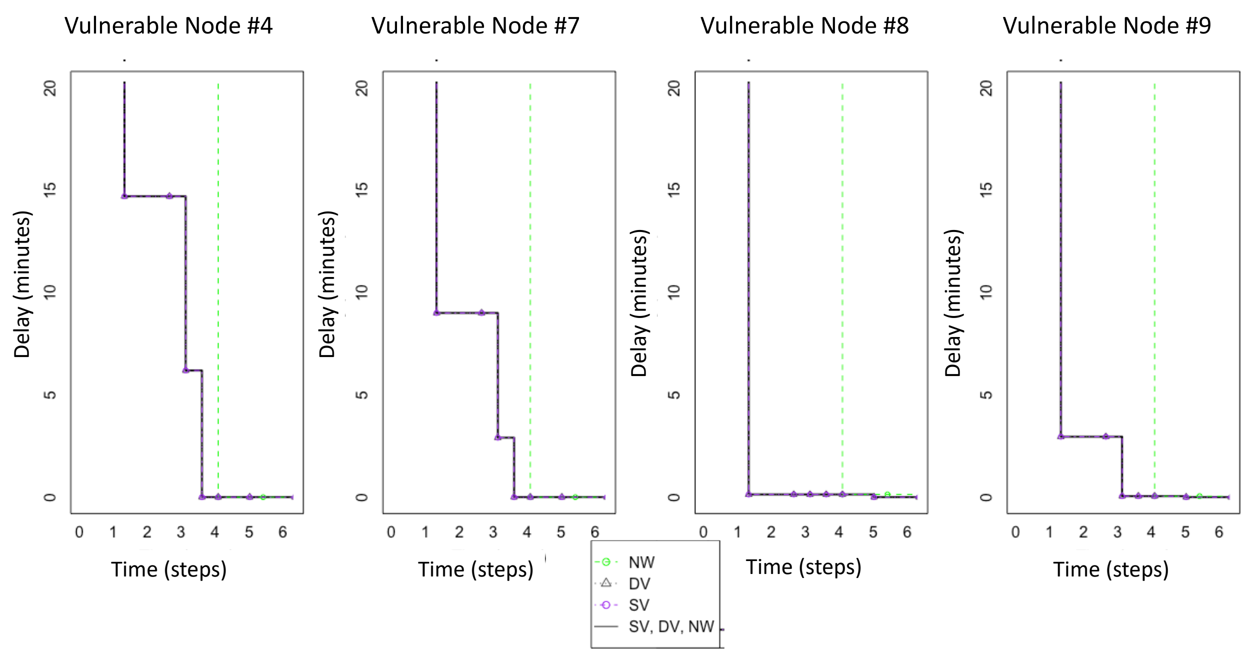


Figure 26. The PID controller using all five context variables performs equal to or superior to control approaches with fewer context variables.

Comparisons consider the small example model, which contains several edges that are identical in length and therefore produce equal performance, as well as a version with arbitrarily lengthened distances, to produce some variance in results. For the example problem, five-variable PID controllers outperform the three- and four-variable cases (Figure 27 and Figure 29). In the second case, where the graph's distances were arbitrarily lengthened, only the controller using solely the localized social vulnerability variable out-performs the designed strategy (Figure 28 and Figure 30). Inspection shows that this performance improvement is spurious, and arises due to the interplay of damage patterns, topology, and arbitrarily assigned distances. (The process of arbitrary lengthening was applied to the edge feature attributes numerically, without accompanying coordinate changes, and therefore potentially produces impossible geometry in Cartesian space.) Therefore, the desirability of the five-variable PID approach is confirmed for this set of decision maker goals. These results also confirm that approaches that take a greedy approach solely based on network centrality measures may not be sufficient to achieve decision maker goals.

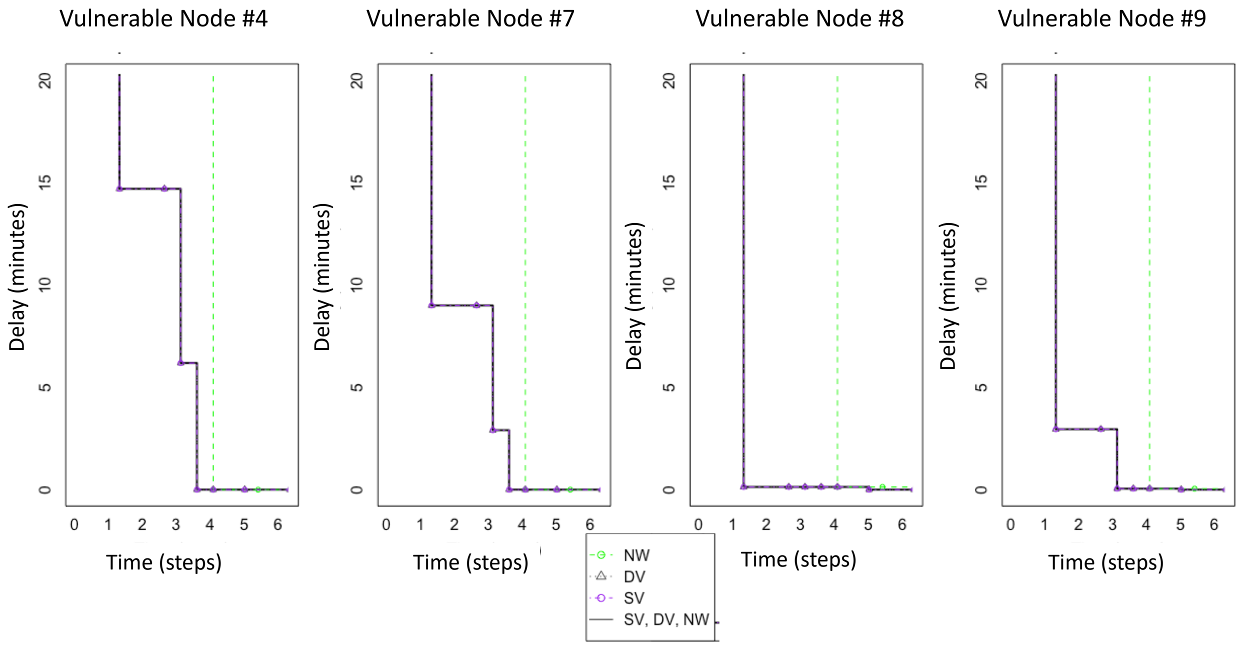


Figure 27. For the example problem, PID outperforms other control approaches using three context variables.

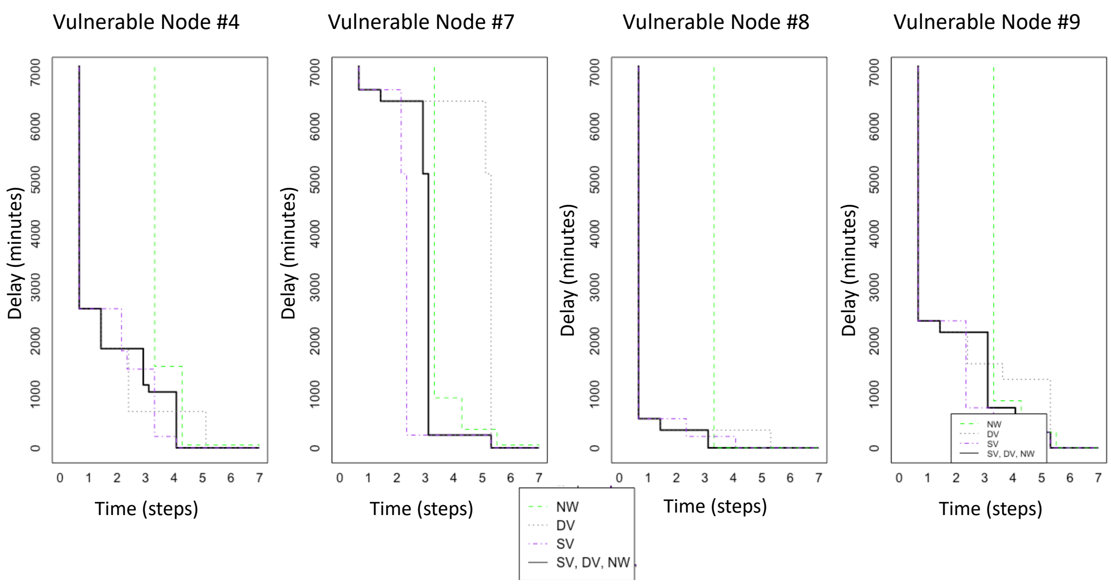


Figure 28. PID outperforms other control approaches using three context variables, in a variation on the example problem that introduces arbitrary increases of edge distances. The only exception is the SV-controller, and that result is spurious due to the process of arbitrarily lengthening some of the edges to produce more variance in performance.

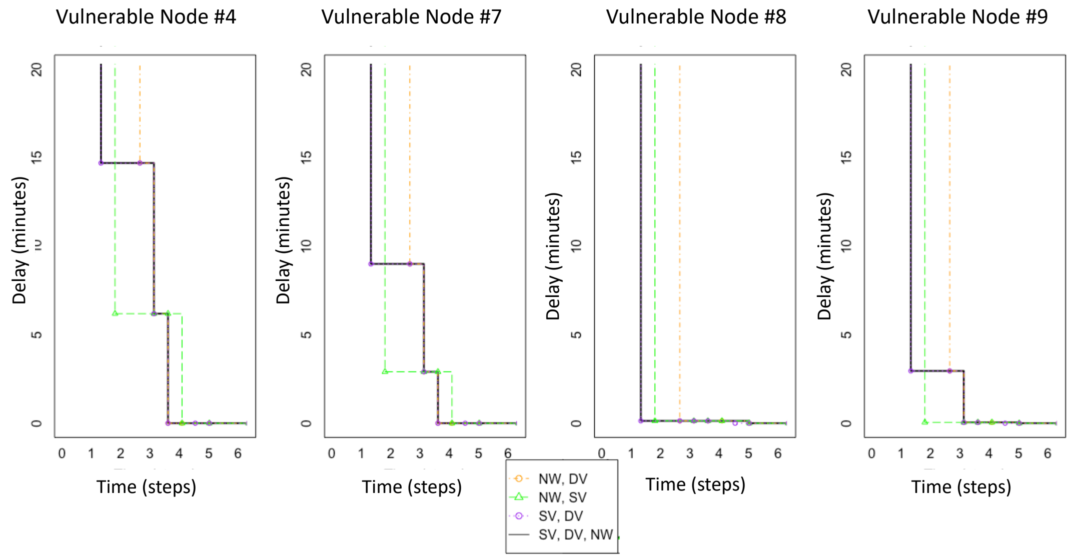


Figure 29. In the example problem, PID using all five context variables outperforms four-variable controllers.

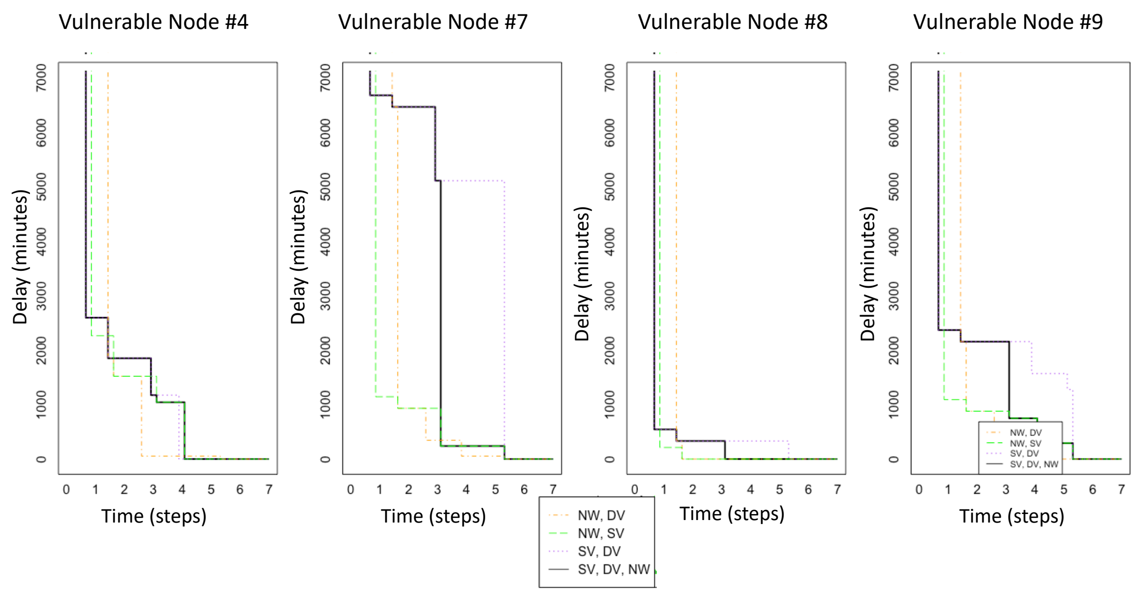


Figure 30. PID using all five context variables outperforms other control approaches using four context variables, in a variation on the example problem that introduces arbitrary increases of edge distances.

7.1.3 External Validation

As noted in the subsection front matter, effectiveness of a real-world intervention is not fully testable in a research environment, so instead, assessment elements are described. Where applicable, solutions to potential external validation problems are also considered. Following the lead of [173], we consider three areas: general equilibrium effects, Hawthorne and John Henry effects, and replicability considerations. The validation problem is described and, where applicable, solutions are suggested.

General equilibrium effects. In a complex system, it is important to consider how feedbacks could counteract the intended effect of an intervention. Major disasters often affect more than one community. If one community designs a recovery strategy according to this methodology and a neighboring community does not use a designed recovery strategy and has a lengthy recovery period as a result, socially vulnerable groups from the neighboring community may move to the other community. Since it is easier to count population than it is to determine whether specific displaced individuals have returned, this outcome would make the designed recovery strategy look even better compared to an ad hoc recovery approach. In addition, new socially vulnerable residents will increase competition for scarce affordable housing with existing residents [174], potentially compounding displacement.

Hawthorne and John Henry effects. Hawthorne effects are where the group receiving the intervention behave differently because of the intervention. Examples include more socially vulnerable populations returning more quickly not just because infrastructure is accessible, but because of increased confidence in government and feelings of community affiliation. John Henry effects are when groups not receiving interventions behave differently as a reaction to the group receiving interventions. For example, demographically similar groups in a neighboring community or just above the social vulnerability cutoff line move permanently. Influential residents successfully lobby for aspects of the recovery strategy to be slow-walked because they disapprove or seek some advantage through delays. Alternatively, groups in neighboring communities compete with the designed recovery strategy by creatively leveraging resources, labor, and technical expertise. [173] note that one solution for these effects is to collect data on recovery for a longer period, with the intent of outlasting these behaviors. Long-term record-keeping may be a good option for long-term recovery since the process can be multi-year in cases of major damage.

Level of care in implementation. A pilot project may receive special care in implementation, making it difficult to replicate the effects in subsequent implementations. [173] recommend clear documentation of implementation procedures and recording compliance rates, recording whether and when the actions outlined in the designed strategy occur. In addition, we recommend using STPA to analyze the work planning coordination process itself to identify and implement potential controls for the process.

Specificity of sample. This example problem was developed for a context of formal housing and reliance on uninterrupted utility access, so this recovery strategy design process may have different levels of effectiveness in areas where large segments of the population are informally housed or experience intermittent utility outages. Communities with ready access to necessary funding and coordination may have more flexibility in restoring service to vulnerable populations by repurposing intact facilities.

[173] suggest that behavioral theories can help structure replicability and generalizability testing by considering whether there is evidence that effectiveness at one location or for one disaster type is likely to be applicable to another scenario. Theoretical frameworks can also be leveraged to estimate whether or how minor variations to the strategy design methodology could matter. In addition to reference to theory, it will be important to test whether rural, exurban, and urban areas require different approaches or different model parameters. This example problem was also developed by researchers with expertise in flood risk, with the intent to extend to other natural hazards, so multihazard applicability must also be tested.

7.2 Limitations

This section outlines the limitations of the proposed dissertation research to describe when it is not appropriate to use the recovery strategy design approach described here, challenges to using this work correctly, and to identify future work.

7.2.1 Limitations on intended use

This research was designed based on the case of flood-related damage to interdependent infrastructure systems (erosion, scour, washouts, permanent inundation, etc.). The case study portion of the research was tested on a local U.S. community, simulating recovery over a months-to-years time frame. It is the researcher's opinion that real-life use of the approach would work best for entities with access to both geospatial data and developers with expertise in database administration.

Even in the US, very rural areas will lack both, and small cities may lack the latter, although this is changing. This approach is also intended to be extendable to any other local situations throughout the world where sufficient infrastructure data is available, but given that this is a research project and not a full software tool acceptance test, the potential for global use will only be investigated qualitatively through review by recovery professionals. Regardless, data availability and the need for technical expertise is one set of use limitations for widespread adoption of this approach.

7.2.2 Limitations due to data uncertainties

Even where appropriate data and expertise are present, there are also numerous limitations in model accuracy due to uncertainties in the data for locales where sufficient data resources do exist. Zio and Aven (2011) summarize uncertainty-related issues in complex systems modeling as lacking, excessive, or contradictory information; measurement and estimation errors;

linguistic ambiguity; and analyst subjectivity. The dominant focus of the following list is information-related uncertainties and the role of measurement and estimation errors in uncertainty.

7.2.2.1 Infrastructure uncertainties

Well-known uncertainties related to infrastructure include lack of or conflicting knowledge about the configuration, placement and sometimes even the existence of components due to factors such as data-sharing restrictions, missing data and non-digital data (e.g., Halfawy and Eng, 2008). Improvements in integrated asset management are necessary to resolve these issues [131], as are increases in post-disaster data-sharing and communication [89]. These gaps, and disagreement on which infrastructure and other systems and processes to focus on for disaster resilience, present difficulties with respect to establishing appropriate pre-disaster baselines [132], and hinder resilience assessment and recovery strategy design.

7.2.2.2 Interdependency uncertainties

Missing infrastructure data and limits to data sharing is also a source of interdependency uncertainty. Even with complete asset catalogs of all infrastructure systems, however, interdependencies may be unclear or difficult to identify. Further, multiple types of interdependencies may be necessary for analysis, but could be ill-suited to representation in the same modeling framework.

In addition to the interdependency matrix originally presented in Table 4, pre-packaged albeit data-intensive methods are available to specify interdependencies (e.g., Klein et al., 2008) or to link infrastructure through market interactions (e.g. Zhang and Peeta, 2011). There is also evidence that Boolean specification of the presence of an interdependency is sufficient for some CIS recovery modeling applications [135], but models considering capacity and demand or analogous concepts have wider applicability. Methods focusing on geographic interdependencies (proximity and access) neglect other types of interdependencies (e.g., Ramachandran et al., 2015), but can be useful with respect to work planning.

7.2.2.3 Damage assessment uncertainties

Additionally, the state of repair and level of infrastructure functioning may be unclear [65], especially at the beginning of the damage assessment process. (For a conceptually related damage assessment strategy which balances the needs of various community groups, please see Balcik [2017].) Damage assessment can include in-person inspections by trained professionals and through citizen reporting mechanisms [156]–[158], which can be complemented by drone- or satellite-assisted methods [159], [160]. However, assessment can be overly subjective and benefits from standardization (e.g., Molinari et al., [2014]).

7.2.2.4 Recovery and reconstruction timeline uncertainties

Even under non-disaster conditions, construction schedules are notoriously uncertain and benefit from probabilistic estimation techniques [176]. Reconstruction timelines may be subjected to additional uncertainty due to:

- Funding acquisition challenges, including potential misallocation or capture of relief funds [177].
- Supply chain bottlenecks and material shortfalls as well as price inflation [178], [179], combined with infrastructure capacity shortfalls due to unnecessary donations [180].
- Skill shortages due to gaps in the availability of appropriate expertise and professional qualifications [51], [158], [181].
- Problems streamlining legal, inspection and permitting processes to accommodate the volume of reconstruction work while still maintaining appropriate construction standards [182].

7.2.2.5 Population location and dynamics uncertainties

Post-disaster displacement takes place in the context of existing migration systems, the dynamics of which influence migration decisions and timelines [183]. Serious damage to infrastructure can be viewed as new constraints on the existing dynamics describing whether, where and how people move. Pre-disaster population dynamics, often obtained through techniques such as a government census and traffic counts, will generally lack the household-level resolution at which migration decisions take place but can provide contextualizing baseline information about approximate population, in-migration and out-migration, and changes in the rates of migration.

While they will not be pursued for this project due to data availability considerations, and, for real-world use cases, privacy concerns, some of the most promising techniques to improve resolution of population data include people-as-sensors approaches where mobile phones are used to capture data for census [184], real-time emergency event detection [69], [185], [186], and even for estimation of carbon footprints due to commutes [187].

The most applicable mobile phone research for reducing uncertainty in population location and dynamics are:

- Sensing and prediction of daily mobility patterns, which generally feature weekly routines cycling through frequent trips to a small number of locations in the same order [188], [189]
- The use of mobile phone data in transportation demand, infrastructure performance models and urban planning [190], [191]

Some evidence that post-disaster mobility patterns stabilize within weeks and are frequently characterized by displacement to previously-visited locations (e.g., Lu et al., 2012). This finding aligns well with the influence pre-event diasporas appear to have on destination choice as described by social science in the context of migration systems (e.g., Haug, 2008; Maroufof, 2017).

7.2.3 Limitations due to assumptions about decision makers

The recovery strategy design element of this research assumes a desire to return to pre-event baseline performance with some or no modification to the community's layout. This approach is therefore limited in the ability to analyze recovery strategies aiming to achieve significantly lower (i.e. decarbonization) or higher (i.e., "build it back better") standards of living. This approach also does not accommodate recovery strategies involving the removal of vulnerable populations through neglect or land grabs. (The researcher argues that this modeling limitation is an ethical strength.) Neither can this approach consider whether certain rebuilding strategies accommodate major influxes of population such as recovery workers who will compete with returning residents for housing. It also does not directly support non-cost-based value judgements about whether to rebuild at all.

Furthermore, this research assumes a nominally functional collaboration and work-planning environment. The approach considered in this research can support effective communication if integrated into daily work planning, but cannot resolve existing dysfunction between cooperating entities. For example, it is assumed that:

- The recovery leadership has the authority to execute the recovery strategy
- Cooperating entities actually do the reconstruction work
- Cooperating entities are communicating about reconstruction activities frequently, accurately, and at the level of detail necessary to support adequate work site logistics and to make updates to the infrastructure damage model used to build the recovery strategy.

These assumptions are a limitation because imperfect communication and communication latencies are features of collaborative endeavors. These assumptions are also a limitation because contractor fraud, poor performance, and reporting problems are common features of disaster capitalism [195].

7.3 Summary

This chapter discussed validation of the model and framework, as well as the limitations of this research. Validation components included process validation, structural validation, and external validation. The process validation assessed whether sufficient and appropriate information was included and analyzed. The structural validation assessed whether the recovery model behaved as expected with respect to strategy design goals. The external validation produced assessment criteria for real-world evaluation, which remains an important area for future work. Limitations included intended use, data uncertainties, assumptions about decision makers.

8 Conclusions and Future Work

8.1 Contributions

This dissertation provided a framework for developing a controller to repair a geographically large interdependent system with many stakeholders that is not suited to straightforward mathematical characterization. The framework employs a satisfactory control approach based on PID principles, applied to a discrete-time, time-varying system. The proposed framework also combines network science and STPA to design a recovery strategy for interdependent infrastructure.

The combination of network science and STPA are complementary, and novel: STPA frames losses in terms of a system, system components, and component interactions [1]. Network science facilitates the depiction of the system, system components, and component interactions using feature-rich edge lists. Additionally, STPA's notion of a controlled process fits well with the "resilience curve" ([2]) framing of recovery problems. Accordingly, this dissertation exploits the control and feedback framing to shape transient state characteristics to limit impacts to residents and to respond to new information, constraints, and disturbances.

This proposed framework was applied to a case study in a real interdependent infrastructure system. Goals were set based on real-world policy considerations, and then formalized into formal control rules using STPA. The PID-based controller that was designed using this methodology produced results that are superior to recovery strategies built without feedback.

Graphical techniques to visualize controller outputs and refine them were also provided and demonstrated. This latter set of tools acknowledges the need for stakeholder input, particularly in public sector systems. Finally, an adaptation of the Resilience Matrix approach is provided as a monitoring tool during implementation of the recovery framework. The RM can be used to assemble evidence that recovery is or is not meeting decision-maker goals.

The result is a practical and theoretically sound decision support methodology that accounts for key locations, proximities, alternatives, interactions, and sources that constrain system users (the problem structure), as well as individual features and "system properties downscaled" to the component level. This framework is designed to be interoperable with common data formats and asset management systems, and can be integrated into a live work-planning application. This work contributes to efforts to support human population resilience by treating peoples' resilience as a function of infrastructure system resilience.

8.2 Future Work

8.2.1 A Sea Level Rise Adaptation Study

An important area of future work involves the treatment of systems where recovery activity involves more than the repair-in-kind action. For example, consider coastal communities facing sea level rise. A common menu of project-level options for individual assets is "protect, accommodate, retreat" as initially described in [196], integrated into policy analysis in documents such as [197], [198], and detailed in planning and implementation guidance such as

[199]. Avoiding exposure in the first place [200] is another option, as is investing in rapid recovery. These adaptation approaches are also applicable to riverine floodplains [201]. A brief sketch of the framework presented in this dissertation, applied to the sea level rise adaptation problem, is described below.

Goals

Like the case study where infrastructure damage is understood to be a practical impediment to resumption of daily life, the sea level rise adaptation problem involves considering an interdependent infrastructure network. Likewise, a performance recovery curve can be devised using estimated future losses along decision maker-defined dimensions of criticality. Goals can be matched to controller rules.

However, in this particular example, this framework will be better suited for exploring the outputs of recovery strategies under different scenarios than creating one definitive recovery strategy. Permutations will result from the need to explore future damage scenarios, not to mention multiple options for reconfiguring the system and multiple possible land use strategies, and other factors. Nonetheless, the starting point is the same: a definition of system losses and hazard states that can lead to those losses. Examples are shown in Table 21 and Table 22.

Table 21. System-level losses.

Number	System Loss Description
A-1	Users must repair or rebuild more than once (repetitive losses [202])
A-2	User cannot access system locations
A-3	Users cannot access utility services
A-4	Users cannot access ecosystem services

Table 22. System level hazards that can lead to losses.

Number	System Hazard Description
H-1	Sea levels do not maintain expected distance from structures, utilities, or access routes
H-2	Sea levels do not maintain expected distance from environmental contaminants in the built environment
H-3	Utilities allow backflow of rising seas
H-4	Mitigation or adaptation activities impair access to system components or ecosystem services
H-5	Laws and funding environment do not permit system modifications (protect, accommodate, retreat)

Graph Representation

As in the case study, a geospatial network representation of the system is very useful. Unlike the case study, the location of individual structures is critical to any resilience strategy involving reconfiguration, and cannot be reduced to nodes in the transportation network. Because utilities are involved in several hazards (at minimum, H-1, H-2 and H-3) and can be a selection criterion in reconfigurations, these, too, cannot be reduced to edges in the transportation network. Therefore, the interdependent infrastructure multigraph will consist of more asset types and feature attributes.

In addition, vacancies in existing buildings and land that can be developed become important in the seal level rise adaptation problem. This requires the addition of capacity or occupancy, as well as vacancy, to the list of node feature attributes. If there is concern reconfiguration changes will tax utilities and roadways, capacity should also be added as an edge attribute. Recognizing that land resources are limited and zoning laws often constrain development, it is also advantageous to add “ghost” nodes, that is, areas that are currently unoccupied but could be, with the addition of structures and, if needed, the attachment of new transportation and utility edges.

Controller Architecture

As with the case study, the sea level rise adaptation problem controller would still seek to minimize some notion of accumulated loss while performance is restored. Construction or reconstruction time remains important for capturing the accumulated loss. Feedback selection and the performance variable(s) of interest depend on the system states and goals.

Constraints differ, too. Any reconfiguration problem must consider zoning laws. Further, analysts should beware potential conflicts between laws, such as where hazard mitigation requirements conflict with national historic perseveration requirements. These are real issues that the author has seen arise in communities of important cultural and historic value.

Review, Iteration and Finalization

The same stakeholder engagement approach and graphical technique can be used for the sea level adaptation problem.

8.2.2 Additional Cases

A number of additional use cases, such as the following, are interesting areas for future research using this methodology.

- This research is intended to be extendable to a multi-hazard recovery, but was designed primarily with flood risks in mind (erosion, scour, washouts, permanent inundation, etc.) and will need to be tested to investigate appropriateness for other hazards
- This research could potentially be used as an ensemble with other operations research models, but this has not been tested
- This research could potentially be used for larger regional studies, but this has not been tested
- This research could potentially be extended to hazard mitigation planning and emergency response based on displacement effects, but this has not been tested
- This research could potentially be extended to climate adaptation planning, but this has not been tested
- This research could potentially be extended to post-conflict reconstruction, but this has not been tested
- This research could potentially be extended to recovery from a pandemic, but this has not been tested.

Testing the above use cases remains, therefore, an important area for future work.

8.3 Summary

This chapter has summarized the research contributions of this dissertation, near-term future work, and possible cases for extending this work. This dissertation contributes to ongoing efforts to support human population resilience by treating peoples' resilience as a function of infrastructure system resilience.

9 References

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