Human-Centered Simulation Modeling to Facilitate Critical Infrastructure Resilience Planning

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A dissertation submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2020

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Abstract

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Planning for timely, effective, and efficient post-disaster infrastructure restoration is critical to prevent prolonged disruptions. Infrastructure resilience planning aims to anticipate damages and disruptions in service, envision the restoration process, and provide recommendations to shorten disruptions. Simulation modeling has computational capabilities to capture domain-oriented complexities such as interdependencies. Several resilience planning initiatives have been conducted collaboratively by emergency management and infrastructure experts in the last two decades in the US. However, no simulation models were used in the initiatives. Modeling methodologies that can adequately facilitate collaborative infrastructure resilience planning are missing in the restoration modeling literature.

This dissertation aimed to facilitate collaborative infrastructure resilience planning. The planning is a complex process as it involves domain- and user-oriented dimensions. The human-centered design process was applied to design and develop a modeling methodology that can support stakeholders in resilience planning by considering both domain- and user-oriented dimensions. For this purpose, eighteen interviews were conducted with experts who participated in the previous resilience planning initiatives to understand the procedure, identify challenges, and explore opportunities of using simulation modeling. Human-centered simulation modeling was created as a conceptual design framework for developing simulation models. This framework identifies essential design components in developing the modeling methodology consisting of user-interaction, system representation, and computation core. This framework enables simulation modeling developers to ensure that the user's needs, strengths, and concerns are taken into account.

There is a lack of modeling methodologies to utilize the design framework and address the identified challenges, especially for complex resource availability scenarios. We developed a process-based discrete-event simulation modeling methodology that is resource-aware and topologically-explicit. This methodology was built as a combination of discrete-event simulation modeling and network modeling. It was applied to simulate a hypothetical electric power network's restoration as a case study to demonstrate the modeling performance, and several sensitivity analyses were performed to validate it computationally. It can provide insights into the restoration process and sequence, scheduling, resource allocation, and service restoration timeframes. This work contributes to restoration modeling literature by considering time-dependent and multi-source resource availability in simulating the post-disaster infrastructure restoration process.

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ACKNOWLEDGMENTS

I would like to greatly thank my advisers, Dr. McDonald and Dr. Dossick, for your inspiration, guidance, and invaluable insights. This dissertation would not have been possible without your support. I am deeply indebted to Dr. Miles for consistently supporting me during my Ph.D. I have been privileged to work with you during the last four years. I would also like to extend my gratitude to Dr. Lowes and Dr. Kaminsky for reading this dissertation. I also appreciate the funding support from the National Science Foundation during my Ph.D. studies.

I would like to thank all experts who have dedicated their professional lives to improving our community resilience, especially those I interviewed during my dissertation's preliminary and final stages in Washington, Oregon, and California.

I am also very thankful to my dear friends Dr. Gloria Fischer and Dr. Mania Orand, for all the advice you gave me during graduate school's challenging times.

My special thanks go to my friends, Kamal, Samin, Alborz, Reza, Hessam, Koosha, Saghar, Shima, Mahlegha, Shahriar, Maryam, Bita, Hossein Agha, and many others who were always there for me.

I want to take this opportunity to sincerely thank my parents, who have always supported me in pursuing my dreams. The sacrifices you have made to keep me and my siblings in school are just unimaginable and unforgettable. I am eternally indebted to you. I would also like to thank my siblings Mehri, Zeinab, Ali, and Mohsen for their unconditional love and support during all these years that I have been away from home.

And last but not least, I would like to thank my dear wife, Farnaz, who has stood up for me through my ups and downs. Farnaz, thank you for all the late nights and early mornings, for being my inspiration and motivation, for keeping me sane during my Ph.D, and for always believing in me. Love you!

DEDICATION

to my dear wife, Farnaz

Chapter 1

INTRODUCTION

1.1 Motivation and Background

Infrastructure systems are susceptible to a broad range of damages during extreme events as they are often outdated and poorly maintained. Prolonged disruptions in critical infrastructure services have negative social and economic consequences. Planning for timely, effective, and efficient post-disaster infrastructure restoration is essential to prevent prolonged service disruptions. Community disaster resilience is defined as "the ability of a community to prepare for anticipated hazard, adapt to changing conditions and withstand and recover rapidly from disruptions" (NIST 2016). Infrastructure resilience planning aims to predict damages and disruptions in serviceability, envision the restoration process, and provide recommendations to speed up the restoration process. Fig. 1.1 is a schematic visualization of post-disaster restoration of infrastructure systems. Several community resilience planning initiatives have taken place in the US in the last two decades in San Francisco (2006-09), Washington state (2009-12), and Oregon state (2010-13) (Poland 2009; WASSC 2012; OSSPAC 2013). Following these initiatives, the National Institute of Standards and Technology (NIST) offered a guideline for community decision-makers to conduct collaborative resilience planning (NIST 2016). Estimating service disruption and restoration timeframes (as shown in Figure 1.1) is a critical component of resilience planning, which proved to be a challenge during the initiatives mentioned above (Ganji et al. 2019). The complexity of infrastructure resilience planning originates from domain- and user-oriented characteristics. Numerous domain-oriented variables, such as hazard intensity, system robustness, redundancy, resource availability, and inter-dependencies, play a significant role in infrastructure restoration. Moreover, user-oriented factors such as inter-organizational collaborations and communications between infrastructure managers and non-expert community stakeholders introduce another level of complexity to the problem. Improving infrastructure resilience

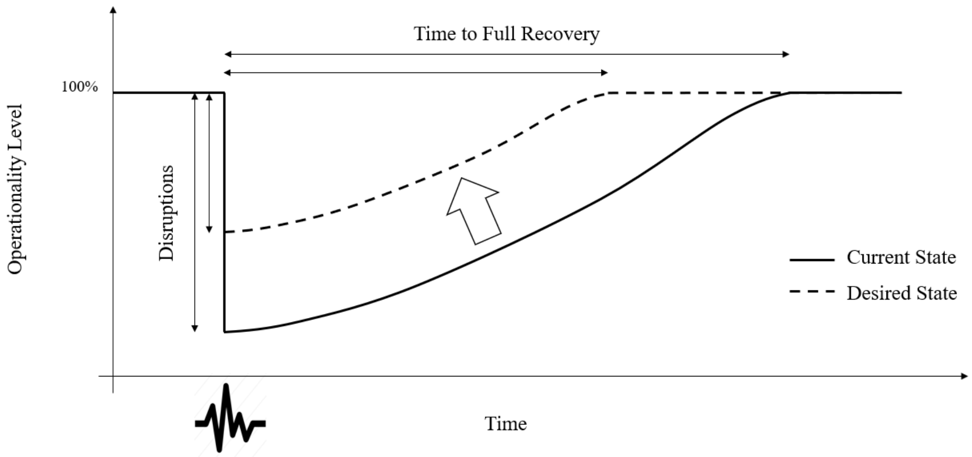


Figure 1.1: Schematic post-disaster infrastructure restoration of current and desired states.

planning entails considering both of these dimensions.

Domain-oriented characteristics of resilience planning can be captured using simulation models. A variety of modeling methodologies are used in research studies to provide insights into infrastructure restoration by characterizing the dynamic relationship between physical damage, restoration times, resource availability, and inter-dependencies. Simulation modeling was used to simulate post-disaster restoration in water and waste-water (Choi et al. 2018; Chmielewski et al. 2016; Tabbucchi et al. 2010), natural gas (Ameri and van de Lindt 2019), electric power (Panteli et al. 2017; Xu et al. 2007; Cagnan et al. 2006) and transportation networks (Liu et al. 2020; Bhatia et al. 2020; Lee and Kim 2007). Simulation modeling was also used to investigate and optimize post-disaster restoration of interdependent infrastructure systems (Lin and El-Tawil 2020; Alemzadeh et al. 2020; Almoghathawi et al. 2019; Gonzalez et al. 2017; Guidotti et al. 2016; Ramachandran et al. 2015; Setola et al. 2012; Min et al. 2011; Xu et al. 2007). Finally, simulation modeling methods were applied to consider agents' decision-making (Talebiyan and Duenas-Osorio 2020; Eid and El-Adaway 2017). However, simulation models were not utilized during the earlier mentioned resilience planning initiatives in the US (Ganji et al. 2019). Instead, recovery timeframes have been estimated based upon expert judgment and through participant discussions. The NIST report lacks any discussion of the computational aspect of the restoration processes.

There seems to be a disconnection between research capabilities and the practical use of infrastructure resilience simulation models.

Available resources are limited in infrastructure restoration following extreme events due to the scale of damages. In this situation, local resources do not suffice for the restoration process. Crews, supplies, equipment, funds, and other forms of resources are purchased and transferred from non-local sources with different timelines and costs. Decision-making for more effective resource allocation is associated with time-dependent resource availability. Prior simulation models fall short of capturing the complexity of time-variant resource availability in the restoration process. Almoghadawy et al. (2019) used a resilience-driven multi-objective restoration model in which a single-type time-invariant resource was used. Lin and El-Tawil (2020) connected nine types of simulators representing nine different restoration steps of interdependent infrastructure systems in their framework. They considered resource-constraints in their modeling framework, but they used a fixed amount of resources during simulated restorations. Ameri and van de Lindt (2019) modeled a natural gas system restoration in a virtual community known as Centerville. However, they also applied one type of resource constraint (crew), which was also time-independent. Talebiyan and Duenas-Osorio (2020) investigated agent decision-making in interdependent network restoration. They concluded that resource constraints impact not only the restoration process but also agent decision-making. However, they also applied a single-type time-invariant resource for each infrastructure system. This shortcoming in restoration modeling can not support decision-making for time-, cost- and source-variant resource availability situations.

1.2 Research Questions and Objectives

This dissertation aims to propose a simulation modeling methodology that supports emergency management agents and infrastructure experts in collaborative resilience planning. To achieve my dissertation goal, the following research questions were defined:

- How can simulation modeling be designed to support collaborative infrastructure resilience planning?

- How can simulation modeling address dynamic time-variant resource availability in infrastructure restoration modeling?

In order to create this modeling methodology, both domain- and user-oriented gaps must be taken into account in the design process. Human-centered design is a process that puts users, their needs, concerns, strengths and weaknesses at the center of the design process of any artifact (Norman 2013), including simulation models. Therefore, we referred to this methodology as "human-centered simulation modeling" (Ganji and Miles, 2018). The human-centered design process, consisting of user research, ideation, prototyping, and usability testing, was followed to develop a well-suited modeling methodology for collaborative resilience planning. I created this methodology through four objectives:

- Objective 1: Examine the process of infrastructure resilience planning and identify needs and challenges (user research)

- Objective 2: Create a conceptual design framework for simulation modeling that integrates the needs of participants in the structure of simulation models (Ideation)

- Objective 3: Develop a simulation modeling methodology that operationalizes the design framework to reliably simulate post-disaster infrastructure restoration (Prototyping)

- Objective 4: Assess the usability of the methodology and identify shortcomings(Usability testing)

1.3 Dissertation Layout

This dissertation follows the three-paper format. Chapter 2 presents detailed information about the infrastructure resilience planning initiatives and provides identified challenges (user research). Chapter 3 offers a conceptual design framework for simulation modeling development for the purpose of infrastructure resilience planning (ideation). Chapter 4 proposes a restoration modeling methodology that utilizes the findings of Chapters 2 and

3 (prototyping). This methodology was presented to six infrastructure managers in order to assess its usability in collaborative resilience planning (usability testing). Finally, a summary of research findings, contributions and limitations are presented in Chapter 5 along with a summary of feedback from infrastructure managers and recommendations for future direction.

In Chapter 2, the previous resilience planning initiatives and the NIST report (NIST 2016) were investigated. I conducted semi-structured interviews with eighteen infrastructure managers and emergency management agents who participated in these initiatives. Subsequently, six primary categories of challenges in the resilience planning initiatives were identified through a qualitative content analysis. Also, opportunities for using simulation modeling in the planning process were explored. This chapter was published as a full paper by the International Conference on Information Systems for Crisis Response and Management. I co-authored this paper with Negin Alimohammadi and Dr. Scott Miles (Ganji et al. 2019).

Chapter 3 offers a conceptual design framework for infrastructure resilience modeling, referred to as human-centered simulation modeling. Several post-disaster recovery assessment reports, community resilience planning reports, and relevant research articles were studied to identify the design components. The developed design framework offers the design components for infrastructure restoration modeling development. I published a paper, co-authored with Dr. Miles, to present the findings of this chapter at the IEEE Global Humanitarian Technology Conference (Ganji and Miles 2018).

Chapter 4 provides details on developing a restoration modeling methodology to facilitate resilience planning. Reviewing the restoration modeling literature, the capability of existing restoration modeling approaches were assessed in capturing key factors in infrastructure restoration. The developed methodology incorporates complex resource availability into infrastructure restoration modeling. This methodology was applied to simulate the restoration of a hypothetical electric power network as a case study. Several sensitivity analyses were also performed for damage intensity, local and non-local crew availability, local and non-local supply availability, and budget allocation using Monte Carlo simulation. This chapter is under submission to the ASCE Journal of Infrastructure Systems, co-authored by Dr. Scott B. Miles and Dr. David W. McDonald.

1.4 Summary of contributions

The work of this dissertation has made the following contributions:

1. We identified six primary challenges that participants faced in the previous resilience planning initiatives. The challenges are listed below.

    - understanding of complex infrastructure networks and its restoration
    - interdependencies among infrastructure systems
    - inter-organizational collaboration and information sharing
    - connections between the built environment (buildings and infrastructure systems) and social institutes
    - communications between the built environment and social institutions' stakeholders
    - communication among infrastructure decision-makers, social stakeholders, and community members

    Chapter 2 provides detailed information about data collection, methodology, and findings. This contribution can lead to improving further collaborative planning initiatives.

2. This dissertation built human-centered simulation modeling as a conceptual design framework for developing simulation modeling methodologies to facilitate collaborative infrastructure resilience planning. This framework offers essential design components under three constructs, including user-interaction, system representation, and computation core. This contribution enables modeling developers to consider the expert's needs, concerns, strengths, and goals in collaborative infrastructure restoration planning. The work that led to creating the human-centered simulation modeling framework is presented in Chapter 3.

3. We developed a resource-aware discrete-event simulation modeling methodology that enables researchers and practitioners consider time-dependent and multi-source resource availability scenarios. Chapter 4 presents the process pursued to develop this methodology. This methodology contributes to the growing restoration modeling literature by flexibly representing complex resource availability in the restoration process. This methodology can support emergency managers and infrastructure managers to make plans and decisions related to resources investments and timing (e.g., for mutual aid contracting) with more detailed representation of resource dynamics.

Chapter 2

CHALLENGES IN COMMUNITY RESILIENCE PLANNING AND OPPORTUNITIES WITH SIMULATION MODELING

Abstract

The importance of community resilience has become increasingly recognized in emergency management and post-disaster community well-being. To this end, three seismic resilience planning initiatives have been conducted in the U.S. in the last decade to envision the current state of community resilience. Experts who participated in these initiatives confronted challenges that must be addressed for future planning initiatives. We interviewed eighteen participants to learn about the community resilience planning process, its characteristics, and challenges. Conducting qualitative content analysis, we identify six main challenges to community resilience planning: complex network systems, interdependencies among built environment systems, inter-organizational collaboration, connections between the built environment and social systems, communications between built environment and social institutions' experts, and communication among decision-makers, social stakeholders, and community members. To overcome the identified challenges, we discuss the capability of human-centered simulation modeling as a combination of simulation modeling and human-centered design to facilitate community resilience planning.

2.1 Introduction

Community disaster resilience is defined as "the ability of a community to prepare for anticipated hazard, adapt to changing conditions and withstand and recover rapidly from disruptions" (NIST 2016: V.1:1). Resilience of community is built upon a variety of community aspects that have been extensively investigated in research studies (Aldrich and Meyer

2015; Comes and de Walle 2014; Chang and Rose 2012). As disasters may cause extreme damage and long-lasting disruptions in community functioning, it is vital for community stakeholders to envision potential damages and expected recovery process beforehand. For this purpose, several community resilience planning initiatives have taken place in the U.S. in the last decade to identify community hazards, anticipate the recovery processes, establish community resilience goals and provide recommendations for decision-makers to achieve better community resilience (OSSPAC, 2013; WASSC, 2012; Poland, 2009).

Community resilience is complicated and multi-dimensional on its own. Community resilience planning, in practice, is a highly collaborative process that involves numerous community stakeholders associated with human-oriented challenges. Participants in community resilience planning include emergency managers, experts and managers of building and infrastructure systems, social stakeholders, and so on. Community resilience planning is technical and domain-oriented and requires a comprehensive understanding of the recovery process of damaged entities in the built environment and social systems. In addition to being a complex puzzle, community resilience planning is a highly user-centered process, requiring collaboration among built environment experts with different areas of expertise, communication among experts of the built environment and social institutions, and information sharing among the planning participants, community stakeholders, governmental and elected officials, and community members. It is essential to recognize and understand the complexity of the planning process and its characteristics. As well, considering that several community resilience planning initiatives taken place in the U.S., it is beneficial to learn from these experiences to facilitate future initiatives.

In this study we investigate the process of community resilience planning and identify challenges that participants experienced in previous planning initiatives as our first research question. The next step is to determine how community resilience planning can be facilitated. Simulation modeling is widely used to model connectedness and interdependencies in network systems such as infrastructure systems (Ramachandran et al. 2015). Several research studies have successfully used simulation models to investigate community disaster recovery processes (Miles at al. 2018). However, no analytical computer-based tools like simulation models have been used in previous planning initiatives. As our second research question, we investigate if simulation models can facilitate planning initiatives, and if so, how they can address the identified challenges. Analyzing interviews conducted with experts who participated in the initiatives, we conclude that combining human-centered design with simulation modeling, referred as human-centered simulation modeling, has the potential to address observed challenges.

2.2 Background

Community resilience is a community attribute that can be improved and adapted over time; it refers to the ability of a community to mitigate and resist against hazards and its ability to recover quickly (Bruneau et al. 2003). Several frameworks have been developed to describe the foundations of community resilience in different domains (Miles 2015; Kuling et al. 2013; Norris et al. 2008). As disasters impact various aspects of a community, community disaster resilience is also considered in diverse dimensions such as social institutions (Aldrich and Meyer 2015; Alipour et al. 2015; Semaan and Hemsley 2015), physical infrastructure (Cimellaro et al. 2011; Davis et al. 2018), economics and business (Chang and Rose 2012), and healthcare (Chandra et al. 2011; Comes and de Walle 2014). Berkes and Rose studied the characteristics of community resilience and integrated two dimensions of social–ecological systems, the psychology of development and mental health, in a framework (Berkes and Rose 2013). Chang et al. developed an approach to characterize communities' infrastructure resilience and identified key challenges including incomplete incentives and partial information (Chang et al. 2014). Berk et al. analyzed coastal state hazard mitigation plans and compared the quality of these plans (Berk et al. 2012). Labaka et al. (2014) presented a framework to identify resilience policies across technical, organizational, economic, and social dimensions (Labaka et al. 2014). Rubim and Borges (2017) conceptualized and characterized resilience in the context of complex systems (Rubim and Borges 2017). Turoff et al. developed a model for interaction among critical infrastructure systems (Turoff et al. 2016). Additionally, many research efforts have attempted to quantify community resilience and identify quantitative indicators and indices to evaluate different dimensions of community resilience (Cutter et al. 2016; Bruneau et al. 2003).

Community resilience planning requires community decision-makers, built environment experts, and social stakeholders to collaborate to identify social goals and their dependencies (NIST 2016: V.1:1). This broad collaboration and communication among experts in different systems and non-experts makes community resilience planning more challenging due to involving human-factors in the planning process. Characteristics and challenges in emergency management have been extensively studied (Scholl and Carnes 2017; van Laere et al. 2017; Turoff et al. 2016; Gonzalez et al. 2012; Maitland et al. 2009; Dilmaghani et al. 2006). However, the existing literature does not specifically identify challenges in community resilience planning. In next section, we introduce three community seismic resilience planning taken place in the US in last decade. The initiatives are a valuable source for finding existing barriers in community resilience planning.

2.3 Community Seismic Resilience Planning in the US

Bruneau et al. (2003) published one of the early research studies to define the concept of community seismic resilience (Bruneau et al. 2003). They defined community seismic resilience as “the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes” (Bruneau et al. 2003). They also proposed a framework to quantify community resilience to be evaluable and measurable. This research and other studies led community experts to apply and quantify community resilience to real communities. Recognizing the importance of community resilience in the research studies, seismic committees and urban planning associations formed and organized planning initiatives to assess resilience of their own communities.

2.3.1 SPUR Resilient City (2006-2009)

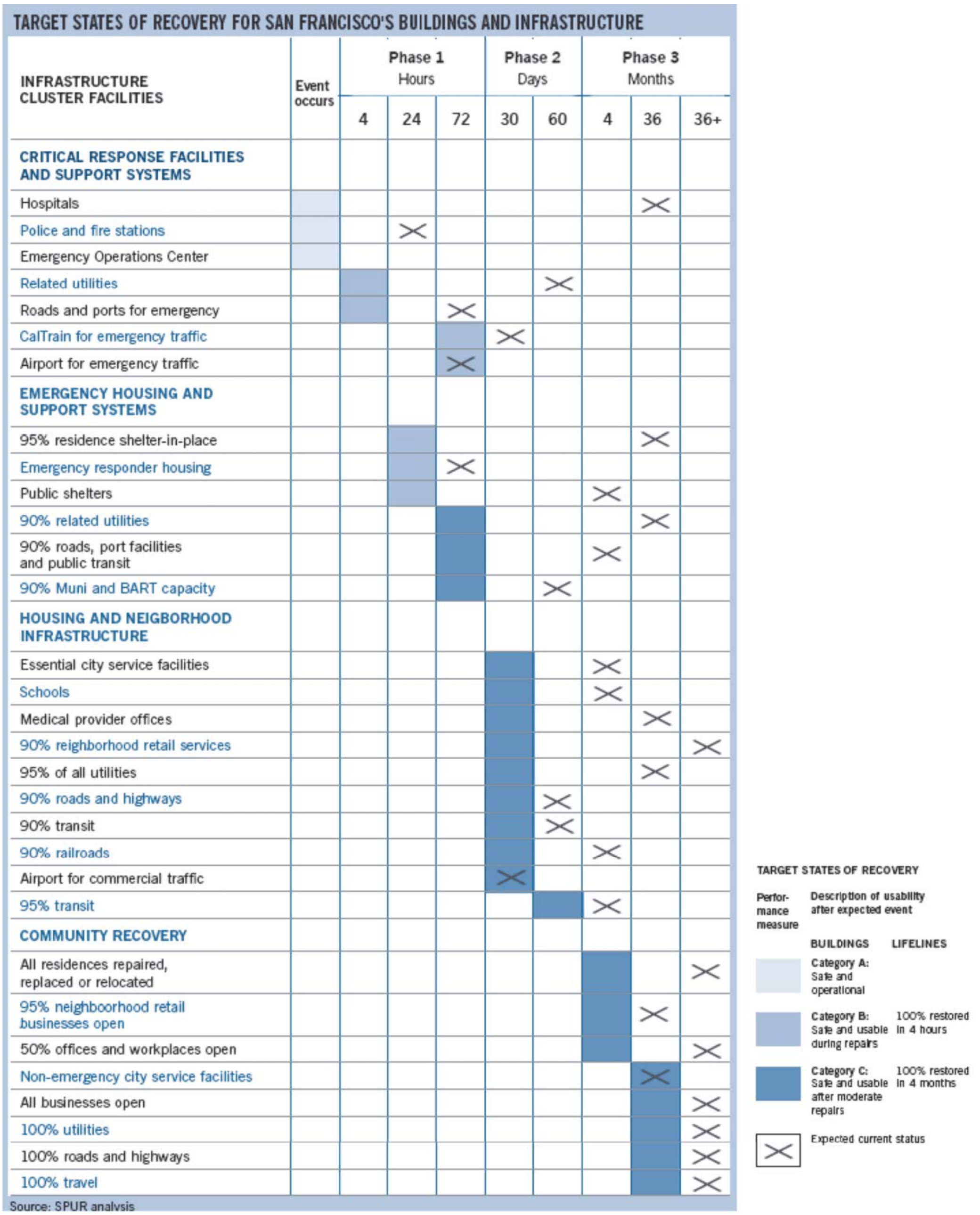
The first attempt at community seismic resilience planning was organized by the San Francisco Bay Area Planning and Urban Research Association (SPUR) (Poland, 2009). Experts from architecture, engineering, urban planning, and public policy planning firms were invited to work together to envision what would happen to the city after a high-magnitude earthquake. In this initiative, participants defined the concept of disaster resilience, selected a single city-wide expected earthquake scenario (10% occurrence in 50 years) as the community hazard level, established desired timeframes of recovery for buildings and infrastructure systems, estimated the anticipated resilience state for identified clusters of buildings and infrastructure systems, and provided recommendations for elected officials and community stakeholders. Comparing anticipated and desired resilience states identifies the gap between where the community is and where it should be (See Fig. 2.1). This concept has become more popular in similar studies. It should be noted that the current (anticipated) recovery timeframes were collaboratively estimated based on experts' judgment. This work inspired seismic committees in other states, and the procedure was followed by other community seismic resilience planning initiatives with some modifications.

2.3.2 Resilient Washington State (2010-2012)

In 2010, the Resilient Washington State (RWS) subcommittee of the Seismic Safety Committee under the Washington State Emergency Management Council launched a community seismic planning initiative for the state of Washington inspired by SPUR (WASSC, 2012). Since RWS held a statewide initiative, they referred to National Seismic Hazard Maps created by the U.S. Geological Survey (USGS) in 2008 to identify community hazard. RWS formed four groups consisting of critical services, utilities, transportation, and housing & economic development sectors, identified their components, and located experts from these sectors. They followed the SPUR procedure, identified community hazard, and presented desired and anticipated recovery timeframes for community entities. They also provided several recommendations for community policy makers and published their report in 2012.

2.3.3 Oregon Resilience Plan (2011-2013)

The Oregon Resilience Plan (ORP) was conducted as a community seismic resilience planning initiative in 2011-2013 by the Oregon Seismic Safety Policy Advisory Commission (OSSPAC) (OSSPAC, 2013). They considered a M9.0 Cascadia earthquake and tsunami as the community hazard for the state of Oregon. ORP consisted of eight task groups: Cascadia Earthquake Scenario, Business and Workforce Continuity, Coastal Communities,



TARGET STATES OF RECOVERY FOR SAN FRANCISCO'S BUILDINGS AND INFRASTRUCTURE

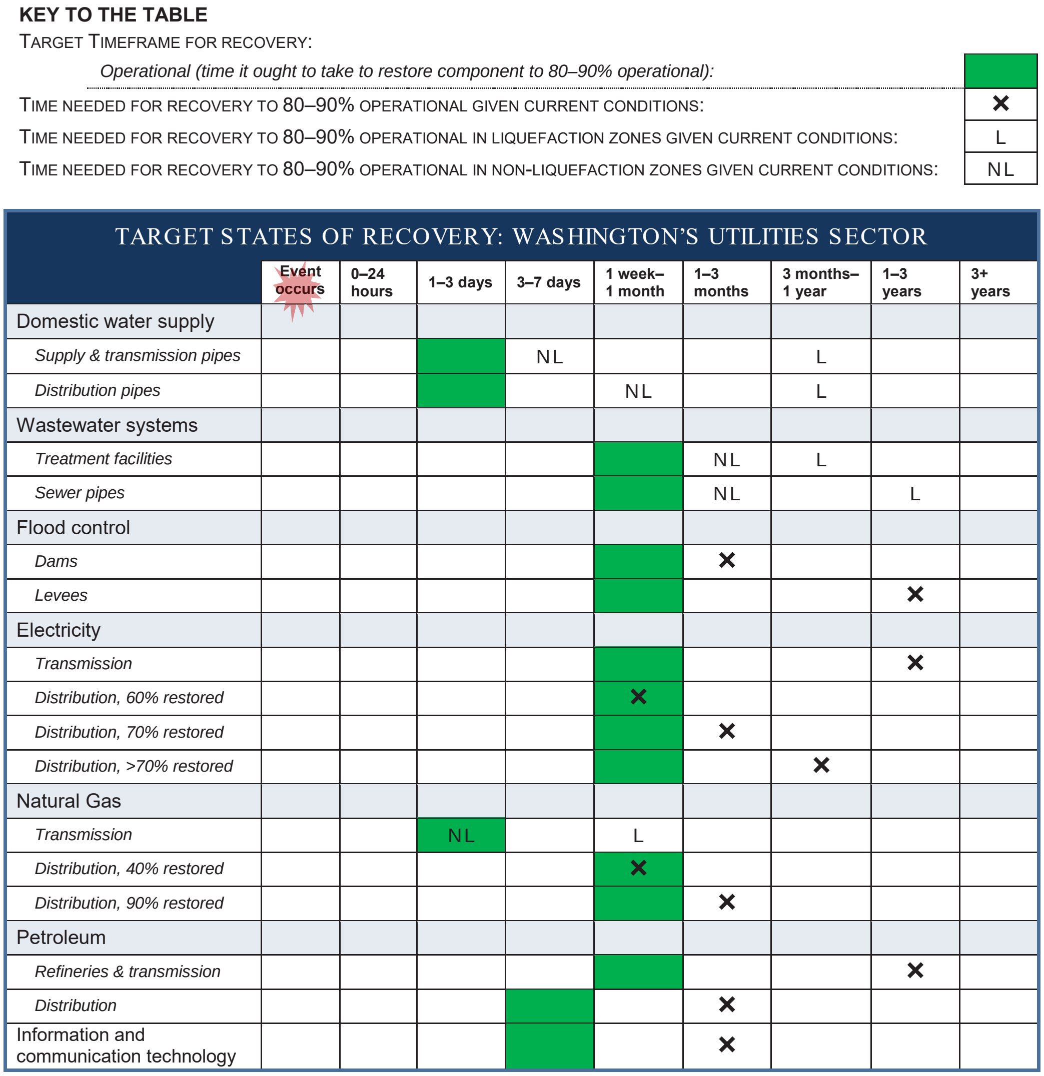
INFRASTRUCTURE CLUSTER FACILITIES	Event occurs	Phase 1 Hours			Phase 2 Days		Phase 3 Months		
		4	24	72	30	60	4	36	36+
CRITICAL RESPONSE FACILITIES AND SUPPORT SYSTEMS									
Hospitals	░							✕	
Police and fire stations	░		✕						
Emergency Operations Center	░								
Related utilities		▒				✕			
Roads and ports for emergency		▒		✕					
CalTrain for emergency traffic				▒	✕				
Airport for emergency traffic				▒ ✕					
EMERGENCY HOUSING AND SUPPORT SYSTEMS									
95% residence shelter-in-place			▒					✕	
Emergency responder housing			▒	✕					
Public shelters			▒				✕		
90% related utilities				▓				✕	
90% roads, port facilities and public transit				▓			✕		
90% Muni and BART capacity				▓		✕			
HOUSING AND NEIGBORHOOD INFRASTRUCTURE									
Essential city service facilities					▓		✕		
Schools					▓		✕		
Medical provider offices					▓			✕	
90% reighborhood retail services					▓				✕
95% of all utilities					▓			✕	
90% roads and highways					▓	✕			
90% transit					▓	✕			
90% railroads					▓		✕		
Airport for commercial traffic					▓ ✕				
95% transit						▓	✕		
COMMUNITY RECOVERY									
All residences repaired, replaced or relocated							▓		✕
95% neighboorhood retail businesses open							▓	✕	
50% offices and workplaces open							▓		✕
Non-emergency city service facilities								▓ ✕	
All businesses open								▓	✕
100% utilities								▓	✕
100% roads and highways								▓	✕
100% travel								▓	✕

Source: SPUR analysis

TARGET STATES OF RECOVERY

Performance measure	Description of usability after expected event	
	BUILDINGS	LIFELINES
░	Category A: Safe and operational	
▒	Category B: Safe and usable during repairs	100% restored in 4 hours
▓	Category C: Safe and usable after moderate repairs	100% restored in 4 months
✕	Expected current status	

Figure 2.1: The current and target recovery states for San Francisco's buildings and infrastructures (Poland 2009)



KEY TO THE TABLE

Target Timeframe for Recovery:

Operational (time it ought to take to restore component to 80–90% operational):	🟩
Time needed for recovery to 80–90% operational given current conditions:	✕
Time needed for recovery to 80–90% operational in liquefaction zones given current conditions:	L
Time needed for recovery to 80–90% operational in non-liquefaction zones given current conditions:	NL

TARGET STATES OF RECOVERY: WASHINGTON'S UTILITIES SECTOR

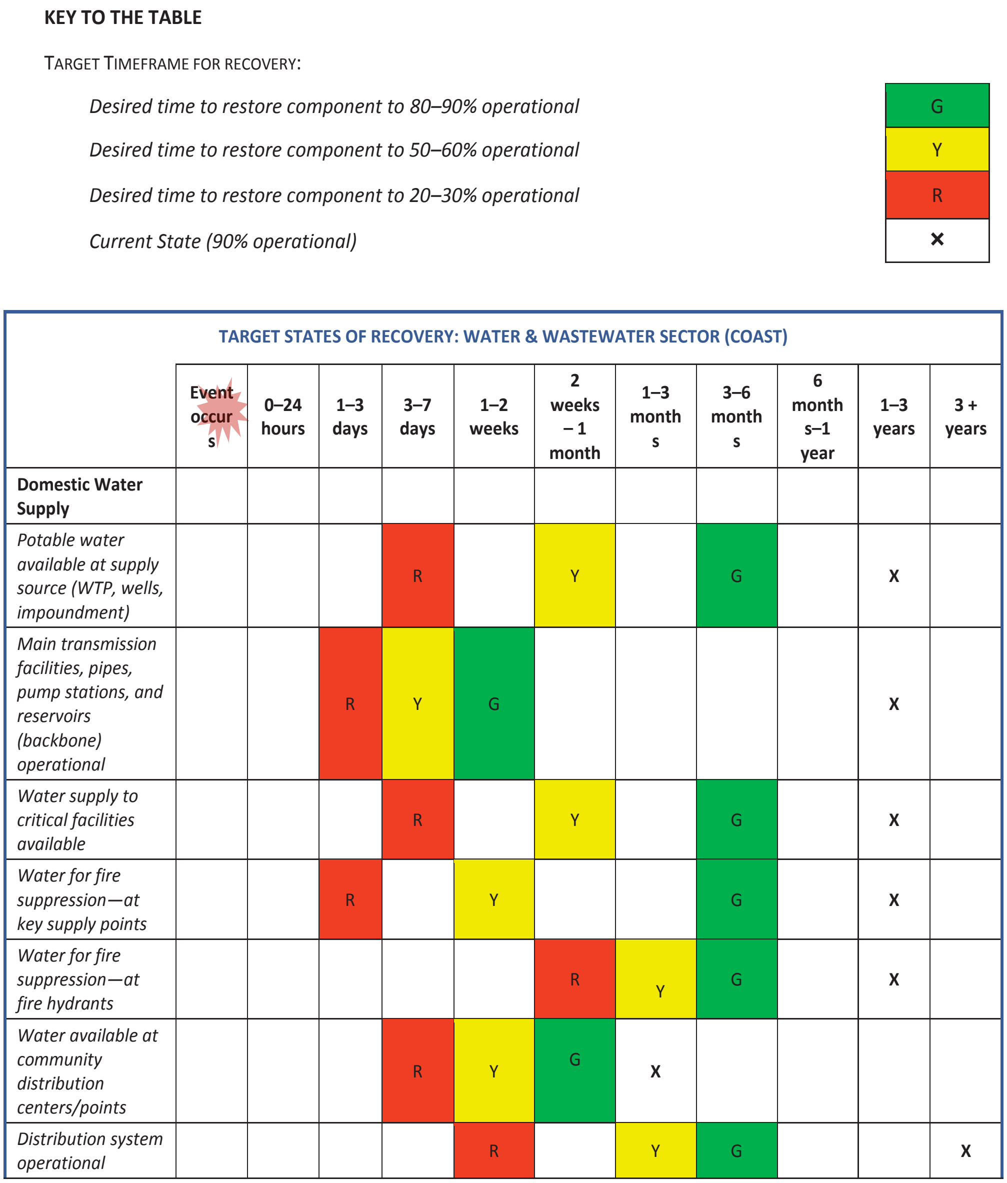
	Event occurs	0–24 hours	1–3 days	3–7 days	1 week–1 month	1–3 months	3 months–1 year	1–3 years	3+ years
Domestic water supply									
Supply & transmission pipes			🟩	NL			L		
Distribution pipes			🟩		NL		L		
Wastewater systems									
Treatment facilities					🟩	NL	L		
Sewer pipes					🟩	NL		L	
Flood control									
Dams					🟩	✕			
Levees					🟩			✕	
Electricity									
Transmission					🟩			✕	
Distribution, 60% restored					🟩 ✕				
Distribution, 70% restored					🟩	✕			
Distribution, >70% restored					🟩		✕		
Natural Gas									
Transmission			🟩 NL		L				
Distribution, 40% restored					🟩 ✕				
Distribution, 90% restored					🟩	✕			
Petroleum									
Refineries & transmission					🟩			✕	
Distribution				🟩		✕			
Information and communication technology				🟩		✕			

Figure 2.2: The current and target recovery states for Washington state's water and waste water system (RWS 2012)

Critical and Essential Buildings, Transportation, Energy, Information and Communications, and Water and Wastewater. The planning process was similar to that of SPUR and RWS, but more detailed and specific to the state of Oregon. Compared to the previous initiatives, ORP perspicuously appointed long-term community goals and social needs. They established desired recovery timeframes of community entities such that business continuity in the state would not be disrupted for more than two weeks to one month. The task groups considered this goal as a criterion to identify desired recovery timeframes (Fig. 2.3). As a result, the existing gaps between the anticipated state and desired state were well understood by community decision-makers and the initiative's audiences.

2.3.4 Community Resilience Planning Guide for Buildings and Infrastructure Systems by NIST (2016)

The National Institute of Standards and Technology (NIST) published a two-volume report, *Community Resilience Planning Guide for Buildings and Infrastructure Systems,* in 2016 examining these initiatives (NIST, 2016). This report brought community resilience planning to the forefront, with significant updates and details. Although the NIST report offered similar reasoning and conclusions as the initiatives themselves, it also provided valuable details on **how to proceed** with systematic community resilience planning. The NIST report identified community representatives who should be involved in planning. It also divided communities into the built environment dimension, including buildings and infrastructure systems, and the social dimension consisting of social institutions such as businesses, industries, and financial systems, and recommended identifying the characteristics of each dimension. More importantly, NIST suggested linking social functions with the built environment, a concept that was not explored in the existing initiatives. In this way, the relationships among numerous systems, in either the social or built environment, are well defined and the community is envisioned as it really is—an integrated whole rather than separate groups that function individually and independently. The NIST report highlighted dependencies and cascading effects, and presented a dependency matrix among infrastructure systems, which had not been explored by the three initiatives although they had noted



KEY TO THE TABLE

TARGET TIMEFRAME FOR RECOVERY:

Desired time to restore component to 80–90% operational	G
Desired time to restore component to 50–60% operational	Y
Desired time to restore component to 20–30% operational	R
Current State (90% operational)	✕

TARGET STATES OF RECOVERY: WATER & WASTEWATER SECTOR (COAST)

	Event occurs	0–24 hours	1–3 days	3–7 days	1–2 weeks	2 weeks – 1 month	1–3 months	3–6 months	6 months–1 year	1–3 years	3 + years
Domestic Water Supply											
Potable water available at supply source (WTP, wells, impoundment)				R		Y		G		X	
Main transmission facilities, pipes, pump stations, and reservoirs (backbone) operational			R	Y	G					X	
Water supply to critical facilities available				R		Y		G		X	
Water for fire suppression—at key supply points			R		Y			G		X	
Water for fire suppression—at fire hydrants						R	Y	G		X	
Water available at community distribution centers/points				R	Y	G	X				
Distribution system operational					R		Y	G			X

Figure 2.3: Desired and anticipated recovery timeframe in water and wastewater sector (OSSPAC, 2013).

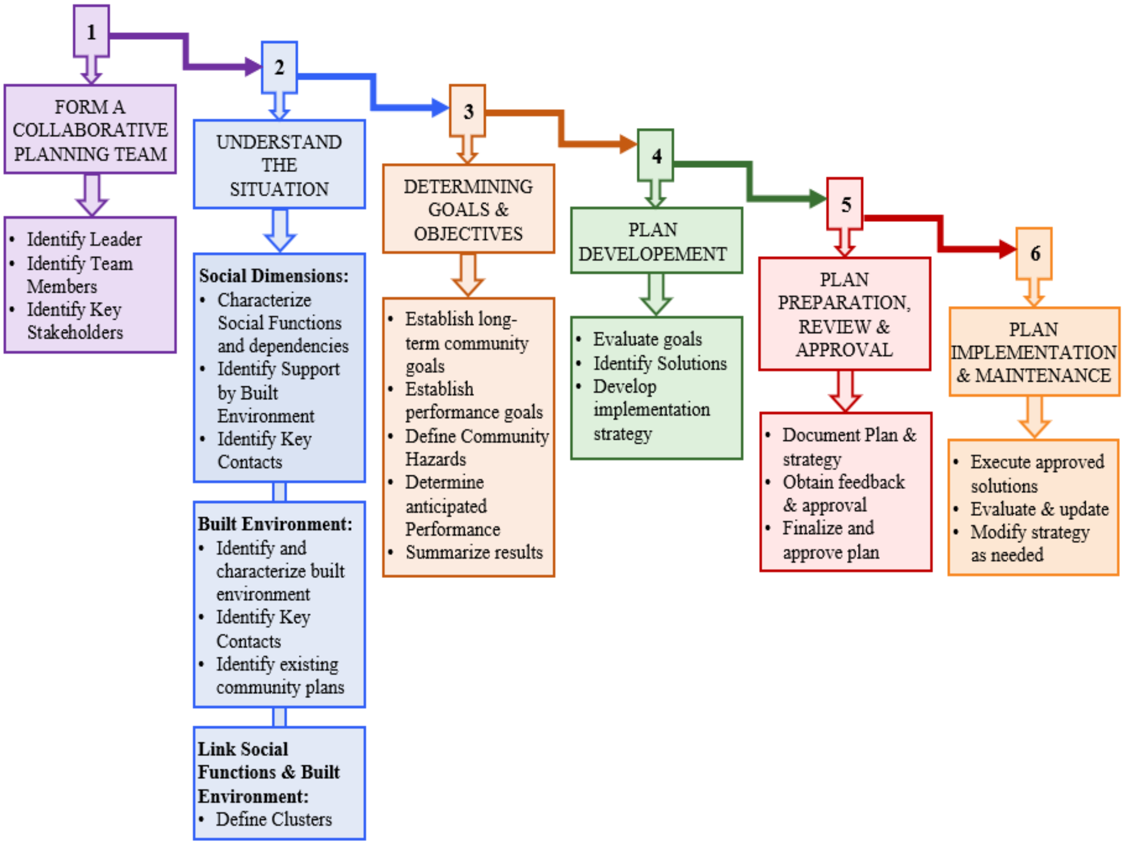


Figure 2.4: The NIST's six steps to perform collaborative community resilience planning.

its significant impact.

Community resilience planning has evolved based on the lessons learned from the planning initiatives, actual events, and research studies. Similarly, the process of resilience planning has been enriched by taking into account more influential concepts, parameters and dimensions, and defining relationships among them. In summary, NIST suggested following the steps presented in Fig. 2.4. Although community resilience planning has grown quickly and the NIST report presented it as a standard and unified procedure, undertaking planning in practice comes with wide variety of surprises and challenges. In this study, we look for challenges that participants in the community resilience planning initiatives experienced. We also discuss possible ways to overcome these challenges.

2.4 Methodology

As mentioned earlier, we examine two research questions in this study. First, we aim to identify challenges appeared in the community resilience planning initiatives, and second, we want to investigate how simulation modeling can help this process from the participants' perspective. For this purpose, we reviewed the procedures and conclusions of three initiatives and conducted semi-structured interviews with the initiatives' participants to learn about the process and observed challenges. Details on the interviewees, data collection, data coding and analysis approach are provided below.

2.4.1 Participants and Data Collection

I contacted several critical infrastructure agents and emergency managers who participated in the initiatives, described the purpose of the interview, and requested a 90-minute in-person meeting to learn about their experience in the initiatives. I invited interviewees from different initiatives to recognize similarities and differences. I also interviewed a manager of a critical infrastructure system who did not participate in any of the initiatives but had conducted several community resilience discussion meetings with experts in infrastructure systems. This interview was to include the perspective of an independent expert who did not participate in the initiatives. Overall, I conducted 90-minute semi-structured interviews with eighteen emergency managers, infrastructure and building experts, and researchers. Seventeen interviews were conducted in-person, and one interview was over the phone. Geographically, the interviewees were from California, Oregon, and Washington (five, seven, and six interviewees from each state, respectively). All interviews were recorded and transcribed with interviewee's permissions for further analysis except one interview where the interviewee did not grant permission to record the conversation. We relied on hand-written notes for that interview and included these notes in our qualitative content analysis. Interviews were voluntary and unpaid, and the interviewees were kind and welcoming. Interviews were conducted from May to September 2018.

2.4.2 Data Analysis and Qualitative Coding

Our data analysis was driven by open-coding thematic analysis. I applied line-by-line coding to five random interviews before establishing a codebook. Initial codes emerged from finding relationships based on the line-by-line coding. By establishing the initial codebook, we coded the entire dataset. For collaborative qualitative coding, we used Code Wizard as a collaborative coding tool (Ganji et al. 2018). Code Wizard consists of programmed Microsoft Excel spreadsheets. Code Wizard is free, appropriate for small to midsize teams and academic research projects, and does not require much training. I first coded the data individually and had another coder repeat the coding separately. Using Code Wizard, after each round of individual coding, we aggregated coded data, evaluated the Inter-Coder Reliability (ICR) coefficient, noted problematic codes, discussed the reasons for disagreement, and revised the codebook. We performed three rounds of coding to meet an acceptable ICR threshold (0.8). We coded data for two themes: (1) challenges and (2) opportunities for simulation modeling.

2.5 Challenges in Community Resilience Planning

Based on our qualitative content analysis, we present the main challenges in community resilience planning identified by the interviewees. We used the term **main** challenges because there were additional challenges mentioned in the interviews that we intentionally ignored. For example, a few issues occurred only in one of the initiatives and were not generalizable for other initiatives, and some other barriers taken place due to the logistics of holding meetings and time limitations.

2.5.1 Complex Network Systems

According to NIST, built environments that support community members and social community functions consist of infrastructure systems and buildings. Recovery of an infrastructure system to be able to provide services to consumers, regardless of its interdependencies with other systems, depends on two factors: (1) recovery of discrete damaged entities, and (2) the connections and dependencies among networked entities. Both factors should be considered in planning since ignoring either one results in a distorted and incomplete picture of the recovery process of infrastructure systems.

In the planning initiatives, participants formed task groups for infrastructure systems, and participated experts joined the groups based on their areas of expertise. Experts identified the main entities of each sector in the task group. Through technical discussions and aggregating experts' judgment, the task groups created anticipated and desired recovery time-frames for identified entities (see Fig. 2.3). Experts typically estimated damages and recovery time-frames based on community hazard intensity, liquefaction and landslide potentials, and type, material, and age of entities.

Experienced experts provided insightful information to estimate required time for recovery of single entities. This information can be used as a basis in community resilience planning. However, overlooking the network and interconnected structure of infrastructure systems underestimates recovery time-frames from the perspective of community members who need these services regardless of the recovery of single entities. System resilience depends on the level of redundancy that exists in the system. This redundancy is gained from the network system and its structure, not just entities. *[Interviewee #7:]"...in water systems, there's so much dependency that exists, you've got to restore this before you restore that, before you restore that, and similarly in capacity... if you're going to restore the distribution system, you have to have sufficient supply to be able to meet that, but there's no need to build the supply capacity any faster than you can build the delivery system to be able to meet those needs."*

Due to lack of appropriate tools, and limited time and budget, the network and dependencies in infrastructure systems were not considered in the planning initiatives. In order to make anticipated recovery timeframe estimates more realistic, the network system should be taken into account in future studies.

2.5.2 Interdependent Network Systems and the Cascade Effect

A damage in an infrastructure system may result in disruption of serviceability of many other systems. This phenomenon, referred to cascade effect, is also observed in the recovery process of interdependent systems. For example, the water system relies on electricity for running pump stations and back-up generators. Therefore, serviceability of the water system depends on not only the functionality of the water system itself, but on the power system as well. Similarly, recovery of both water and power systems is contingent on access to damaged entities, which makes recovery process of water and power systems dependent on recovery of transportation system. The significant impact of interdependencies among infrastructure systems and buildings was noted in the planning initiative reports and discussed in more detail in the NIST report. However, interdependencies have not been taken into account for estimating anticipated recovery timeframes of built environment in the planning initiatives.

[interviewee #10:] "there are significant interdependencies. It's hard to really comprehend to what level they are important. To me, power is the big one. What can happen until power is restored? Not a whole lot...you probably can have some restorative construction happen without power, but even that's a challenge. Everything relies upon power, and how resilient is the power. What are those interdependencies, does that back everything else up in recovery?"

2.5.3 Inter-Organizational Collaboration

In addition to the domain-oriented characteristics presented above, community resilience planning is challenging due to its inter-organizational nature. For example, infrastructure systems and buildings are managed by different agencies, companies, and organizations with dissimilar procedures, priorities, and goals. Even a single infrastructure sector might be managed by multiple companies and decision-makers. Planning to make a community resilient entails all decision-makers from different organizations coming to agreement on how to proceed and what goals to pursue. Time needed for a community to recover after a disaster depends on the efficiency of experts' collaboration. For example, achieving desired recovery time-frames requires experts and managers in companies that are part of the power system (if there are multiple companies providing electric service for the community) to know how to plan for resilience to achieve these goals and how different policies might affect resilience of the entire community. Therefore, inefficient and ineffective inter-organizational collaboration is a big challenge in community resilience planning.

[Interviewee #2:] "In the power system, for example, there are multiple power system providers and they each have their own proprietary information, and probably many of them have done studies. [A company in infrastructure system] has studied some of their things, [another company in infrastructure system] has probably studied some of theirs, maybe they haven't studied everything, but a real challenge is getting access to that information, for starters."

Similarly, interviewee #4 explains other challenges that emerge when decision-makers and stakeholders are from the public and private sectors and comply with different regulations:

[Interviewee #4:] "[infrastructure] is public and private, that's the important thing. Almost none of it is purely public, and so [...] there is proprietary information that those private sector companies hold close and have a right to hold close. And so, there are regulatory agencies, there's the utility and transportation commission, and they will honor their right to proprietary information. They try to work out planning with them, but some of it, for instance, even though you might say you want the hospital to come back first, [...] depending on the way the power outage happened, it may be that you have to fix something somewhere remote to there, because you also have to figure out how to bring the system back, and just bringing back one small branch of the system, even if it does feed the most vulnerable sector, may not do you the most good if bringing back a major substation gets you the most bang for your buck in the first twelve hours. And how they make that decision, again, is private."

2.5.4 Connections between Social Institutions and Built Environment

Citizens and community members found social institutions to address their needs. NIST categorized social institutions in eight groups: (1) family/kinship; (2) the economy; (3) government; (4) health; (5) education; (6) community service organizations; (7) religious, cultural, and other organizations that support belief systems; and (8) the media. While the goal of community resilience is closely tied with the recovery of social institutions, these institutions themselves rely on functionality of the built environment (including infrastructure systems and buildings). Consequently, desired recovery timeframes for the built environment are established based on social needs. Social and built environments are connected in community resilience planning and it entails identifying "links between social functions to the supporting built environment" (NIST 2016: V.1:8). The importance of identifying these links has been gradually recognized in the community resilience planning initiatives.

The NIST report devotes an entire chapter to identifying these links. However, the three initiatives, while recognizing the importance of identifying these links, did not really consider these links to estimate anticipated or desired recovery timeframes. NIST and the planning initiatives present desired and anticipated recovery timeframes for the built environment by percentages of functionality of systems entities. For instance, the desired recovery time for functionality of 80-90% of distribution pipes is determined 1-3 days in Washington state (WASSC, 2012). The desired time to restore 50-60% of electric transmission lines in the "non-tsunami coast zone" in Oregon was determined 1-3 weeks (OSSPAC, 2013). However, it is not clear how these timelines have been assigned to support social institutions and community members where connections between the built environment and the social dimension are lacking. As another example, the ORP defines the desired recovery timeframes of infrastructure systems such that businesses, as a social entity, would not experience disruption in having infrastructure services longer than two weeks. Imagine a hypothetical scenario in which 60% of electric transmission lines have been recovered in two weeks (determined as desired recovery timeframe in ORP), but business institutions are relied on the 40% unrecovered systems. In other words, although the desired recovery timelines for the built environment may be met, it is not certain whether or not businesses would receive services from the built environment in two weeks.

[Interviewee #6:] "I think the other biggest shortcoming was there was not the opportunity to go through and say, "here is an integrated set of recommendations drawn from each of the areas that together get us the furthest down the line to resilience and . . . address the question of what's the appropriate sequencing and balancing of these things."

It should be noted that connection and dependence between the social dimension and built environment is mutual. While we described how recovery of the social dimension depends on the built environment, recovery of the built environment also relies on social dimensions. For example, recovery of infrastructure systems or buildings is executed by experts, crews, engineers, and infrastructure managers. As community members, they need social institutions such as healthcare and finance/economic institutions to be able to first survive and then participate in the recovery process.

[Interviewee #7:] "... their experience [New Orleans Water and Sewer Board] was so revealing to me. When [Hurricane Katrina] happened, they had all of this flooding, they had all of these facilities out. More than half of their workforce did not come back to work, and so how can you restore the system and establish service to the community if you don't have the workforce necessary to be able to do anything more than basically keep the lights on? [...] I can't just take just anybody and put them on a backhoe and tell them how to repair a pipe. I need trained people who are able to respond to this event and aid in the restoration and recovery of our water system. [...] The other thing I want to leave you with is it goes way beyond just infrastructure. I touch on obviously the people part of it, and that's key, but the business operations side of what we do is equally important, and again, water is a wonderful example as a utility, but it's true with most every other lifeline with the exception of maybe transportation. Somebody has to pay the bill. And so, if we're out of business, we're not sending out bills, we're not collecting revenue, we're not paying out bills, and pretty soon... the good news is I can restore the water system, but I can't pay for the fuel because nobody will take my credit card. I can't pay the electric bill to run the pumps that I need, and so I don't have the ability to run a business, to be able to sustain this organization, to cut paychecks to the people that I need so desperately to be able to repair the pipes."

2.5.5 Communication and Information Sharing between Experts in Built Environment and Social Institutions

Built environment experts such as managers, agents and decision-makers in infrastructure systems and social stakeholders involved in the planning must work together closely. As mentioned earlier, NIST states that decision-making for recovery planning is based on social needs and community goals. Since social dimension like social institutions depend on the built environment to be functioning, experts on the both sides must communicate to share required information. In addition to identifying physical connections and dependencies between these dimensions, collaboration and communication between stakeholders in these two groups are challenging for community resilience planning.

[Interviewee #13:] "So, as we move into thinking about resilience, which is about more than the structure, it's about the occupancy, it's about more than one building, it's about the organization like a community. We have to be open to working with other groups, and this is a challenge, because those other groups never heard from us, in fact they're much bigger than us. They don't want to really hear engineers, and they have almost no patience."

One important aspect of this collaboration and communication is prioritization, which is challenging step in community resilience planning. Prioritization is inevitable due to time and resource limitations, and potential conflicts in community recovery. Communities have similarities but are completely different in terms of their built environment structures and social needs and cultural differences. Therefore, as NIST concludes, there is no global priority list or gold standard for decision-making in community recovery planning, and priorities should be determined in a community-to-community basis. It underlines the significance of needs to strengthen collaboration, communication and information sharing among decision-makers from any dimension.

[Interviewee #7:] "... there are competing needs for limited resources. How as a community do we prioritize those limited resources to be able to meet the needs of the recovery, to be able to get recovery balanced and do it in a way that limits loss of life and expedites the overall recovery process? This is so challenging."

2.5.6 Information Sharing and Communication between Experts and Community Members

This category of challenges in community resilience planning came as a surprise in our interviews. The final audience of community resilience planning initiatives is members of the community and their elected officials. Executing the decisions made in community resilience planning is a very costly and lengthy process that requires the support of the community. Experts in community planning share information with community decision-makers, elected officials, community policy makers, and finally community members. They aim to inform community members and decision-makers about the hazards that threaten their community and warn them about potential consequences of such disasters. They also envision the community's preparedness to resist and bounce back after the expected disaster and point out the gaps between the current and desired states of preparedness. Making a community resilient requires a budget and resources which are usually obtained from taxpayers. Resilience planning cannot successfully proceed if community members do not properly understand its importance and support long-term investments in it.

[Interviewee #10:] "So, [this is] all state taxpayers' money going in to support this grant program to get this money out. Some of the successes and challenges associated with getting the grant program up and running, included people who didn't understand why it was important to have safe schools... schools' job [is to] educate, not to do seismic mitigation of schools. So, there was a really big learning curve for [...] really a lot of people."

Considering the notes above, communication with the wider community is challenging because it has its own complexities and requires specific types of skills, especially when people have incorrect perceptions about the likely post-disaster condition.

[Interviewee #6:] "I think it was not well understood on the part of the public... [T]hat was one of the most important things that the resilience plan did was really put some parameters on it that the public could access, and I think that a lot of the public perception in the past had either been "oh, it's not going to be that big of a deal, I don't need to worry about it" or "it's going to be the end of the world, so why should I worry about it, there's nothing I can do, everything is going to be completely destroyed." Some of the commentary that came out from Tohoku, and some of perceptions that people got from the New Yorker article kind of fueled that notion of "oh my god, it's going to be this total disaster and nobody's going to survive, there's no point in preparing." And the resilience plan, I thought, the clearest message of it was "pretty much everybody is going to survive, and you're going to get up the next morning and not going to be able to flush the toilet for three months. That's going to be your problem." That's what we have to address, is that massive disruption to everyday life that is going to make it very difficult to live here, and certainly going to make it very

difficult to continue to be employed here. And so . . . although at the time I felt like we're just doing this, engineers are just kind of guessing in terms of the damage and they tend to guess conservative when put in those kinds of situations, I think it still ended up with the right overall message which is "this is going to be really difficult, but there are things you can do to solve, to fix it, and move ahead with it."

2.6 Facilitating Community Resilience Planning by Simulation Models

Reviewing the reports published after the planning initiatives and based on the interviews, we noticed that other than Hazus, which was used limitedly for damage and loss estimations, no analytical computer-based tools have been used in any planning initiatives. For example, estimating anticipated recovery timeframes of damaged community entities are computationally challenging tasks in the planning initiatives. However, use of analytical computer-based tools such as simulation models was lacking in the planning process.

Simulation models are nowadays used in numerous fields such as engineering, urban planning, and supply chain management. The capability of simulation modeling to improve different phases of emergency management is widely recognized in research communities like Information Systems for Crisis Response and Management (ISCRAM). Similarly, in practice, Federal Emergency Management Agency (FEMA) emphasizes the importance of tools in emergency management, noting that "innovative models and tools" are one of three strategic needs to accomplish recovery planning (FEMA, 2012). Simulation modeling is also used in community resilience. The interviewees were asked about how simulation modeling could help them in community resilience planning. It should be noted that most of the interviewees had experience or knowledge about simulation modeling and its capability in community resilience planning. For other interviewees who had no experience, background or information in using simulation models in this field, we shortly explained how simulation modeling works and provided some examples from the literature. We analyzed their answers and categorized their responses based on the codebook that we had established to identify the challenges since (1) we could maintain the consistency of presented concepts for our audiences, and (2) we could benefit from the details provided by interviewees to understand what tasks and functionalities are needed to handle by simulation modeling in this process.

The interviewees' responses reveal what limitations and challenges can be addressed by simulation modeling and where simulation models can facilitate them. In the following, we present the benefit of using simulation modeling to address each category of identified challenge.

2.6.1 Complex Network Systems

As discussed previously, infrastructure systems are complex networks. In such complex systems, it is extremely difficult to predict how recovery proceeds and when these systems would be able to provide services to others, including community members, social institutions, and other dependent infrastructure systems. Simulation modeling has the capability to consider this complexity, and many research studies have used simulation modeling to simulate the post-disaster recovery process of infrastructure systems and housing as mentioned in background section. The interviewees also mentioned that simulation modeling would be helpful in community resilience planning.

[Interviewee #5:] "I believe if there were modeling tools available to estimate downtime, the connectedness, and the dependencies of the different lifeline sectors, . . . and how doing certain fixes would improve the rapidity of getting things up and running quickly, I think it would help with building resilience and mitigation projects."

Simulation modeling also makes planning much easier if experts would like to update data. If a simulation model is already set, new updates in system entities taken place over time can be simply applied to the model to adjust outputs accordingly.

[Interviewee #8] "And a tool would be nice to have, something where [... it] allows you to improve the data. So, you can put in with what you know, understanding your margin is bigger, but as you get better data, that comes around [...] that can be updated and give you better results."

[Interviewee #12] "we need to figure out the things that we can't work around after the disaster ... that's what the days, weeks and months are about, to identify how much time they can have to get something going again but do that kind of simulation so that you can understand what you can work around."

2.6.2 Interdependencies Among Infrastructure Systems

The advantage of using simulation models to capture the complexity of system interdependencies in community resilience planning was mentioned by the interviewees more than other simulation modeling capabilities. Simulation modeling has been widely used to simulate interdependencies among critical infrastructure systems in urban planning.

[Interviewee #7:] "simulation modeling would really be critical to illustrate this interdependency effect . . . and again, I had not noodled through it, everything, when I give this talk at many different seminars, I talk about interdependencies and how everything is connected to everything."

[Interviewee #14:] "If there was a way to facilitate the collaboration over the issue of interdependence, right, if there was a way to synthesize the data that reflects the way one system depends on another, and then use that to run scenarios."

[Interviewee #2:] "I think, what you're talking about [possibility of using simulation modeling], in terms of being able to model those interdependencies, [is] very valuable, and then being able to communicate that, again, to the community, to our power providers, and having redundant systems, redundant load paths to bring power into the community, that's the ultimate goal."

2.6.3 Inter-Organizational Collaboration

Planning for community resilience is highly collaborative. Experts need to collaborate with each other since organizations have their own plans, policies, and priorities, but their decisions impact other groups' planning. This collaboration is difficult to facilitate when several organizations are involved; this is another area where simulation modeling can be used, as it can facilitate information sharing among experts.

[Interviewee #11:]"So the kinds of things that I want to see [if I had simulation models] are probably more rooted to other infrastructures, you know, the buildings, roadways, bridges [...] if I had to then bring resources in, it would also give me an idea of what I might be able to work with there. [...] But if I can't get from here to there, if there's something blocking, today I can't plan on that."

2.6.4 Connecting Social Institutions and Built Environment

As discussed earlier, a significant challenge in community resilience planning is connecting built environment entities and social institutions because they mutually rely on and support each other. This is extensively described by NIST due to its critical impact on planning. However, these connections and links were not identified and considered in detail in the planning initiatives due to their extreme complexity. Simulation models can be incorporated to facilitate community resilience planning in this regard. The interviewees also mentioned this and provided some details of what they expect from simulation models to help them.

[Interviewee #8:] "If you could have a model and say "what would be the outcome if we fixed up the road system first" or what would be impacted, any buildings, there would be a lot of URM [Underrepresented Minority]. You know, what would be our payback for looking, solving, retrofitting all of our URMs versus... To be able to ask some of these questions, when these things come up for planning purposes, this is where we really ought to be ..."

2.6.5 Communication between Built Environment and Social Institutions Experts

Experts in built environment and social institutions need to communicate and share information to make sure that decision-making comprehensively considers both dimensions and their limitations. Simulation modeling can improve this communication by simulating recovery processes based on different scenarios and providing the consequences of these scenarios for experts to analyze. Since community resilience deals with many dimensions in a community, it is likely to overlook consequences that are critically important for some experts or decision-makers. Simulation modeling helps experts to quickly and inexpensively see how the recovery process changes based on their decisions.

[Interviewee #14:] "just thinking about this idea of scenario-based thinking, if there's a way to help people sort of wargame the way these things play out. "Here's what it looks like now. We wargame. We run an exercise. We get some results. We make changes. We do it again. Hopefully we're even closer. By seeing what changes, we need to make, we're getting closer." So that kind of simulation might be intriguing."

As well, simulation modeling can help prioritize decision-making. It can provide timelines, expenses, and, more importantly, social impacts of decisions made. As a result, decision might be changed if inappropriate consequences threaten community values.

[Interviewee #8:] "One of the questions that there's no really good tool for saying, for doing scenario planning. [...] you accepted that this is risk, so what do you do with all of that? So, how much does it cost you to do all of that stuff, over what amount of time? Where should I put my dollars? What should I do first? What should I do second?" [Interviewee #2:] "So, we're just coming up with a time, but what's not in there, I always call this the five percent problem, the standard for restoration is always ninety-five percent, but who is the five percent that doesn't get the power, and that we stop caring once we're at ninety-five percent? I want to know, you know, because I did the study in [a community in the U.S.] where I found that Hispanic populations literally were restored slower than white populations."

2.6.6 Information Sharing and Communication between Experts and Community Members

Effective communication and information sharing between experts and non-expert community members, or non-expert elected officials, is necessary in community resilience planning. Study participants and interviewees drew attention to the benefit of simulation modeling in this regard and mentioned how it can improve this process.

[Interviewee #7:] "I think it [community resilience planning] depends on what the community's values are going to be, but it's a tremendous opportunity to have that conversation in advance [...] a tool like what you're talking about in terms of simulation allows conversation with the board or the public or the decision makers to happen in advance, so that when the event occurs you've got some guidance in terms of how to work"

[Interviewee #7:] "More importantly, in many respects, as you go through this system planning process and the investments in the infrastructure over time to build the hardened backbone and harden the facilities, your system investments are consistent with those values and the ability to make the restoration in that kind of priority sequence."

2.7 Discussion

In this study, we identified the challenges associated with the previous community resilience planning initiatives taken place in California, Washington and Oregon. For this purpose, we interviewed experts, critical infrastructure managers, and emergency management agents who participated in the initiatives. Due to the capability of simulation modeling to address the challenges mentioned in the research studies (Ganji and Miles 2018; Miles et al. 2018), we asked the interviewees to share their opinions about how simulation modeling would support the planning initiatives and presented the findings in the previous section.

Simulation modeling is widely used in community resilience, emergency management and disaster recovery. Simulation modeling has been evolved through various approaches including (1) resource-constrained modeling, (2) machine learning, (3) dynamic economic impact modeling, (4) system dynamics simulation, (5) agent-based simulation, (6) discrete-event simulation, (7) stochastic simulation, and (8) network modeling (Miles et al. 2018). Several research studies used simulation modeling in disaster recovery of various elements of communities such as water and wastewater system (Tabucchi et al. 2010), power systems (Çağnan et al. 2006) and housing recovery (Longman and Miles 2019; Burton et al. 2017; Miles and Chang 2011). It shows the capability of simulation modeling to capture complexity of these network systems mentioned as the first challenge by the interviewees. The next challenge, the interdependencies among critical infrastructure systems, is also addressed in the literature of urban planning (Turoff et al. 2016; Banuls et al. 2013; Ouyang 2014). Integrating the built environment including buildings and critical infrastructure systems and social institutions, the forth challenge, is applied in simulation modeling of disaster recovery process (Ganji and Miles 2018).

While simulation modeling can address the first, second and forth challenges, other challenges are user-oriented and human-factors are involved. Human-centered design has the potential to address the user-oriented challenges. Human-centered design considers the concerns, values, and perceptions of all stakeholders in design of simulation models in a problem-solving process (Baxter and Sommerville 2011). Ganji and Miles (2018) presented a conceptual framework of characteristics of disaster resilience and recovery planning in two main categories including domain- and user-oriented characteristics. They argued how combining human-centered design and simulation modeling is capable to overcome not only domain-oriented challenges, but also user-oriented challenges, and developed human-centered simulation modeling as a conceptual framework for such models.

Chapter 3

TOWARD HUMAN-CENTERED SIMULATION MODELING FOR CRITICAL INFRASTRUCTURE DISASTER RECOVERY PLANNING

Abstract

Critical infrastructure is vulnerable to a broad range of hazards. Timely and effective recovery of critical infrastructure after extreme events is crucial. However, critical infrastructure disaster recovery planning is complicated and involves both domain- and user-centered characteristics and complexities. Recovery planning currently uses few quantitative computer-based tools and instead largely relies on expert judgment. Simulation modeling can simplify domain-centered complexities but not the human factors. Conversely, human-centered design places end-users at the center of design. We discuss the benefits of combining simulation modeling with human-centered design and refer it as human-centered simulation modeling. Human-centered simulation modeling has the capability to make recovery planning simpler and more understandable for critical infrastructure and emergency management experts and other recovery planning decision-makers. We qualitatively analyzed several resilience planning initiatives, post-disaster recovery assessments, and relevant journal articles to understand experts and decision-makers' perspectives. We propose a conceptual design framework for creating human-centered simulation models for critical infrastructure disaster recovery planning. This framework consists of three constructs: 1) user interaction with design features that end-users interact with, including model parameters assignment, decision-making support, task queries, and usability; 2) system representation that refers to system components, system interactions, and system state variables; and 3) computation core that represents computational methods required to perform processes.

3.1 Introduction

Critical infrastructure is vital to the functioning of communities; however, it is also vulnerable to a broad range of hazards. Critical infrastructure is required to stay functional, mitigate hazard impacts, or be minimally damaged during and in the aftermath of disasters (Church et al. 2004; Matthews and Matthews 2013; Bruneau et al. 2003). In practice, however, disasters often damage various components of critical infrastructure that are outdated and poorly maintained. Timely and effective recovery of critical infrastructure after extreme events is crucial. Recovery "involves the actions taken in the long term after the immediate impact of the disaster has passed to stabilize the community and to restore some semblance of normalcy" (Altay and Green 2006). Major disruption of a sector of critical infrastructure and its recovery time-frame may impact the performance and recovery of other sectors greatly. Effective recovery entails understanding various aspects of the critical infrastructure disaster recovery process, such as vulnerability, recovery management, and recovery time-frame of damaged components.

The complexity of the recovery process makes it difficult for decision-makers to clearly understand the process, highlighting the need for better tools to better understand the process. The Federal Emergency Management Agency (FEMA) emphasizes the importance of tools in emergency management, noting that "innovative models and tools" are one of three strategic needs to accomplish recovery planning (FEMA Jan. 2012)[1]. A well-known example of such a tool is Hazus, which was created by FEMA as "a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes" (FEMA 2011)[2]. There is a lack of such tools for pre- or post-event disaster recovery planning. Recovery planning currently uses few quantitative computer-based tools and instead largely relies on expert judgment.

In last ten years, several resilience planning initiatives in the U.S. have brought experts in critical infrastructure and emergency management together. The purpose of these initia-

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[1] Strategic Foresight Initiative. "Crisis Response and Disaster Resilience 2030: Forging Strategic Action in an Age of Uncertainty." The Federal Emergency Management Agency (FEMA), January 2012

[2] FEMA. "Hazus: FEMA's methodology for estimating potential losses from disasters." (2011).

tives was to provide recommendations for decision-makers to shorten the recovery process. This included collaboratively estimating target recovery timeframes and expected recovery timeframes of infrastructure systems subjected to potential hazard scenarios. Although the initiatives were successful in gathering many experts from different disciplines to undertake collaborative resilience planning and offer extensive recommendations, analytical computer-based tools were rarely used to facilitate the planning process or associated decision-making (Poland 2009; Barkley 2009; WASSC Nov. 2012; WASSC Sep. 2010; WASSC Feb. 2012; OSSPAC Feb. 2013). This is not surprising given the lack of such analytical computer-based tools that have the potential to aid experts and decision-makers in collaborative recovery planning.

In this Chapter, we aim to propose a conceptual design framework for development and design of analytical human-centered simulation modeling to aid in critical infrastructure recovery planning. The framework is based on the characteristics of critical infrastructure disaster recovery planning, and the desires and limitations of experts and decision-makers. We first investigate characteristics of critical infrastructure disaster recovery planning. We then introduce human-centered simulation modeling as a paradigm for creating analytical computer-based tools for this purpose. We discuss why this approach has potential to effectively support and improve collaborative planning for critical infrastructure disaster recovery. Subsequently, we describe in detail the conceptual design framework for development and design of human-centered simulation modeling for recovery planning. This framework is based on a qualitative analysis of literature on disaster recovery from end-user's perspective and can be used for creating simulation modeling for end-users to promote and facilitate recovery planning.

3.2 Characteristics of Critical Infrastructure Disaster Recovery Planning

Understanding critical infrastructure disaster recovery planning and shedding light on its complexity is essential. We discuss important characteristics of critical infrastructure recovery planning in three increasingly focused levels: 1) critical infrastructure in general and as a system, 2) critical infrastructure disaster recovery as a process, and 3) critical infrastructure disaster recovery planning.

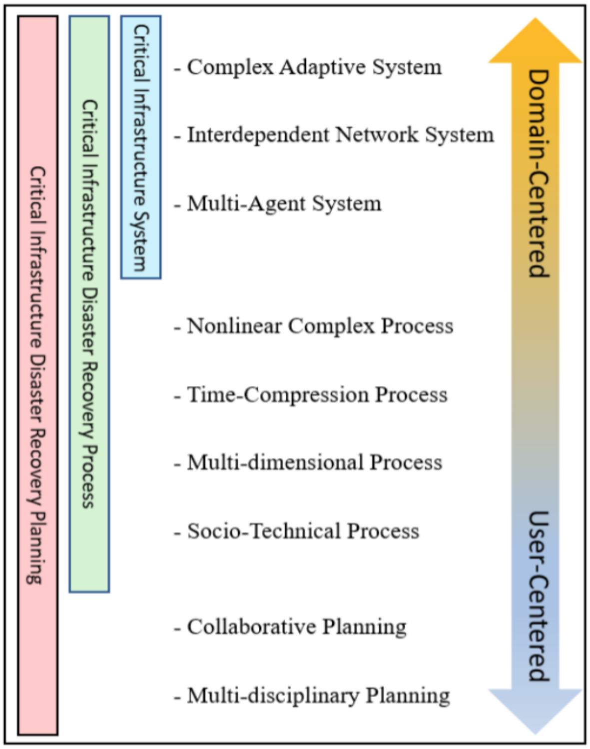

Figure 3.1: Characteristics of critical infrastructure disaster recovery planning

As can be seen in Fig. 3.1, the characteristics of critical infrastructure disaster recovery planning can be located along a spectrum, with the two ends of domain- and user-centered aspects. The upper characteristics in Fig. 3.1 are more domain-centered and the lower ones are more user-centered. Domain-centered aspect represents the characteristics of critical infrastructure and its recovery process that are less impacted by human factors. User-centered aspect, on the other end of the spectrum, focuses on the characteristics that are heavily influenced by human factors.

3.2.1 A: Critical Infrastructure as a System

Critical infrastructure systems are irreplaceable services and required capital to offer those services (Miles 2015; Brand 2009). Services are defined as “the link between capitals and their benefits to communities” (Miles 2015). The major characteristics of critical infrastructure systems are discussed below.

A.1: Complex Adaptive System: When a system is not complex, it is likely that an analyst would be able to predict the consequences of a change in the system. A large-scale system contains smaller systems within it, which are referred to as subsystems. As the number of subsystems and interrelationships increases, especially if the relationships in the system are nonlinear and adaptive, the system becomes too complicated to be easily understood. This is considered a complex system (Bruijn & Herder 2009). The consequences of changes in inputs are unpredictable in such cases. Critical infrastructure systems are complex adaptive systems since "they are all complex collections of interacting components in which change often occurs as a result of learning process" (Rinaldi et al. 2001).

A.2: Interdependent Network System: There is remarkable evidence of infrastructure interdependency in the real world, cited in literature that demonstrates how a failure in one component causes several unanticipated degradations of other infrastructure sectors (Panzieri & Setola 2008; and . Pederson, et al. 2006). Critical infrastructure sectors are complex networks on their own, but even more complex when considering dependent and interdependent relationships with other sectors. Rinaldy et al. (2001) divide interactions in critical infrastructure into dependency and interdependency. A dependent relationship is a unidirectional "linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other." An interdependent relationship is bidirectional, meaning the state of each infrastructure correlates to the state of the other and the two depend on each other. Critical infrastructure interdependencies are categorized into four groups: physical, cyber, geographical, and logical (Rinaldi et al. 2001).

A.3: Multi-Agent System: Critical infrastructure involves many agents from various organizations at different levels such as federal, state, county, and city, and is managed and controlled by public and private organizations. Critical infrastructure systems are interconnected, and individual agents' performance and decisions affect the entire network's performance. Agents act independently due to having potentially different goals and priorities. Thus, it is essential to take into account the multi-agent nature of critical infrastructure when planning for recovery to ensure that agents are able to cooperate to set and reach global goals with minimal supervision (Amin 2001; Pipattanasomporn et al. 2009).

3.2.2 B: Characteristics of the Critical Infrastructure Disaster Recovery Process

For the purposes of this Chapter, recovery is a long-term process that can be defined as returning to normal or reaching a better or new situation (Bruneau et al 2003; Quarantelli 1999). The main characteristics of critical infrastructure disaster recovery are provided below.

B.1: Nonlinear Dynamic Process: Disaster recovery is a nonlinear, unorderly, and dynamic process aimed at restoring the community to its normal pre-disaster conditions by reconstruction of damaged components. Recovery is a time-dependent process such that its timeframe does not change proportionally to input variables change (Jordan & Javernick-Will 2013).

B.2: Time-Compressed Process: In normal conditions, a low rate of loss of capital services is observed due to infrastructure components reaching the end of their life cycle and being replaced. However, unusually large and immediate loss of capital services occurring due to disasters results in an unusual increase in the rate of new capital services, with a corresponding increase in decisions, information flow, financing, and institutional formation. This increased pace of activity distinguishes the disaster recovery process from the normal process of replacing outdated capital services (Olshansky et al. 2012). This situation "opens unusual opportunities for reorganizing or relocating capital facilities. Strategies of replacement may become available that would not be worth pursuing at normal rates of capital replacement" (Olshansky et al. 2012).

B.3. Multi-dimensional Process: Efforts have been made to explore, theorize, assess, and analyze recovery of sectors of critical infrastructure independently, such as built environment (Mieler et al. 2015), business and economic (Marshall & Schrank 2014; Chang et al. 2012), social (Nakagawa & Shaw 2004; Aldrich & Meyer 2015), health care (Camilleri et al. 2003), transportation system (Tierney 2009), water and sewer system (Matthews & Matthews 2013; Matthews 2016), and electric system (Xu et al. 2007). However, critical infrastructure is heavily interdependent. The recovery process of a dimension of critical infrastructure impacts the recovery process of other dimensions. For example, recovery of the drinking water system depends on recovery of the power system because the former simply needs electricity to function. This makes critical infrastructure disaster recovery a multi-dimensional process (Campanella 2006; Cimellaro 2011). Multi-dimensional recovery also causes different rates of recovery in different dimensions (Wein et al. 2011).

B.4. Socio-Technical Process: Critical infrastructure should be considered a socio-technical system (Ottens et al. 2006), meaning that it has both a social and technical condition and there is a reciprocal relationship between its human and technical aspects such that "efficiency and humanity would not contradict each other" (Ropohl 1999). Critical infrastructure disaster recovery is influenced by these technical and social aspects. Government agencies, social communities, and politicians impact the recovery process, for example by allocating resources and determining priorities. This interaction between the social and technical is observed in the aftermath of disasters, both in the short-term (emergency response) and in the long-term phases of recovery (Leavitt 2006). Leavitt and Kiefer (2006), for instance, provided the human and political impacts on the critical infrastructure recovery failure that occurred after Hurricane Katrina due to decision-makers not understanding the technical complexity of infrastructure interdependency.

3.2.3 C: Critical Infrastructure Disaster Recovery Planning

Planning for critical infrastructure disaster recovery takes place by diverse groups of experts and stakeholders, who are not necessarily experts in all or any sectors of critical infrastructure. Planning for disaster recovery adds additional complexity that must be addressed when creating simulation modeling.

C.1: Collaborative Planning: Collaborative planning is engagement of government stakeholders, public and private business stakeholders, and community and organizational stakeholders in the process of planning. Collaborative planning can facilitate information sharing among stakeholders and the community, enhance decision-making, and raise the "community's ability to work toward collective goals" (McAllister 2015). Experts in critical infrastructure and emergency management have undertaken several initiatives to envision resilience and recovery timeframes and provide recommendations to governmental decision-makers in the U.S. (McAllister 2015) These initiatives have emphasized the highly collaborative nature of resilience planning. The National Institute of Standards and Technology (NIST) recommends forming a planning team as the first step toward community resilience planning for buildings and infrastructure systems (McAllister 2015).

C.2: Multi-disciplinary Planning: Because critical infrastructure systems and their recovery are multi-agent and multi-dimensional, recovery planning is required to be multi-disciplinary (Chang 2010; and Mileti 1999). Multi-disciplinary planning gathers experts from diverse areas of expertise. These experts may have different technical languages and terminologies, priorities, and criteria. They also possibly have unequal levels of truthfulness and familiarity with analytical computer-based tools.

3.3 Toward Human-Centered Simulation Modeling

The purpose of this Chapter is to offer a conceptual design framework for creating computer-based analytical tools, such as simulation models, for critical infrastructure disaster recovery planning. These tools are required to be usable and understandable by critical infrastructure and emergency management experts who participate in recovery planning. In this Chapter, we refer to them as “end-users.” To this end, we discussed the main characteristics of critical infrastructure disaster recovery planning, sorted along a spectrum with domain- and user-centered ends (Fig. 3.1). This list grounds the foundation of the conceptual design framework. It also indicates the complexities of recovery planning that require computer-based tools to address. Accordingly, we build our framework in two steps to consider both aspects.

3.3.1 Simulation Modeling to Capture Domain-Oriented Dimension

Simulation modeling is capable of capturing the domain-centered characteristics of critical infrastructure recovery planning shown in Fig. 3.1. Simulation modeling of critical infrastructure explicitly represents the behavior or functioning of such networked and interdependent systems. It enables modelers to manipulate system details and explore the influence of different system characteristics. Simulation modeling is widely employed for modeling of critical infrastructure systems and their interdependencies (Pederson, et al. 2006; Ouyang 2014). It has been used to simulate different sectors of critical infrastructure disaster recovery such as power systems (Çağnan et al. 2006; Ouyang & Duenêas-Osorio 2012), water systems (Tabucchi et al. 2010), and transportation networks (Lee & Kim 2007). Simulation modeling is also used for modeling interdependencies among infrastructure systems for modeling restoration in the aftermath of extreme events (Ramachandran et al. 2015).

In general, the end-user's needs, expectations, and limitations are poorly addressed in the critical infrastructure recovery simulation modeling literature. Simulation models can be challenging for decision-makers, emergency managers, and critical infrastructure experts to comprehend (Miles 2011). End-users may have inadequate familiarity with and experience in using simulation modeling. Additionally, the ease of collaboration with other end-users affects how comfortable and willing they are to use simulation modeling.

3.3.2 Human-Centered Design to Capture User-Oriented Dimension

The literature on socio-technical system design can help address this gap for designing simulation models for use in critical infrastructure recovery planning. Socio-technical system design is aimed at promoting, improving, and using the characteristics of socio-technical systems in system design, and has been developed in different ways over time (Mumford 2006). Baxter and Sommerville (2011) provide seven categories of socio-technical system design approaches: 1) Soft system methodology, 2) Cognitive work analysis, 3) Socio-technical method for designing work systems, 4) Ethnographic workplace analysis, 5) Contextual design, 6) Cognitive systems engineering, and 7) Human-centered design. Baxter and Sommerville (2011) analyzed the seven approaches based on how well they cover three phases of the systems engineering life cycle—analysis, design, and evaluation—and a set of principles defined for their study (Baxter & Sommerville 2011). They conclude that human-centered design is best suited for socio-technical system design.

Human-centered design is "a process of assuring that the concerns, values, and perceptions of all stakeholders in a design effort are considered and balanced" (Rouse William 2007). It facilitates innovative approaches for identifying and incorporating human (user) needs in the process of problem-solving. Norman (2013) states human-centered design is “the process of ensuring that people’s needs are met, that the resulting product is understandable and usable, that it accomplishes the desired tasks, and that the experience of use is positive and enjoyable’ (Norman 2013). Human-centered design is an iterative process that involves potential end-users throughout the development process. Functionally, human-centered design is often conducted in a process that repeats four overlapping steps until user needs are effectively met. These four steps are user research, prototyping, usability testing, and implementation.

While simulation modeling can capture domain-centered features to enable emergency management and critical infrastructure experts to undertake system and process monitoring and decision-making, human-centered design can be incorporated in the model development process to improve the usability of simulation models for end-users. We propose to combine human-centered design and simulation modeling and refer to this synthesis as human-centered simulation modeling.

3.4 Human-Centered Simulation Modeling Design Framework

We discussed the characteristics of recovery planning and the capability of human-centered simulation modeling for supporting critical infrastructure recovery planning briefly in previous sections. However, more information and details of end-users’ concerns regarding recovery planning is needed to form and extend the conceptual design framework. In this section, we lay out a conceptual design framework for developing human-centered simulation models. This design framework aims to describe the design components required to develop human-centered simulation models.

3.4.1 Data Sources for Framework Design

For this purpose, we collected and reviewed relevant data from three sources: 1) resilience planning initiatives, 2) post-disaster recovery assessments, and 3) research articles. We then qualitatively analyzed them to understand potential end-users’ points of view related to the recovery and recovery planning. The collected data are briefly introduced below.

I. Resilience planning initiatives: Three initiatives have taken place in the U.S. in the last ten years to envision seismic community resilience on the state or city scales: the

San Francisco Bay Area Planning and Urban Research Association (SPUR) Resilient City initiative, Resilient Washington State (RWS), and the Oregon Resilience Plan (ORP). These initiatives are valuable sources of information. They were performed by experts, managers, and decision-makers who would be the potential end-users of human-centered simulation models for critical infrastructure disaster recovery planning. Resilience planning is heavily connected to and has much in common with recovery planning, especially the pre-disaster recovery planning phase. Reviewing the initiatives provides insights into the objectives, concerns, and limitations of end-users (Poland 2009; Barkley 2009; WASSC Nov. 2012; WASSC Sep. 2010; WASSC Feb. 2012; OSSPAC Feb. 2013).

The initiatives commonly aimed to establish and present the target recovery timeframe of various components of the community subjected to the expected seismic hazard, and estimate expected recovery timeframes of potentially damaged components. They also offer recommendations to improve community seismic resilience. The initiatives organized focus groups, for example a transportation group, and categorized the participants into these groups based on their areas of expertise. Each group or sector presented target and estimated expected recovery timeframes of services and components of the group. These estimates were obtained from debates, discussions, and participants' judgement. Noticeably, no analytical computer-based tools such as models were used in the resilience planning process. This shows the potential for using human-centered simulation modeling to support resilience and recovery planning (Poland 2009; Barkley 2009; WASSC Nov. 2012; WASSC Sep. 2010; WASSC Feb. 2012; OSSPAC Feb. 2013).

II. Post-disaster recovery assessments: Another source of understanding real-world recovery processes and experts' perspectives is post-disaster recovery assessment reports published after investigation of post-disaster recovery of infrastructure disruptions. These after-action recovery assessments are usually prepared for governmental departments to assess efficiency of recovery processes and provide recommendations for infrastructure system operators to be prepared for future disasters. These documents are beneficial for our purposes because they assess practical planning operations performed by emergency managers and infrastructure system agents. These reports offer recommendations from various agents and organizational collaborations and identify the need for creating and using appropriate tools for damage assessment, recovery monitoring, and decision-making (Southern California Edison reports 2011, and 2012; Entergy New Orleans, Inc. 2013; Entergy Louisiana reports 2013; Davies Consulting 2012; Westport Fire Department 2012; U.S. Department of Commerce 2012).

III. Research articles: Emergency management and infrastructure experts' experience is also addressed in research articles. Although we found representations of agents, practitioners, participants, and decision-makers to be poor in research studies, several articles do provide relevant information. We reviewed abstracts of papers published in and after 2000 in the journals *Natural Hazards* Review and *Earthquake Spectra* and identified articles that presented the experience and concerns of end-users. These studies investigate end-users via interviews and participatory studies, or by presenting frameworks for tools and usability testing (Fothergill 2000; Hecker 2000; Roy & Claire 2000; Flax et al. 2002; Uddin & Engi 2002; Allouche & Bowman 2006; Gillespie et al. 2004; Lindell et al. 2007; Wald et al. 2008; Perry et al. 2011; Liel et al. 2013; Chang et al. 2014; Holand 2015; Little et al. 2015; Nastev et al. 2017 and Unal & Warn 2017).

We conducted qualitative content analysis of the literature described above to create a human-centered simulation modeling design framework shown in Fig. 3.2. Three main constructs emerged from the qualitative analysis are: user interaction, system representation, and computation core. Collectively, the three constructs include 11 elements, which are described below.

3.4.2 User-Interaction

User interaction addresses design features that the end-user interacts with in human-centered simulation models. This construct has four elements, comprising model parameter assignment, decision-making support, task queries, and usability, as summarized in Table 3.1. The model parameters construct consists of three components: (a) hazard status parameters that provide hazard information such as scenario, size of disaster, and aspects of disaster (e.g., earthquake, liquefaction, landslide, hurricane, flood); (b) system status parameters such as vulnerability and resilience of components, damaged components and level of damage,

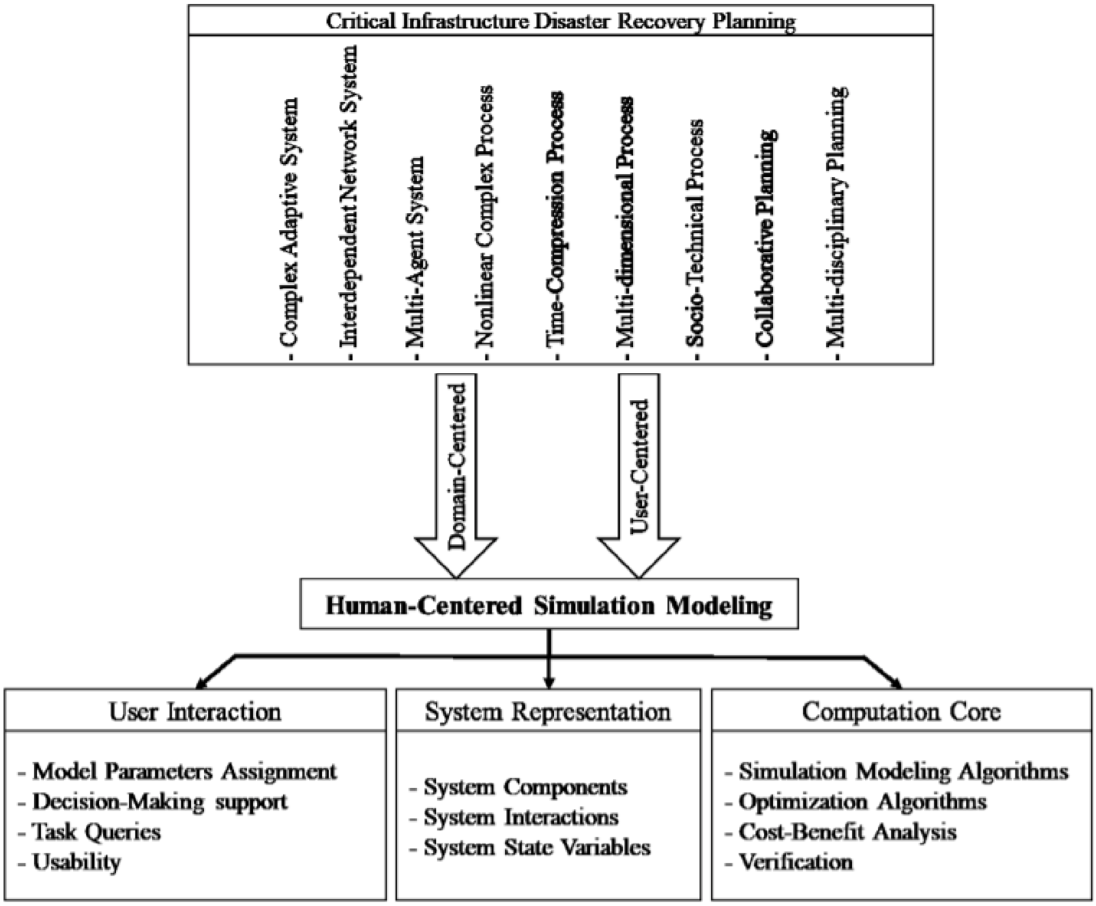

Figure 3.2: Conceptual design framework of human-centered simulation modeling for critical infrastructure recovery planning

time, cost, and resources required for recovery of damaged components, type of clients, and number of impacted clients; and (c) resource parameters that define system resourcefulness such as number of available crews, budget, materials, etc.

Decision-making support represents features that support the end-user's decision-making to prioritize and target goals built upon prioritization and target recovery time-frames. Prioritization represents features that enable the end-user to prioritize the recovery process. The end-user may plan to prioritize recovery of specific clients. For example, an end-user might desire to first recover critical buildings such as hospitals, or to prioritize damaged components whose recovery would provide services to more people. Also, target recovery time-frames of damaged services may be determined differently based on the end-user's decision-making.

Task queries point out information that the end-user desires to track within the recovery process and consists of time-variant indicators, critical path, and comparative analysis. Time-variant indicators enable the end-user to track desired recovery indicators over time such as recovery timeframes of components, sectors, or an entire modeled system; budget, cost, and resources over time; and social indicators. Critical path identifies critical recovery paths based on desired criteria such as finding the closest recovery path that provides services to a client or the least expensive path to recovery of selected clients. Comparative analyses facilitate end-user's comparison of the consequences of different parameters or decisions such as cost-benefit analysis, sensitivity analysis, and scenario analysis.

Usability represents the ease of use and learning by the end-user, including data navigation (e.g., simplicity of import and export of data with different formats, appropriate and understandable visualizations), help bar (e.g., memo, tutorial, item definition, guide documents), and knowledge transferability (i.e., transferability of organization and distribution of knowledge from researchers and tool developers to end-user and improvement of end-user's communication).

3.4.3 System Representation

“System” refers to entities, components, networks, and interconnections of a modeled infrastructure sector. Systems in this framework can be used for any type of infrastructure systems such as built or social systems. Systems can be conceptually broken down into system components, state variables, and interactions. System components represent (a) entities of systems under consideration such as electric power entities, water system entities, clients, and geographical information of entities, and (b) resources involved with the recovery process for damaged systems, such as time, cost, crews, and material required. System interactions illustrate connections between components categorized into (a) in-sector interactions, which represent network and directivity of connections in a sector, (b) cross-sector interactions, referring to interdependencies between two different sectors, and (c) system state variables that refer to the state of components and entities such as the functionality of an electric substation, recovery time-frame of a component, or the available budget.

3.4.4 Computation Core

To perform desired tasks and produce outputs of modeled systems, computational algorithms are required to be implemented in simulation modeling. Computation core consists of processes as “mechanisms by which the system and its components make the transition from one state to another over time. Processes dictate how the values of the involved components’ state variables change over time” (O’Sullivan- page 5). As discussed earlier, simulation modeling has the capability to simulate processes in critical infrastructure disaster recovery and estimate time-frames of variable changes. Computation core contains numerical methods to determine the required time, budget, and resources for recovery of a damaged component or sector. It also includes optimization algorithms to support optimal values such as minimum time and resources and optimal number of crews required for recovery. Cost-benefit analysis entails implementation of computational algorithms in this regard. The critical path for recovery of targeted components or clients can be determined by implementation of appropriate shortest path methods depending on the type of directivity of connections. Similarly, evaluation of system resilience from a redundancy perspective entails employing corresponding computational methods. Finally, another aspect of computation core that has been frequently mentioned by potential end-users as a necessity is verification of results of human-centered simulation models by simulation of a previous real-world disaster recovery experience.

3.5 Conclusion

Disaster recovery planning for critical infrastructure is complex and heavily reliant on expert judgement. In this Chapter, we presented its characteristics based on a spectrum of domain- and user-centered dimensions. We discussed the capability of human-centered simulation modeling to simplify the recovery planning process for decision-makers. We created a conceptual design framework for design and development of human-centered simulation modeling. This framework consists of three constructs. User interaction represents design features for end-users to interact with simulation modeling. It enables end-users to assign desired parameters of hazard status, system status, and resources in models. System representation indicates components, interactions, and state variables of modeled systems. Lastly, computation core contains computational algorithms to perform processes and analyses, and produce desired outputs. This framework helps human-centered simulation modeling developers be informed about the components required to be incorporated in the design and development of models to support end-users. It is worth noting that the use of the framework is focused on planning for recovery of damaged components of communities. However, recovery planning comprises other various aspects that do not fit in this framework such as damage assessment, inter-organizational decision-making hierarchy, public awareness and engagement, and so on. Future studies may explore other aspects of recovery planning and the potential for creating computer-based tools to facilitate those aspects.

Chapter 4

RESOURCE-AWARE DISCRETE-EVENT SIMULATION TO IMPROVE POST-DISASTER INFRASTRUCTURE RESTORATION MODELING

Abstract

There is a lack of infrastructure restoration modeling methodologies in the literature that can flexibly represent complex resource dynamics, particularly that are resource-aware, process-based, and multi-state. We developed a process-based discrete-event simulation modeling methodology that is topologically-explicit and resource-aware. We applied this methodology to simulate restoration of a hypothetical electric power network as a case study. Using this case study, we conducted sensitivity analyses of damage intensity, local and non-local crew availability, local and non-local supply availability, and budget allocation using Monte Carlo simulation. Purchasing additional surplus supplies does not shorten restoration above a certain threshold. Faster arrival times of non-local crews does not significantly reduce total restoration time, but does notably increase the resilience of the network (i.e., higher initial rate of restoration). This methodology can support emergency managers and infrastructure managers to make plans and decisions related to resources investments and timing (e.g., for mutual aid contracting) with more detailed representation of resource dynamics.

4.1 Introduction

Critical infrastructure systems, such as water, wastewater, gas, and electricity are vulnerable to regional hazards because of inadequate design, poor maintenance, age, or dependence on other systems, with the potential for extensive damage. Prolonged disruptions in critical infrastructure services can cause negative social and economic consequences, such as widespread business closures. Effective community disaster recovery is often contingent on efficient restoration of damaged infrastructure. These issues emphasize the importance of better understanding and improving infrastructure restoration and finding ways to improve restoration.

There are a range of different modeling methodologies used in research and practice to provide insights into infrastructure restoration. Computational modeling is increasingly popular and potentially effective means for understanding and improving critical infrastructure restoration. The use of modeling to investigate infrastructure systems' restoration and their interdependencies has significantly grown in the last decade (Miles et al. 2019). Infrastructure restoration models exist for representing water and wastewater systems (Choi et al. 2018; Chmielewski et al. 2016; Tabucchi et al. 2010), natural gas systems (Ameri and van de Lindt 2019), electric power (Panteli andMancar ella 2015; Xu et al. 2007; Çagnan et al. 2006) and transportation networks (Liu et al. 2020; Bhatia et al. 2020). Infrastructure restoration models have been developed to characterize interdependent infrastructure systems' restoration (Almoghathawi et al. 2019; Guidotti et al. 2016; Ramachandran et al. 2015; Karakoc et al. 2019). Several studies have been conducted using restoration models to understand how to optimize restoration processes, including interdependent infrastructure systems (Lin and El-Tawil 2020; Alemzadeh et al. 2020; González et al. 2017; Xu et al. 2007). Some other studies investigated planning and decision-making for infrastructure restoration by modeling agent's interactions (Talebiyan and Duenas-Osorio 2020; Eid and El-Adaway 2017).

Infrastructure restoration models can characterize the dynamic between physical damage, service disruption, temporary service provision, and permanent system repair. Infrastructure restoration models can represent restoration processes generically (i.e., applied to multiple types of systems) or specific to different types of infrastructure systems. Restoration models can help comprehend the complexities of critical infrastructure systems and how to improve their performance. Ultimately, restoration modeling should inform pre- and post-event policy, planning, and programming to minimize the amount of time customers have to go without the services infrastructure systems provide.

Access to resources, such as money, replacement parts, and repair crews, heavily affects the speed of restorating services and repairing damaged entities, such as electric substations. After extreme events, the resources available for restoration are constrained. In such situations, the resources that do not suffice for the entire restoration process, or its availability and dynamics makes restoration too long. Consequently, infrastructure managers order and transfer resources from non-local sources, while their availability timelines and costs are significantly different, impacting restoration considerably. However, there is a lack of methodologies to represent this issue in infrastructure restoration modeling.

We developed a discrete-event simulation modeling methodology that is topologically-explicit and resource-aware. It is intended to better represent, relative to existing methodologies, infrastructure management and decision support objectives related to resource dynamics, which were determined through a prior study by the authors (Ganji et al. 2019). We synthesize relevant literature on infrastructure restoration modeling and resource dynamics in the following section. In the subsequent section, we describe the discrete event simulation methodology for modeling infrastructure restoration. For demonstration, verification, and sensitivity analysis, we outline a case study of applying this methodology to model a hypothetical electric system and simulate its restoration. We performed a sensitivity analysis of the implemented model using the case study to understand the influence of varying damage and resource variables. After describing the approach and results of this analysis, we provide interpretation of the findings and discuss the significance of the new methodology. We conclude the chapter with a description of limitations and recommendations for future work.

4.2 Modeling Complex Resource Dynamics in Infrastructure Restoration

Availability and allocation of resources are critical factors in infrastructure restoration. After extreme damaging events, local resources often do not suffice for restoring damaged infrastructure. In such conditions, infrastructure restoration requires resources from non-local sources, often through mutual aid agreements. Repair crews are an example of such a resource. Some crews work at agencies or companies within a jurisdiction. These crews are immediately available and their quantity is not likely to fluctuate much because they can stay until they complete repairs. When damage is extensive, local crews are insufficient, and restoration requires non-local crews. These crews join the restoration later, their numbers may fluctuate, and they typically leave before the restoration is completed. Similarly, utility organizations have limited surplus parts and supplies for maintenance. For extensive damage, the surplus will be insufficient and non-local supplies are required. Transporting non-local supplies takes longer and induces additional costs, particularly when time or resources are constrained. This dynamic between local and non-local resource availability affects infrastructure restoration performance and strategies. Exploring the impact of time-dependent resource availability entails simulating the process, scheduling, resource allocation and restoration of functionality of impacted infrastructure systems. Therefore, infrastructure restoration simulation models used for this purpose should address the following objectives (Ganji et al. 2019): a) complex time-dependent availability of multiple types of resources, b) dependencies within and between infrastructure networks, and c) process modeling. In this section, we provide a brief overview of different methodologies for modeling infrastructure restoration. We offer a limited critique of these methodologies in support of our proposed methodology.

Miles et al. (2019) categorized restoration modeling methodologies into seven categories: resource-constrained, system dynamics simulation, agent-based simulation, discrete-event simulation, network modeling, machine learning, and stochastic modeling. These methodologies are not mutually exclusive and might be applied individually or conjointly for restoration modeling, as is proposed in the following section. Resource-constrained models aim to sequence a set of activities in the least amount of time, while accounting for precedence requirements and limited resource availability. System dynamics simulation represents complex systems behavior as a result of interactions between interconnected stocks (entities that can be accumulated or depleted) and flows (entities that make stocks increase or decrease). Agent-based modeling simulates complex systems as the behavior emerging from actions and reactions between autonomous agents with distinct decision criteria. Discrete-event simulation (DES) models systems as a sequential and parallel transactions associated with distinct events that change the states of entities within the system. Network modeling uses topological graph structures to represent entities (nodes) and their relationships (arcs). Machine learning techniques–the simplest being linear regression–identify patterns empirical to categorize other data or make predictions. Stochastic modeling is a sample-based method that uses probability distributions to represent the influence of randomness on a system's behavior.

There is a lack of infrastructure restoration modeling methodologies in the literature that can flexibly represent complex resource dynamics, particularly that are resource-aware, process-based, and multi-state (e.g. functionality). Although resource-constrained modeling can represent the influence of resource availability it does not represent discrete entities and state changes of those entities. It is difficult to apply to highly complex systems, with many activities, precents, and types of resources. System dynamics simulation is also not effective at representing diverse state changes of interacting entities, except for conflating resources and entities. Pure agent-based models are not good at representing resource dependencies and interactions, while processes cannot be defined apriori (instead are emergent). Discrete-event simulation, as originally conceived, does not account for shared resources or represent interacting processes. Network modeling alone is limited in how it can represent dynamic processes, particularly those governed by resource constraints and prioritization of entity interactions. To develop and train models machine learning requires large and diverse empirical datasets, which are not common for large system restoration after extreme events (but increasingly so). More importantly, machine learning is not capable of representing system dynamics. Stochastic modeling requires empirical data to define probability distributions or they must be assumed or conceptually grounded. Stochastic modeling on its own is not appropriate for representing multi-state, entity-based systems.

Specific research has addressed several of the limitations described above to represent infrastructure restoration processes, resource dynamics, and (inter)depencies. Almoghadawy et al. (2019) proposed a resilience-driven multi-objective restoration model to maximize the system resilience. They applied a single-type time-invariant resource in their model. Lin and El-Tawil (2020) developed a simulation framework that connects nine types of simulators representing nine different steps of restoration of interdependent infrastructure systems. Simulators are in charge of simulating hazard, damage and recovery processes. They investigated the impact of interdependencies among water, gas and electric systems through a case study. Although they applied different resource availability scenarios, the resource limits were fixed during simulated restorations. Ameri and van de Lindt (2019) developed a DES model to examine the restoration of a natural gas system in a virtual community known as Centerville. Similar to the previous studies, they also used an invariant resource to represent crew availability. Talebiyan and Duenas-Osorio (2020) studied agent decision-making through post-disaster restoration of interdependent networks. They proposed optimization-based decentralized decision-making methods. They showed that availability of resources impacts not only the restoration process but also agent decision-making. However, they also applied a single-type time-invariant resource for each infrastructure system. The limitations described above make it difficult to gain insight into several questions. For example: what if the number of crews becomes halved or doubled after three weeks? How many non-local crews are needed to join the process and for how long? How does surplus supplies, available inside impacted communities, impact restoration? Shin et al. (2018) developed a resource-aware discrete-event simulation methodology but not applied to infrastructure restoration.

4.3 Methodology and Implementation

This section describes the modeling methodology that we developed to meet the infrastructure restoration modeling objectives described in the previous section. The methodology synthesis aspects of approaches described above into a new process-based discrete-event simulation (PBDES) framework that is resource-aware and topologically-explicit (Figure 4.1). The framework can be applied to model different types of networked infrastructure, such as water, wastewater, natural gas, electric, and communication systems, as well as the interdependence between them. Elements of the PBDES consist of entities (e.g., lift stations), entity attributes (e.g., pumping capacity), entity states (e.g., damaged), time-limited processes (e.g., repair), events (e.g., mutual aid request), and (competitive or non-competitive) resources (e.g., repair crew).

Process interactions between entities and resources are conceptualized as discrete events. The specific entities and entity attributes depend on the particular type of modeled infrastructure system. All entities in the PBDES have four possible sequential states: damaged, processing (e.g., under repair), functional (but no service), and operational (to provide service). The occurrence of events depends on completion of processes and or availability of sufficient resources. There are three general types of resources: budget (i.e., available funds), supplies (e.g., spare transformer) and crew (e.g., line workers). The PBDES can represent dynamically changing resource constraints, with entities competing for those constrained resources. The state change of one or more entities results in the triggering or interruption of one or more processes, as well as the modification of one or more resources. There are three processes: supply transport, crew transport, and entity repair. The duration of the transport processes depends on if the resources are available locally (or not) and type (e.g., high- vs. low-voltage transformer). The duration of repair depends on the entity type and level of damage.

There are six possible events in the PBDES: supply requests, supply allocation, funds request, fund allocation, crew request, and crew allocation. Required supplies for repairing a given entity are determined and requested. Supplies are allocated from local sources, if available, or non-local sources (e.g., through mutual aid), if not. Funds are requested and allocated to pay for non-local supplies or mutual aid crews, if and when funds are available. The required number of crew members for repairing a given entity is determined and requested. Crews are allocated, if and when available. When repairs are complete for a given entity, the allocated crews are released to be allocated to a different entity.

The PBDES is made topologically-explicit through network modeling to simulate the influence of the functional state of one entity (e.g., damaged pump station) on one or more other entities (e.g., inoperable feeder line). With these entity relationships represented, it's possible to generate an entity restoration sequence list. This list consists of damaged entities. A primary sort of the list is based on the relative value of the priority attribute for each entity. Entities with higher priority values receive resources sooner. Priority values can be set manually or based on attribute values, entity type, location, and optimization algorithm outputs. (Optimization is out of scope of this Chapter.) A secondary sort of the list is based on the topological dependencies of entities across the network and the shortest path from the damaged entity to an appropriate operational entity (computed using Dijkstra's method).

Primary parameters of the PBDES include process duration, entity damage, maximum resource availability, resource costs, and topology. Duration variables are associated with

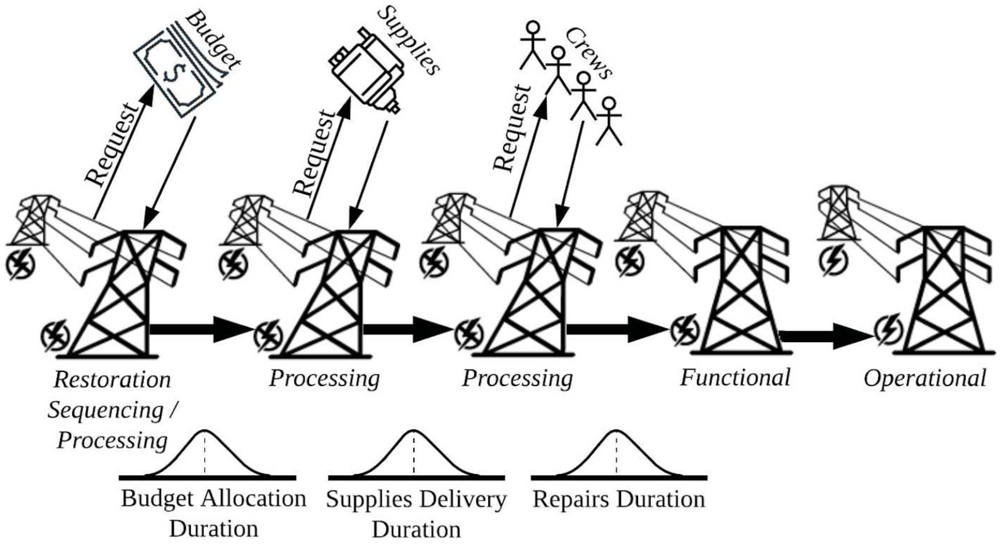

Figure 4.1: Illustration of the process-based discrete-event simulation framework that is resource-aware and topologically-explicit for modeling infrastructure restoration.

supply transport, crew transport, and repair processes. These variables can be assigned stochastically, estimated by experts, or characterized with empirical data from past restoration events. These parameters can be quantified as scalar values or probability distributions. Use of probability distributions helps characterize parameter uncertainties and facilitate Monte Carlo analysis. Maximum resource availability governs entity competition (i.e., if there are infinite resources there is no competition). Maximum availability is characterized by a time-variant function. The resource availability function can be assumed (as a scenario), estimated by experts, determined by current mutual aid agreements, or based on empirical data from past restoration events. The cost of procuring supplies can be assigned stochastically, estimated by experts, determined by current mutual aid agreements or based on market data. To initialize the functional state of the entities, data on damage is required to determine whether each entity in the modeled system is non-functioning because of direct damage. Currently, damage is treated as a binary variable to limit the scope of the work. Additional states can be added in the future, for example based on the recovery-centered damage states of Burton et al. (2016). To be topologically-explicit and enable network modeling, all entities have attributes to represent the links to other entities, including the directionality of those links.

We implemented the PBDES restoration modeling framework above by extending[1] the open source Python library called SimPy. SimPy is relatively unique in its capability to represent shared resources where multiple entities or processes attempt to use a resource of limited capacity. It is also the only extensible pure Python library for implementing a process-based approach to discrete-event simulation. We incorporated the open source Python library NetworkX into the framework to make entities topologically explicit and perform network modeling to assess infrastructure functionality during restoration.

4.4 Case Study Application

In this section, we present a case study of the PBDES modeling methodology described in the previous section. The case study is intended to demonstrate the application of the

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[1] The implemented python version can be found at `https://github.com/AbbasGanji/DESaster-Infrastructure-Restoration` and `https://zenodo.org/record/4399191`

model and provide the basis for the sensitivity analysis described in the next section. We applied the modeling methodology to simulate the restoration of a hypothetical electric power distribution system that has suffered significant damage. The case study entities, network topology, damage scenario, resources, event assumptions, and process parameters are described below.

The entities of the hypothetical electric power network include 8 high-voltage substations, 27 low-voltage substations, 10 high-voltage transmission lines, 34 low-voltage distribution lines, and 4 electricity generation sources. The network is assumed to be a closed system, independent of any larger network. All connections between substations–transmission lines or distribution lines–are bidirectional except those that connect a high-voltage substation to a low-voltage substation.

Initial entity damage–a binary variable–was calculated using a uniform random number generator, assuming 0% damage probability for sources and 50% for all other entities. (Other scenarios were modeled in the sensitivity analysis described in the next section.) With this random scenario, the following entities were damaged: 5 high-voltage substations, 11 low-voltage substations, 4 transmission lines, and 20 distribution lines. The network topology and initial entity damage is shown in Fig. 4.2.

Crews–one of the three required restoration resources–were assumed to be available locally and non-locally (e.g., through mutual aid). The total number of available local crews was held constant over time, while availability of non-local crews varied with time. Local crews were made available immediately (t=0). Some non-local crews were made available at t=10 days, with additional non-local crews arriving at t=20 days and eventually zero non-local crews available after t=60 days. The complete distribution of local and non-local crew availability is presented in Fig. 4.3. (It is possible to simulate more than two sources of crews, each with different temporal distributions.)

Repair supplies were assumed to be available both locally and non-locally. The amount of local supplies were constrained to different amounts for the four respective entity types. (Power generation sources were not allowed to be damaged.) Non-local supply availability was assumed to be infinite. Local supply transport duration was assumed zero, while a different non-zero transport duration was assumed for the four respective entity types.

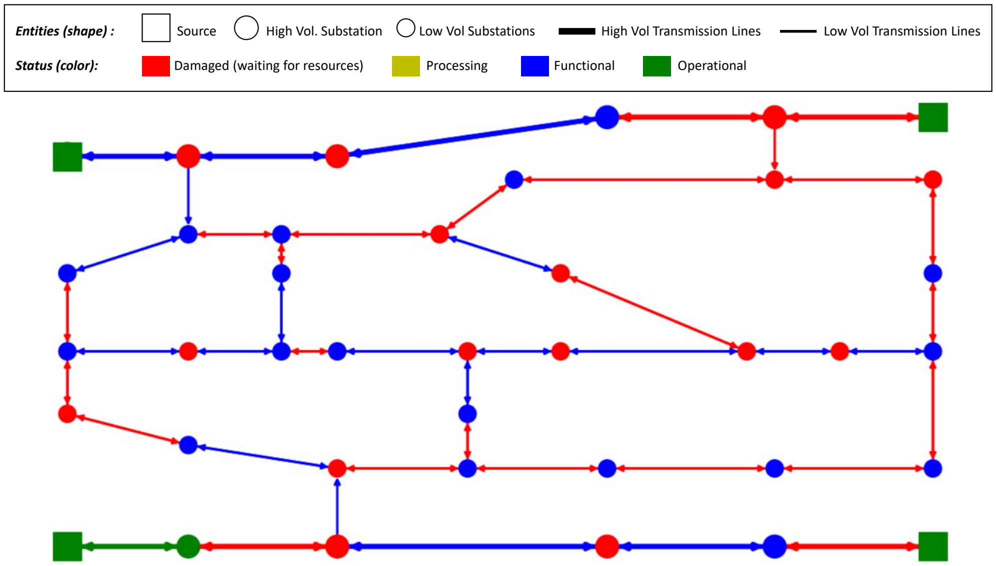


Figure 4.2: The hypothetical electric power network for the case study consists of five types of entities. The entities are color coded according to their state (damaged, processing, functional, or operational) at t=0 after a hazard event.

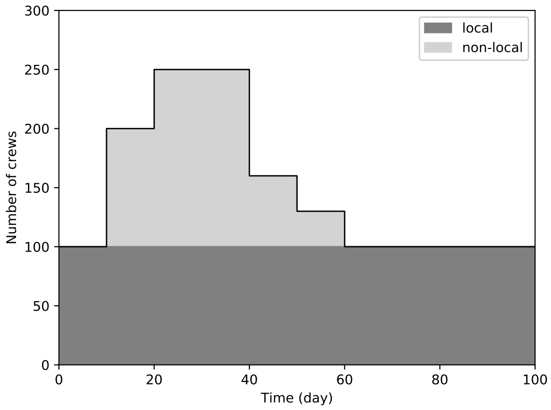


Figure 4.3: Crew availability consisted of local and non-local crews used for the case study.

Table 4.1: Supply availability provided from different sources.

Supply	Internal Sources			External Sources		
	Available Units	Shipping Time (day)	Cost ($k)	Available Units	Shipping Time (day)	Cost ($k)
High-voltage substation	3	0	0	inf	60	850
Low-voltage substation	7	0	0	inf	40	350
High-voltage transmission lines	5	0	0	inf	30	220
Low-voltage distribution lines	12	0	0	inf	30	200

Availability and transport durations for local and non-local supplies are listed in Table 4.1. (It is possible to simulate more than two sources of supplies, each with different constraints, costs, and transport durations.)

Budget for paying for resources was assumed to be infinite. The cost of non-local (and local) crews was assumed to be zero to simplify illustration and analysis. The cost of local supplies was assumed to be zero (i.e., sunk cost). The costs of non-local supplies were assumed based on the entity type. These costs are shown in Table 4.1.

As described in the previous section, the modeling methodology generates a restoration sequence list for defining the order that damaged entities are made operational. The list is first sorted based on the priority value assigned to each entity; it is then sorted based on the shortest functional path to an electricity generation source. We defined three priority levels (any number is possible) and randomly assigned a priority level to each damaged entity. Supplies are requested and paid for as soon as the restoration sequence list is computed. Supplies are allocated to each entity in the order defined in the restoration sequence list.

The total cost of supplies for the case study damage scenario is about $15.5m.

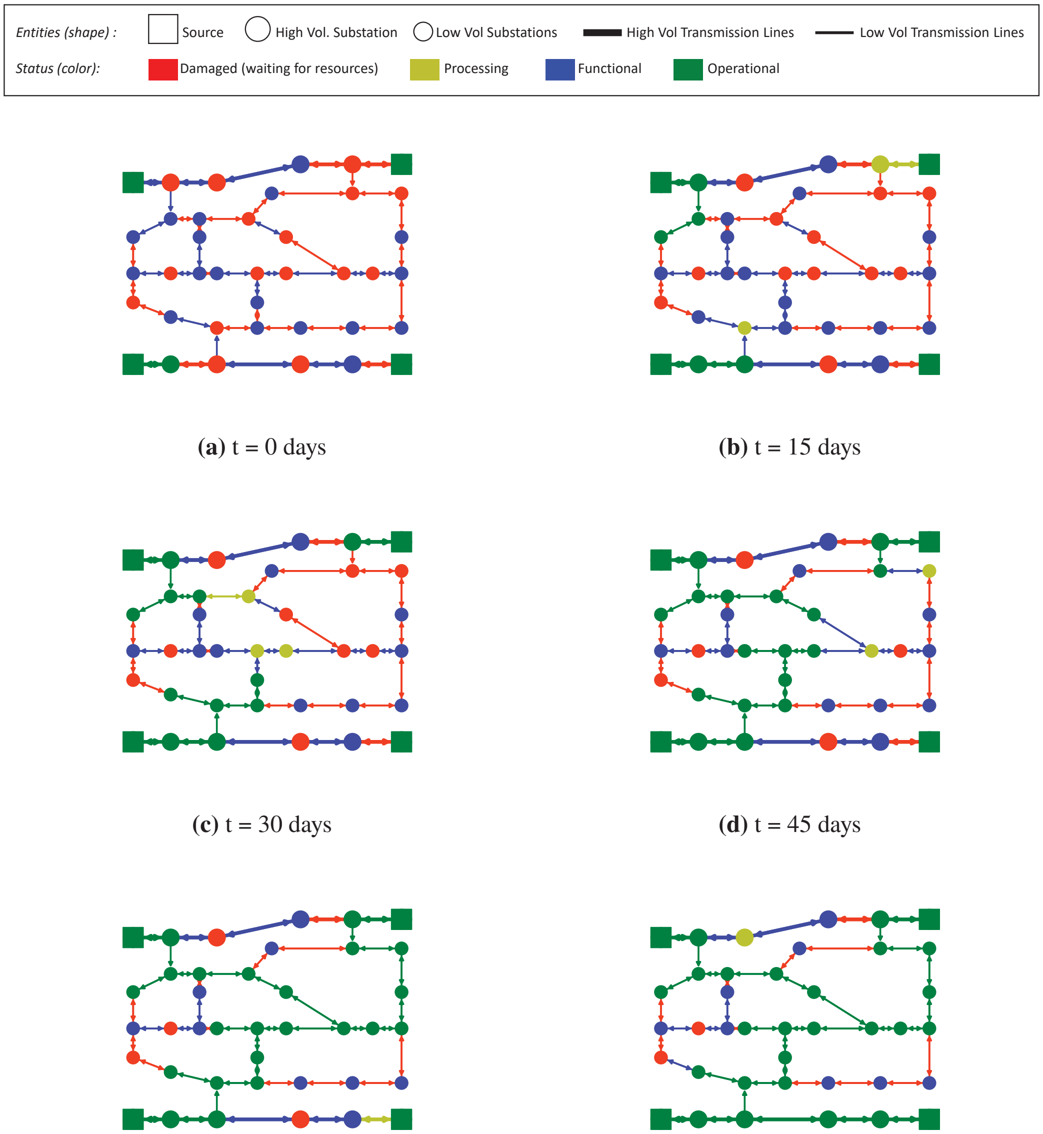
Running the case study simulation results in 103 days for all damaged entities to pass through the processing and functional states to become operable (final state). Entity states across the network for six points in time are topologically shown in Fig. 4.4 to illustrate the restoration simulation. Any changes in the status of entities and resources are recorded during the restoration process. The process and resource allocation proceeded such that substations with higher priority level restore faster. Fig. 4.5 presents the state duration for each entity. This illustrates the relationship between relative priority, entity states, and network topology. Fig. 4.6 shows the cumulative number of entities in each state over time.

4.5 Sensitivity Analysis

We conducted a sensitivity analysis of the case study simulation to verify the PBDES (implemented correctly relative to the conceptual framework and free of errors). The sensitivity analysis was specifically designed to understand the model behavior with respect to damage, crew availability, and supply availability variance. The sensitivity analyses and results for these three methodology elements are described in turn below.

4.5.1 Damage

To understand the role of initial damage state, a Monte Carlo analysis was conducted using the case study simulation. The number of initial damaged entities was randomly varied with all other parameters the same as described in the previous section. One thousand trials were run, with each trial having a different number and topology of damaged entities through a random selection. The percentage of damaged entities varied between 0% and 100%. Figure 4.7 shows the results of the Monte Carlo analysis, relating the percentage of damaged entities and the cumulative time to restore all damaged entities. As expected, the relationship between damage percentage and restoration time is monotonically increasing. The relationship is also linear, which is likely an oversimplification (e.g., increasing damage likely means increasingly difficult transportation). There is variance in the restoration time for a given damage percentage. This is illustrative of the different topological paths possible



(a) t = 0 days

(b) t = 15 days

(c) t = 30 days

(d) t = 45 days

(e) t = 60 days

(f) t = 75 days

Figure 4.4: The system functionality at 0, 15, 30, 45, 60 and 75 days. The entities are color coded according to their state (damaged, processing, functional, or operational).

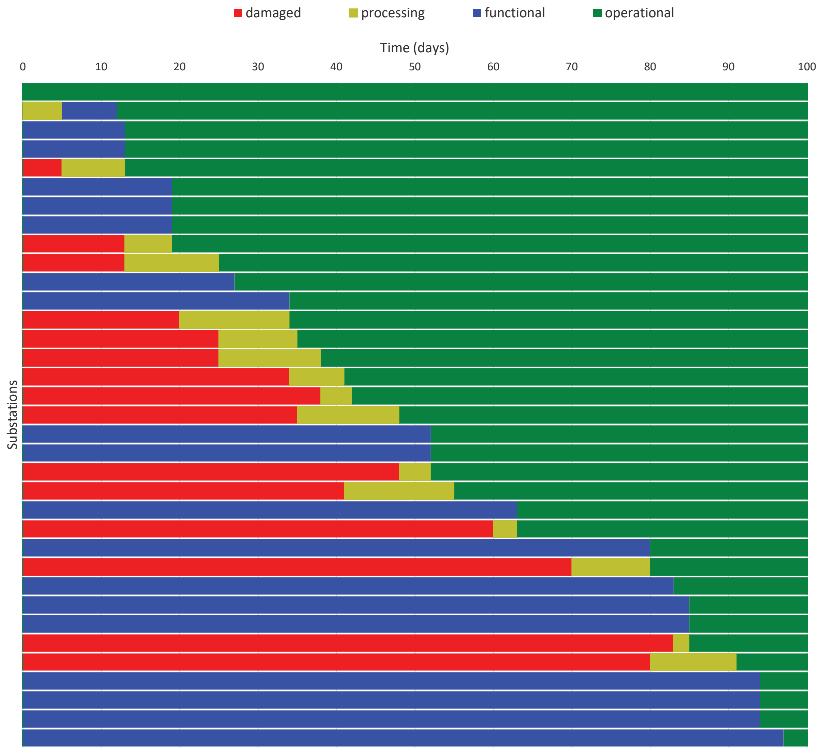


Figure 4.5: Functionality states of the substations during the restoration process.

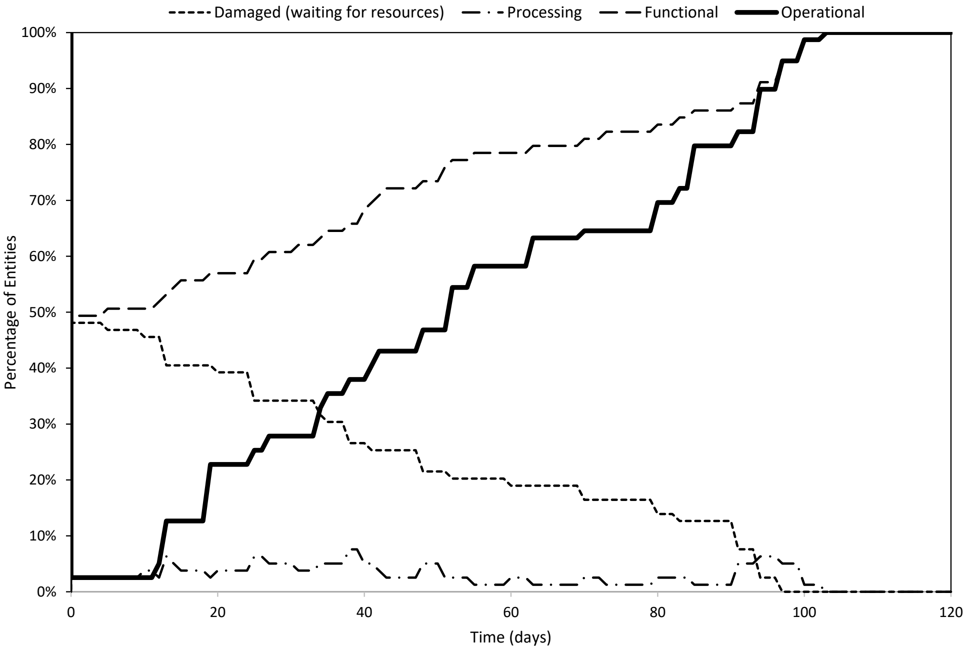


Figure 4.6: The system restoration progress over time.

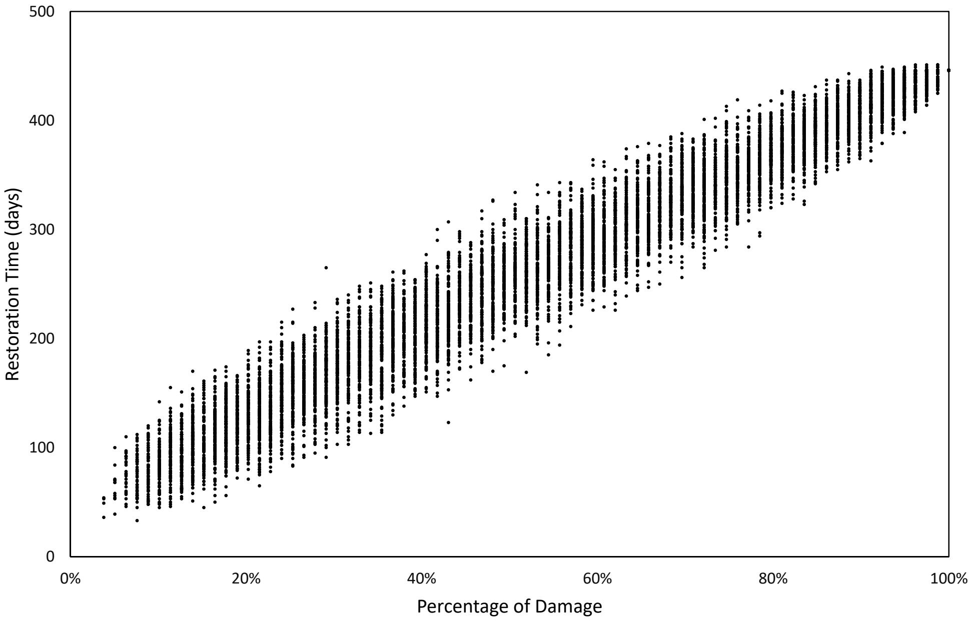


Figure 4.7: Restoration times estimated based on various damage scenarios while other variables are fixed.

for damaged entities to go from damaged or functional to operational and the dynamic of resources used.

4.5.2 Crew Availability

We analyzed the sensitivity of the case study simulation to variance in local and non-local crew availability. We first performed a Monte Carlo analysis to understand the relationship between local crew availability, entity damage percentage, and restoration time. No non-local crews were made available. All the other parameters of the case study simulation were the same as described in the previous section. One thousand trials were run with random combinations of local crew availability, entity damage, and damage topology. Local crew

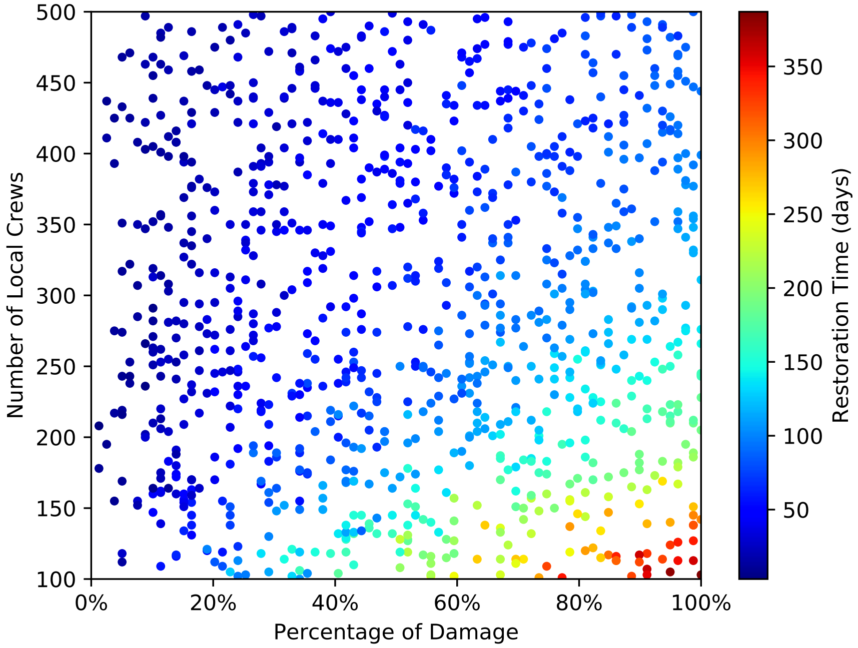


Figure 4.8: Estimated restoration times corresponding to percentage of damage, and the number of local crews participating in restoration.

availability was randomly varied between 100 to 500. Damage percentage was randomly varied between 0% and 100%. Multiple trials for the same damage percentage will likely produce a different damage topology. The results of the sensitivity analysis is shown in Fig. 4.8, relating local crew availability, damage percentage, and recovery time. As expected, for a given damage percentage, the relationship between local crew availability and restoration time is monotonically decreasing in most cases. For lower damage percentages, increasing crew availability does not significantly reduce restoration time, which is reasonable given the few number of entities needing repair.

We conducted additional sensitivity analysis to verify and better understand model behavior with respect to the temporal distribution of non-local crew availability. The temporal distribution of availability was assumed to be a step function defined by the three parameters shown in Figure 4.9: initial crew availability in days (t_0), duration of crew availability

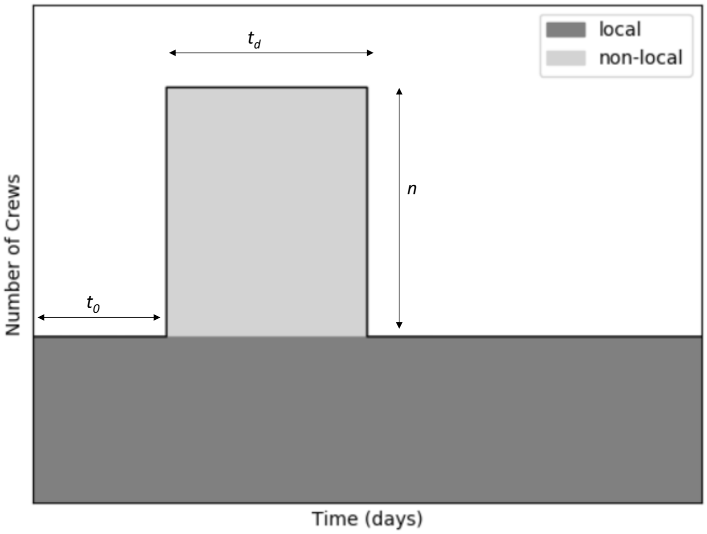


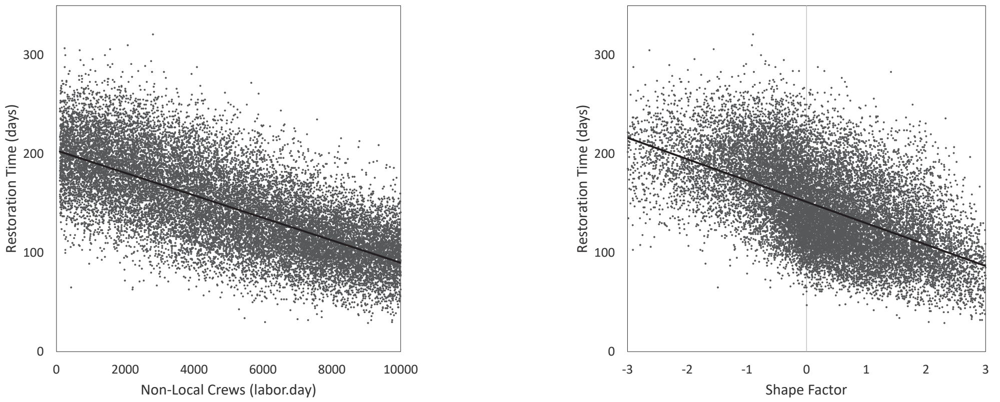
Figure 4.9: Parametric crew availability defined by three variables consisting of arrival, duration and number applied in the sensitivity analysis.

in days (t_d), and the number of temporal non-local crews (n). A Monte Carlo analysis was conducted by randomly varying three quantities: t_0 in units of days, $n.t_d$ in units of crew-days, and $ln(n/t_d)$ as a unitless distribution shape factor. 20,000 trials were run, with random combinations of t_0 between 0 and 75 days, $n.t_d$ between 0 and 10,000 crew-days, and $ln(n/t_d)$ between -3 and 3. We increased the number of trials due to multiple varying variables. We assumed that 100 local crews were available. All other parameters of the case study described in the previous section remained the same. (The damage percentage of the network remained constant at 50% but a new random damage topology was drawn for each trial.)

Fig. 4.10 presents the results of the Monte Carlo analysis for understanding the influence of varying the temporal distribution of non-local crew availability. Figure 4.10a shows that increasing crew-days ($n.t_d$) results in monotonically decreasing restoration time, as expected, with no heteroscedasticity. The large variance in restoration time for a given number of crew-days is heavily driven by the variance in entity damage topology. The linearity of the relationship illustrates an implicit assumption that the crew coordination efficiency (or similar factors) remains constant with increasing number of crews, which is only moderately reasonable to assume. Figure 4.10b shows that increasing shape factor ($ln(n/t_d)$) results in monotonically decreasing restoration time, with some heteroscedasticity. This is expected behavior: if the maximum crew availability is held constant, longer crew availability duration reduces restoration time. The linearity reflects a similar assumption as in Figure 4.10a. The large variance is again driven by the random damage topology. The heteroscedasticity is because of taking the log of a ratio. Figure 4.10c shows that there is a weak relationship between what day crews are first available (t_0)–between 0 and 75 days–and restoration time. This was not specifically expected but reflects that trials with high crew-day and shape factor value combinations can make up for crews arriving as many as 75 days after t_0. While t_0 does not strongly influence the total restoration time, it does strongly influence the overall restoration process, which is analyzed next.

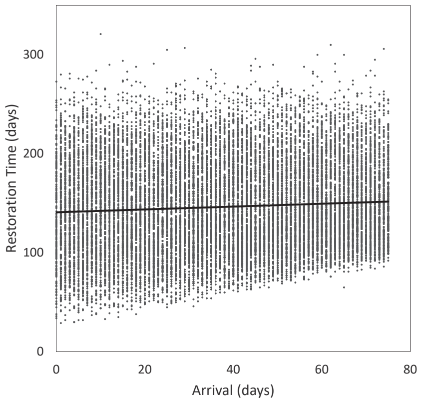
To better understand the influence of initial crew availability (t_0), we used the resilience index of Bruneau et al. (2003). This index quantifies system resilience as the area under the restoration curve (in this case), normalized by total restoration time so that index values range from 0 (low resilience) to 1 (high resilience). Theoretically, there are infinite resilience index values for a single total restoration time, which is relevant for our analysis. A resilience index value was calculated for each restoration curve generated from the respective 20,000 trials. The resilience index values were plotted against the same three quantities– t_0, $n.t_d$, and $ln(n/t_d)$ –shown in Figure 4.11.

Figure 4.11a and Figure 4.11b provide the same insight as Figure 4.10a and Figure 4.10b, respectively, with higher resilience values corresponding to lower restoration times. Figure 4.11c, which shows the relationship between initial crew availability (t_0) and resilience index, shows a stronger relationship than in the corresponding plot of restoration time in Figure 4.11c. For the same total restoration time, longer initial crew availability times translates to monotonically decreasing resilience index values (smaller areas under restoration curves).



(a) Estimated restoration time according to the amount of non-local crews

(b) Estimated restoration time according to shape factor



(c) Estimated restoration time according to arrival time

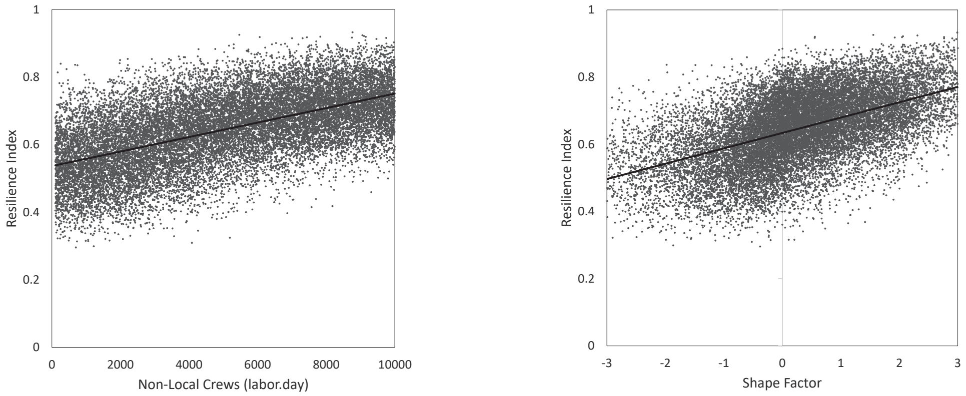
Figure 4.10: Estimated restoration time shows strong correlations with the amount of non-local crews and shape factor. It does not show significant correlation with the arrival time.

Up to some time, a delay in crew availability may not significantly increase restoration time. But that delay will significantly reduce how many entities are operational at any given time before complete restoration. As expected, this means that with longer delays more customers have to wait longer for restored service.

4.5.3 Supply Availability

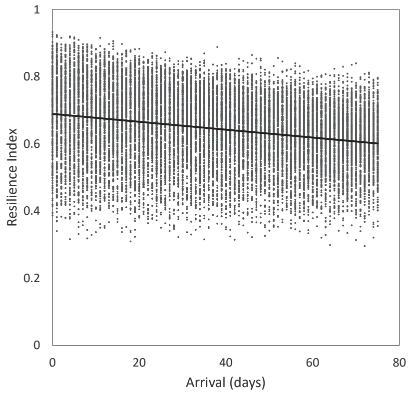
We conducted a sensitivity analysis to verify and understand the behavior of the PBDES model with respect to supply and budget availability (but not transport duration). Other than supply availability, the PBDES was parameterized the same as the case study application described above, including non-local supply transport duration). A Monte Carlo analysis was conducted where 1,000 trials were run with different ratios between local supplies and non-local supplies. (Like the crew availability sensitivity analysis, a different damage topology was computed with each entity having a 50% damage probability.) The cumulative supply total between local and non-local supplies was set to the necessary number of supplies to fully restore the damage topology of a particular trial. Across the trials, the number of local supplies was randomly varied between zero and the total number of required supplies for full restoration. Non-local supply values were set as the inverse of local supply values. The cost of purchasing local supplies prior to the damaging event was tallied, assuming the cost was equal to the non-local supply costs listed in Table 4.1. This was done to represent pre-event investment in surplus supplies and facilitate visualizing analysis outputs.

Figure 4.12 shows the results of the Monte Carlo analysis, relating pre-event cost of local supplies and total restoration time for each of the 1,000 trials. Restoration time monotonically decreases with increasing investment in local surplus supplies, as expected. The large variance is driven by the different damage topologies. Zero dollars spent on surplus supplies (the origin of the plot in Figure 4.12) indicates that restoration was simulated using only non-local supplies. At some change point the curve of each trial flattens out, indicating that all supplies necessary for restorating the entity damage topology of the trial were purchased prior to the damaging event. The change point is the investment in surplus supplies



(a) Estimated resilience index according to the amount of non-local crews

(b) Estimated restoration time according to shape factor



(c) Estimated restoration time according to arrival time

Figure 4.11: Resilience index shows strong correlations with the amount of non-local crews, shape factor and the arrival time.

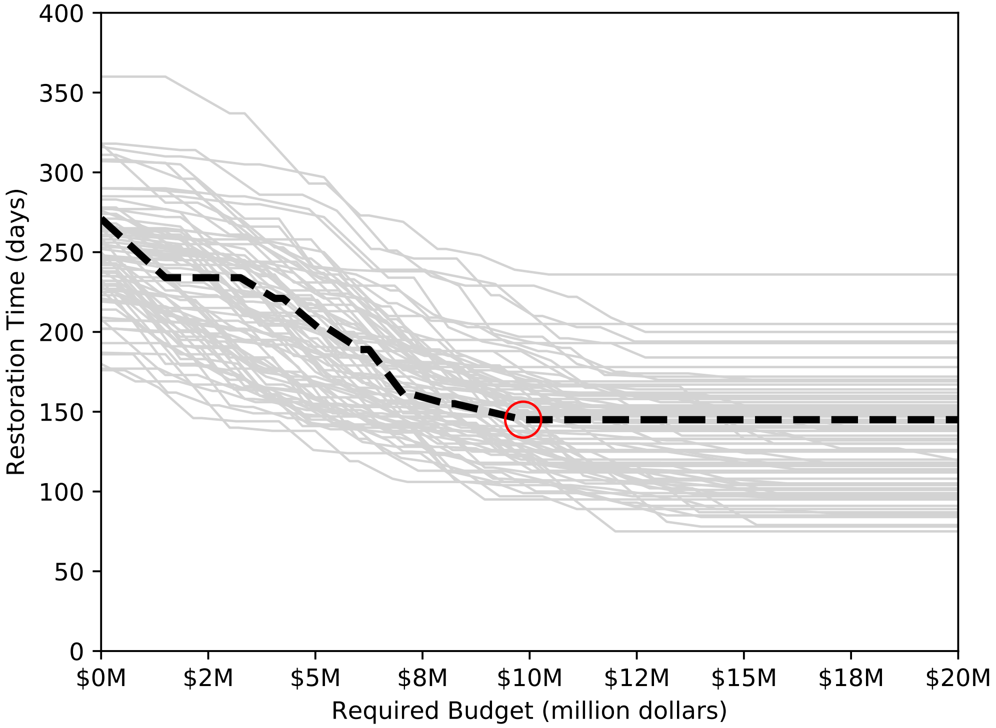


Figure 4.12: The dashed line represents the relationship between investment and restoration time of a random damage topology and the circle points out to the maximum effective investment concept where more investment does not decrease restoration time for a specific damage scenario (trial).

necessary for minimizing the restoration time for the particular damage topology. We refer to this investment value (at the change point) as the Maximum Effective Investment for a specific damage combination. Gathering Maximum Effective Investment data points provides insights for decision-makers to estimate how much investment is required to restore serviceability of an infrastructure network in less than a threshold. It is possible to disaggregate Maximum Effective Investment to compute the average number of each type of supply to purchase (requiring that each value be rounded to the nearest integer for practical purposes).

4.6 Conclusion

We developed an infrastructure restoration modeling methodology that improves representation of resource dynamics. The methodology is based on a new process-based discrete event simulation (PBDES) that is resource-aware and topologically-explicit. We implemented multiple types of resources: crews, supplies, and budget needed to repair damaged entities. The methodology represents time-variant crew and supply availability from local and non-local sources. We applied this methodology to simulate restoration of a hypothetical electric power network as a case study. Using this case study, we conducted sensitivity analyses of damage intensity, crew availability, supply availability, and budget allocation using Monte Carlo simulation. The behavior was generally as expected, providing confidence in the veracity of the methodology implementation. As expected, restoration time decreases with lower damage, more local crews, longer duration of non-local crew availability, and more locally-available surplus supplies. Faster arrival times of non-local crews does not significantly reduce total restoration time, but does notably increase the resilience of the network (i.e., higher initial rate of restoration).

The presented infrastructure restoration modeling methodology can support emergency managers and infrastructure managers to make plans and decisions related to resources investments and timing (e.g., for mutual aid contracting) with more detailed representation of resource dynamics and the consequences of different scenarios. For example, it can inform managers how to efficiently invest in pre-event locally-based surplus to shorten restoration time. Such investments require organizational, political, and, sometimes, political support. This methodology can provide evidence and a basis for communicating that evidence to build that support. After an extreme disruption, this methodology can help users better estimate needed non-local crews and schedule their participation.

This work contributes to a growing literature on infrastructure restoration modeling (Lin and El-Tawil 2020; Alemzadeh et al. 2020; González et al. 2017; Xu et al. 2007). It specifically addresses the limited representation of resource dynamics in existing modeling methodologies in the literature. Several restoration modeling studies represent resource constraints restoration modeling, noting the critical role of resources in restoration (Almoghathawi et al. 2019; Lin and El-Tawil 2020; Ameri and van de Lindt 2019; Talebiyan and Duenas-Osorio 2020). The methodology presented here increases fidelity of resource dynamics for multiple types of resources. Three types of resources are included in the above case study but the methodology facilitates representing other resource types, as well as additional attributes for the current resources.

The developed methodology can be alternatively implemented and improved in several ways. Damage estimation is out of the scope of this work, so damage of the case study network was assumed in a simple manner. The methodology can be paired with existing damage estimation models. The primary parameters described in the methodology section can all be represented by probability distributions to induce stochasticity in the simulation or represent empirical uncertainty. In the case study, service restoration is synonymous with repair or replacement of permanent entities (e.g., substation). Temporary service provision can be represented by including additional entities (e.g. mobile substations) that are treated as complex resources (this capability has been coded). The case study simulated a single type of infrastructure system: electric power. The methodology does facilitate simulating interdependent infrastructure systems. This requires defining a larger variety of entity types (e.g. water pump), processes (pump repair), state-based event triggers (e.g., water pump operability requires operability of topologically connected electric distribution line), and system specific resource types and how these resources govern respective processes. Restoration prioritization and sequence generation is controlled by a priority variable and the functional dependencies of entities in the topological network. This can be done manually (e.g., a decision maker assigns priority values to entity types) or through optimization. Optimization is out of the scope of this work but can be incorporated in future studies, for example the approach of (Talebiyan and Duenas-Osorio 2020). Incorporating efficient optimization techniques would facilitate back-calculation of desirable resource attributes (number and timing) to meet specific decision goals.

Chapter 5

DISCUSSION AND CONCLUSION

This dissertation aimed to answer two research questions:

- How can simulation modeling be designed to support collaborative infrastructure resilience planning?
- How can simulation modeling address time-variant resource availability in infrastructure restoration modeling?

This dissertation followed the human-centered design process to answer the two research questions. We identified the primary challenges in Chapter 2, created the human-centered simulation modeling design framework in Chapter 3, and developed a modeling methodology in Chapter 4. The second research question was answered in Chapter 4 by developing a process-based discrete-event simulation modeling methodology that can flexibly represent complex time-variant resource availability in infrastructure restoration. However, answering the first research question still requires evidence of the developed methodology's capability to support infrastructure stakeholders in the planning process. For this purpose, we returned to the infrastructure stakeholders to assess the modeling methodology's capability from their perspective. The next section describes the approach used in this regard, leading to answering the first research question.

5.1 Usability Testing

The fourth and last step in the human-centered design process is usability testing. It refers to evaluating a product created in the previous steps by potential users. Several approaches exist for usability testing, such as paper prototype testing, individual in-depth interview, focus group, heuristic evaluation, and card sorting. Concept value testing was used in this study. Concept value testing is performed in the early stages of product development to evaluate the basic product idea. Although this approach is modest compared to more popular usability testing approaches, developers can refine their product from the end user's perspective in the early stages. Thus, it is inexpensive and fast. The concept value testing approach can be used flexibly in different forms and detail levels. It was used to assure this methodology's capability to support infrastructure resilience planning from the domain expert's perspectives. The goal was to ensure the infrastructure restoration process's main complexities were captured. Information sharing and inter-organizational collaborations in collaborative resilience planning could be potentially improved by using this simulation modeling methodology.

In this study, I reached out to six infrastructure managers who were experienced in infrastructure resilience planning. In the meetings, the developed methodology was presented through a case study for thirty minutes. In the presentation, I shortly introduced myself, the research project, and the meeting outline. I presented a few questions (provided below) to think about during the presentation. I briefly explained the methodology and the research path, and the developed simulation modeling methodology. I then walked through the hypothetical case study presented in Chapter 4. The goal was to assess whether or not main complexities were captured, and experts and engineers could provide all required information in infrastructure systems from their perspectives. I also presented the visualizations presented in the case study in Chapter 4. After the presentation, the interviewees participated in a semi-structured interview that lasted approximately thirty minutes. They were asked to assess different aspects of the methodology in supporting infrastructure resilience planning and identify missing items, shortcomings, and unaddressed challenges. More details are provided in Appendix B. The semi-structured interview consisted of the following questions.

- Can such simulation models support experts in infrastructure systems to perform resilience planning, and envision post-disaster restoration, overall? Why? Why not?

- Does it capture the main complexities and influential factors that impact estimating infrastructure disaster restoration timeframes? What else is essential to include?

- Does it improve information sharing and inter-organizational collaborations between emergency management and infrastructure system agents in resilience planning?

- Does it improve communications and information sharing between infrastructure agents and non-expert community stakeholders?

The experts' feedback was strongly optimistic about the overall methodology, with few recommendations. The interviewees found the methodology valuable to facilitate infrastructure resilience collaborative planning. They stated that the required data, the simulation model, and generated outputs seemed logical and understandable. They mentioned that the primary factors impacting the restoration process were captured in the model. The interviewees expressed that the developed methodology could improve inter-organizational collaboration by facilitating information sharing between interdependent infrastructure systems. They found it supportive of communications between experts and non-expert community stakeholders, especially while speaking to the public, by enabling infrastructure managers to compare different improvement scenarios. They also indicated a few missing components and recommended considering the following items to improve the modeling methodology.

- There are different types of crews with varying areas of expertise that were oversimplified in the model

- Temporary restoration was also not addressed.

- The partial capacity of system operationality in post-disaster was not also taken into account

These enhancements and additional features can be addressed in the future version of the modeling methodology.

5.2 Summary of Findings

5.2.1 Objective 1: Examine the process of infrastructure resilience planning and identify needs and challenges

Eighteen participants were interviewed to provide insights about the community resilience planning process, complexities and opportunities. Participants mainly were experienced managers and experts in infrastructure systems and emergency management. They could provide information about infrastructure restoration in practice, such as the repair mechanism, system vulnerability, inter-dependencies, estimated cost, and required time and resources (crews, supply, and equipment). These information could be used in the developed modeling methodology. The interviews were semi-structured and conducted individually and in-person. Performing qualitative content analysis, six main challenges were identified to perform community resilience planning:

- understanding of complex infrastructure networks and its restoration
- interdependencies among infrastructure systems
- inter-organizational collaboration and information sharing
- connections between the built environment (buildings and infrastructure systems) and social institutes
- communications between the built environment and social institutions' stakeholders
- communication among infrastructure decision-makers, social stakeholders, and community members

5.2.2 Objective 2: Create a conceptual design framework for simulation modeling that integrates the needs of participants in the structure of simulation models

This objective aimed to create a conceptual design framework. The design framework was required to develop simulation models for critical infrastructure resilience planning. This framework was built to assure the created simulation models address the challenges, capture the primary domain complexities and take advantage of experts knowledge. Several post-disaster recovery assessment reports, community resilience planning reports, and relevant research articles were collected and qualitatively analyzed to identify the design components needed to address in modeling and characterize infrastructure resilience planning. A conceptual design framework for infrastructure resilience simulation modeling was created subsequently. This framework consists of three constructs: user interaction, system representation, and computation core. User interaction represents design features for end-users to interact with simulation models and perform tasks. System representation indicates components, interactions, and state variables embedded in models. Lastly, the computation core contains computational algorithms required to perform processes and analyses and produce desired outputs.

5.2.3 Objective 3: Develop a simulation modeling methodology that operationalizes the design framework to reliably simulate post-disaster infrastructure restoration

The developed modeling methodology aimed to fill two gaps: considering complex time-dependent resource availability and supporting collaborative resilience planning. Accordingly, this modeling methodology was developed in two steps. The existing modeling methodologies in the literature of infrastructure restoration modeling was reviewed. We investigated and identified the capabilities of these methodologies to address the gaps and utilize the opportunities provided by expert's involvement in the collaborative resilience planning. We found the existing methodologies insufficient while using itself. For example, discrete-event simulation modeling is powerful if a complex system or process can be decomposed into discrete events. Infrastructure restoration can be seen as a complex process consisting of plenty of discrete events such as repairing damaged entities. It can utilize participants' expertise and knowledge as experts were able to reliably estimate timeframes, required resources (e.g., the number of crews, supply, equipment, budget), and cost for each single events. However, this methodology does not consider the network structure of infrastructure systems. Thus, we combined discrete-event simulation and network modelings and developed a process-based discrete-event simulation modeling methodology that is topologically-explicit and resource-aware.

5.2.4 Objective 4: Assess the usability of the methodology and identify shortcomings

A concept value testing was used to assess the usability of the developed modeling methodology. Six infrastructure managers were interviewed to identify the capability of the developed modeling methodology in supporting participants to collaboratively evaluate infrastructure resilience states, inter-organizational collaboration and information sharing, and communicating with non-expert community stakeholders (e.g, government officials, community decision-makers and community members). The interviewees found the developed modeling methodology capable to support the collaborative planning process. They proposed three missing pieces required to take into account in further steps: more complicated and realistic types of crews according to their expertise, temporary restoration and the partial capacity of system operationality.

5.3 Contributions

Collaborative infrastructure resilience planning is a complex process. It involves domain-oriented dimensions such as complex infrastructure networks, interdependencies, and resource-constraints in the planning process. Moreover, user-oriented dimensions including inter-organizational collaboration and information sharing between expert and non-expert stakeholders makes it even more complex. This dissertation investigated the planning process and identified six main challenges faced in the previous resilience planning initiatives. This work introduced human-centered simulation modeling as a conceptual design framework for infrastructure resilience planning. This framework was built by combining human-centered design and simulation modeling. It enables simulation modeling developers to include infrastructure stakeholders' concerns and needs into modeling development. This framework was used to develop a simulation modeling methodology that addresses main complexities in infrastructure restoration planning such as infrastructure network, interdependencies, resource constraints, and prioritization, and improve experts collaboration and their communication with non-expert community stakeholders.

Modeling methodologies require the capability of simulating the restoration process, analyzing complex infrastructure networks, capturing dynamic resource availability, and taking advantage of expert knowledge to facilitate collaborative infrastructure resilience planning, as discussed in Chapter 4. However, none of the prior modeling methodologies are individually sufficient to meet the criteria. Miles et al. (2019) state, "the greatest advancements in disaster recovery modeling will likely result from continued and expanded research on integrating modeling approaches, particularly when one is a simulation approach." Following this key, we combined discrete-event simulation modeling with network modeling to develop a process-based discrete-event simulation modeling methodology that is resource-aware and topologically-explicit. This methodology contributes to the growing literature on infrastructure restoration modeling (Lin and El-Tawil, 2020; Alemzadeh et al., 2020; Gonzalez et al., 2017; Xu et al., 2007). While the most recent progress in the literature of infrastructure restoration modeling has emphasized the importance of resource constraints, they applied a single-type and time-independent resource constraints in their post-disaster restoration models (Almoghathawi et al., 2019; Lin and El-Tawil, 2020; Ameri and van de Lindt, 2019; Talebiyan and Duenas-Osorio, 2020). This work addresses the limited representation of resource dynamics in existing modeling methodologies in the literature. Moreover, this dissertation contributes to the literature of restoration modeling by addressing the need for human involvement in collaborative infrastructure resilience planning.

Due to the multi-dimensionality nature of post-disaster infrastructure restoration, the recovery timeframes were estimated with low confidence in collaborative planning efforts that did not utilize simulation modeling. The methodology presented in this dissertation breaks down this complex puzzle into smaller pieces based on the user's areas of expertise. These pieces include construction and repair, system operation, finance, dependencies, and resource availability. This breakdown allows each participant to contribute their knowledge and experience to the model. For example, construction management experts can estimate an repair duration and cost for an entity in different levels of damage. Operation management can determine the criticality of system components and link them to social elements, which is essential in evaluating system resilience in different regions of a jurisdiction. Financial experts can reasonably estimate post-disaster budget availability provided from city, county, state and federal sources. In inter-organizational level of collaboration, it facilitates inter-organizational collaboration and information sharing between interdependent infrastructure systems. The resource-aware discrete-event simulation modeling methodology can leverage these expertise (expert's advantage), perform complex system and network analysis (computational modeling's benefit), and provide desired outputs. Six infrastructure managers assessed the methodology and confirmed its usability to support the resilience planning community.

The developed methodology can facilitate the cost-benefit analysis for investments in the infrastructure system by simulating the effect of dynamic resource availability in different scenarios. For example, infrastructure managers often submit improvement plans, known as capital improvement proposals (e.g., system upgrades and new constructions) and seek funds from other community decision-makers such as local and federal government. The developed modeling methodology can support these experts by demonstrating how an investment can reduce the gap between the current and community-desired resilience states compared to other investment plans. It can help managers decide on investment opportunities in pre-event locally-based surplus to shorten restoration time efficiently. Such investments social, economical and, sometimes, political support. This methodology can help users better estimate needed non-local crews and facilitate their availability after extreme events.

5.4 Limitations

To accomplish this dissertation's goals, the human-centered design process was simplified which limits the design findings' generalizability. As the first step in the human-centered design process, user research requires collecting diverse samples representing the target population. Although a diverse set of participants in terms of role, sector, and jurisdiction were selected and interviewed, the interviewees had only participated in seismic community resilience planning initiatives. The modeling methodology is computationally capable of handling various hazard scenarios. However, the challenges identified through the user research phase and the design framework might present unforeseen challenges when used for resilience planning scenarios others than seismic.

The concept value testing method was applied to assess the utility of the developed methodology. This approach was inexpensive and fast, and effective in the early stages. More elaborated usability testing methods are needed to use such that participants can collaboratively perform resilience planning while using the modeling methodology. It is highly valued in the human-centered design community to triangulate findings by applying multiple usability testing approaches. A more in-depth usability testing process can be precious in future studies.

The developed methodology was built upon the discrete-event simulation modeling approach. It was combined with network analysis to simulate system topology and connectivity. Restoration sequence lists were generated by executing a basic optimization algorithm implemented in the methodology. The network analysis algorithm used to create the restoration sequence is not computationally efficient. Increasing the number of entities and the network size may lead to a significant increase in computational cost. Optimization is out of this study's scope, but it is noteworthy to mention that advanced optimization algorithms can be applied to improve this methodology's computational performance. Also, the restoration sequence list is not determined to only minimize the restoration path in practice. For example, adjacent damaged entities get repaired altogether due to their practicality. It is vital to introduce and utilize practical rules to the models to generate the restoration sequence list.

5.5 Recommendations

Iterating the human-centered design, including evaluating the accuracy of simulations by experienced experts for different hazard scenarios and identifying other hidden challenges in practice, can result in a more accurate representation of infrastructure restoration. According to the experts' feedback, the partial capacity of system operationality and temporary service restoration is missing in the modeling methodology, both of which can significantly impact resource allocation for long-term restoration. The next step to improve the accuracy of simulated infrastructure restoration and usability of this tool is to incorporate the experts' feedback into the modeling methodology.

The developed modeling methodology enables users to evaluate system resilience once system robustness, dependencies, and resource availability and constraints are provided.

This method can illustrate the gap between the current and desired resilience states. Decision-makers can compare the consequences of different decisions on the resilience state to find the most favorable direction to reduce the gap. However, as the number of variables included in the model increases, comparing numerous scenarios becomes challenging. Machine learning techniques can reverse the data flow direction. Creating big datasets using simulation models leverages using machine learning techniques to support decision-making, optimize resource allocation, generate restoration sequence more optimally, and comprehensively explain relationships between variables.

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Appendix A

PARTICIPANTS INTERVIEW PROTOCOL

Below is the interview protocol used for interviewing experts who participated in the community resilience planning initiatives. The interviews were semi-structured and in-person. They were conducted individually and lasted up to 90 minutes. The Human Subjects Division at the University of Washington assessed the study and potential human factors involved in 2018. This study received IRB exemption (STUDY00004345) and its risk level was identified as "No greater than minimal risk".

1. Introduction
   (a) Introduce myself and the study
   (b) Explain the purpose of the research
   (c) Describe the interview outline
   (d) Ask permission to record the interview
   (e) Inform that the interviewee can interrupt the interview whenever they like or refuse to answer any question
   (f) Let the interviewee ask any questions or ambiguity about the interview
2. Questions
   (a) Can you please briefly tell us about yourself, your background, experience, and role in the [name of the initiative] community resilience initiative?
   (b) What task group or sector were you a member of? Can you please tell me about your group?
   (c) What were the goals of the initiative and more specifically your group?

(d) Can you please briefly tell me about the procedure that you and your teammates followed to achieve the goals?

(e) Can you describe how you identified community hazard?

(f) Can you please describe how the desired resilience state were determined?

(g) Did you consider community priorities? If so, how were they defined? How did you consider the community priorities? If not, how does it impact the current resilience state? Who should define them and how?

(h) How did you estimate the current resilience state?

(i) Did you use any software, analytical tools, simulation models, etc. to evaluate the current resilience state?

(j) What complexities and variables were considered in your estimations?

(k) Were there other influential factors that you were not able to include? Why?

(l) Did you face any challenges in evaluating the resilience state?

(m) Can you please let me know about your collaboration with other experts in your group? Did you experience any barriers to collaborate or communicate with other experts in your team?

(n) Can you please tell me about your collaboration and communication with other teams? Did you share information? Did you find anything challenging in your communications?

(o) Who participated in the initiative? What other stakeholders should be included? Why?

(p) Did you communicate with non-experts participants or other community stakeholders that did not participate in the initiative? Did you experience any challenges in these communications?

(q) Would you conduct the initiative differently if you wanted to do it again? What would you change?

(r) Have you ever used any types of simulation models in your projects? What do you think about advantages and disadvantages of using simulation models in community resilience planning?

(s) I asked my questions. Is there anything else that you would like to share with me?

(t) Thank the interviewee and close the interview

Appendix B

CONCEPT VALUE TESTING INTERVIEWS

Concept value testing is covered in Chapter 5.1. The participants were shown a presentation in 30 minutes. The presentation can be found in Section B.2 below. Then, a semi-structured interview was conducted in 30 minutes. The interview questions, provided in Section B.1, were shared with the interviewees at the beginning of the presentation.

B.1 Interview Protocol

The following is the semi-structured interview protocol.

- Can such simulation models support experts in infrastructure systems to perform resilience planning, and envision post-disaster restoration, overall? Why? Why not?
- Does this tool facilitate involved agents in envisioning post-disaster restoration? What's missing?
- Does it capture the main complexities and influential factors that impact estimating infrastructure disaster restoration timeframes? What else is essential to include?
- Does it improve information sharing collaborations between emergency management and infrastructure agents to perform the planning?
- Does it improve information sharing and inter-organizational collaborations between emergency management and infrastructure system agents in resilience planning?
- Does it improve communications and information sharing between infrastructure agents and non-expert community stakeholders?

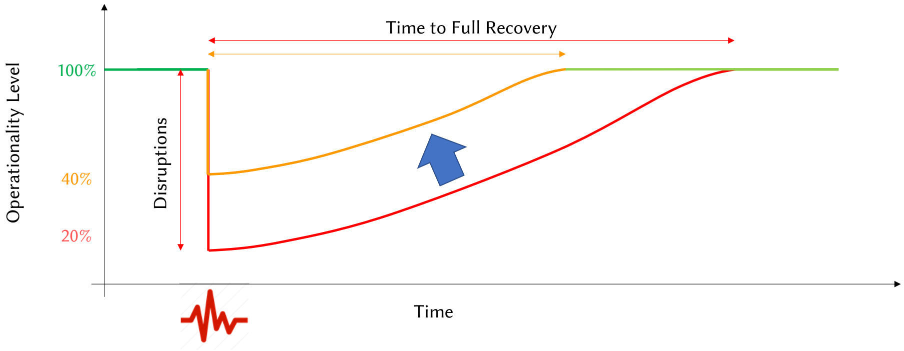
B.2 Presentation

Facilitating Critical Infrastructure Resilience Planning

Using simulation modeling

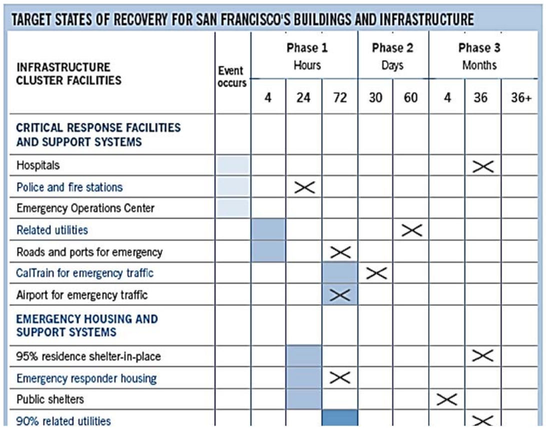
Abbas Ganji (PhD Candidate)
University of Washington
November 2020

Critical Infrastructure Resilience Planning



Seismic Resilience Planning: SPUR (2006-2009)

- Identified a specific seismic hazard scenario
- Identified potential risks
- Anticipated expected recovery timeframe
- Proposed desired recovery states
- Provided recommendations for community decision-makers



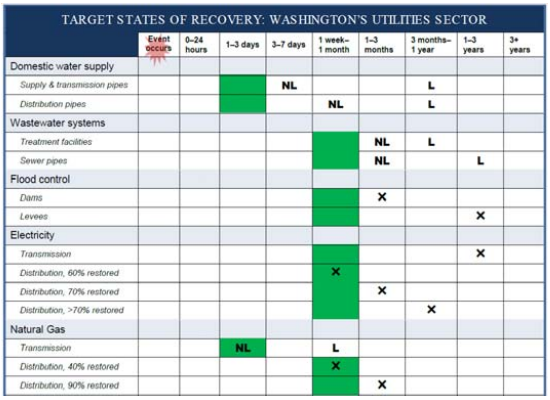
TARGET STATES OF RECOVERY FOR SAN FRANCISCO'S BUILDINGS AND INFRASTRUCTURE

INFRASTRUCTURE CLUSTER FACILITIES	Event occurs	Phase 1 Hours			Phase 2 Days		Phase 3 Months		
		4	24	72	30	60	4	36	36+
CRITICAL RESPONSE FACILITIES AND SUPPORT SYSTEMS									
Hospitals	🟦							X	
Police and fire stations	🟦		X						
Emergency Operations Center	🟦								
Related utilities		🟦				X			
Roads and ports for emergency		🟦		X					
CalTrain for emergency traffic				🟦	X				
Airport for emergency traffic				🟦 X					
EMERGENCY HOUSING AND SUPPORT SYSTEMS									
95% residence shelter-in-place			🟦					X	
Emergency responder housing			🟦	X					
Public shelters			🟦				X		
90% related utilities				🟦				X	

Source: C. Barkley, Lifelines: Upgrading Infrastructure to Enhance San Francisco's Earthquake Resilience", San Francisco, CA: San Francisco Planning & Urban Research Association (SPUR), February 2009.

Seismic Resilience Planning: RWS (2009-2012)

- Considered National Seismic Hazard Maps as expected hazard
- Anticipated expected recovery timeframe
- Proposed desired recovery states
- Provided recommendations for community decision-makers



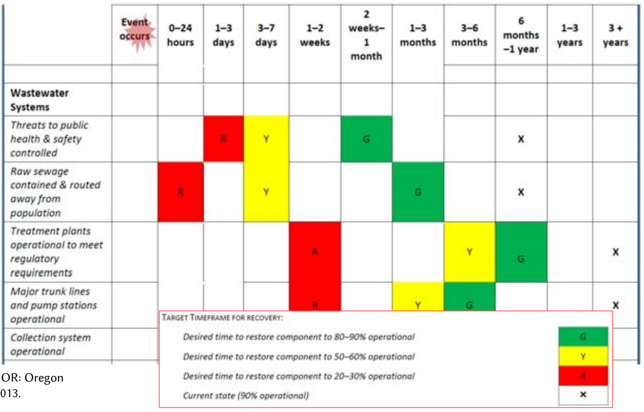
TARGET STATES OF RECOVERY: WASHINGTON'S UTILITIES SECTOR

	Event occurs	0–24 hours	1–3 days	3–7 days	1 week–1 month	1–3 months	3 months–1 year	1–3 years	3+ years
Domestic water supply									
Supply & transmission pipes			🟩	NL			L		
Distribution pipes			🟩		NL		L		
Wastewater systems									
Treatment facilities					🟩	NL	L		
Sewer pipes					🟩	NL		L	
Flood control									
Dams					🟩	×			
Levees					🟩			×	
Electricity									
Transmission					🟩			×	
Distribution, 60% restored					🟩 ×				
Distribution, 70% restored					🟩	×			
Distribution, >70% restored					🟩		×		
Natural Gas									
Transmission			🟩 NL		L				
Distribution, 40% restored					🟩 ×				
Distribution, 90% restored					🟩	×			

Source: WASSC, Resilient Washington State Workshop September 17, 2010 Final Summary Report." Olympia, WA: State of Washington Emergency Management Council Seismic Safety Committee. September 2010.

Seismic Resilience Planning: ORP (2011-2013)

- M9.0 Cascadia earthquake and tsunami
- Anticipated expected recovery timeframe
- Defined high-level community goal: business continuity in 2-4 weeks
- Proposed desired recovery states



	Event occurs	0–24 hours	1–3 days	3–7 days	1–2 weeks	2 weeks–1 month	1–3 months	3–6 months	6 months –1 year	1–3 years	3 + years
Wastewater Systems											
Threats to public health & safety controlled			R	Y		G			X		
Raw sewage contained & routed away from population		R		Y			G		X		
Treatment plants operational to meet regulatory requirements					R			Y	G		X
Major trunk lines and pump stations operational					R		Y	G			X
Collection system operational											

TARGET TIMEFRAME FOR RECOVERY:

Desired time to restore component to 80–90% operational	G
Desired time to restore component to 50–60% operational	Y
Desired time to restore component to 20–30% operational	R
Current state (90% operational)	X

Source: OSSPAC, The Oregon Resilience Plan", Salem, OR: Oregon Seismic Safety Policy Advisory Committee. February 2013.

Outline

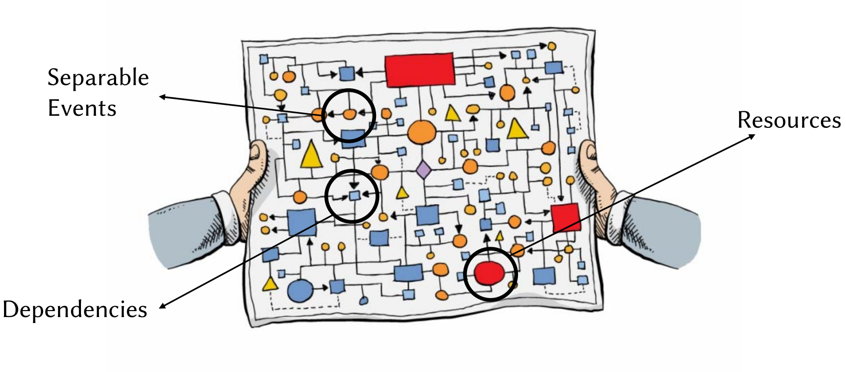
1- Proposing a prototyped simulation model

- 1-1- Applied methodology
- 1-2- Hypothetical case study

2- Getting feedback

- 2-1- Does it improve infrastructure resilience planning, overall?
- 2-2- Does it consider main complexities? What's missing?
- 2-3- Does it improve information sharing between involved agents?
- 2-4- Does it improve communications between infrastructure experts, community stakeholders, community members?

Discrete-Event Simulation Modeling

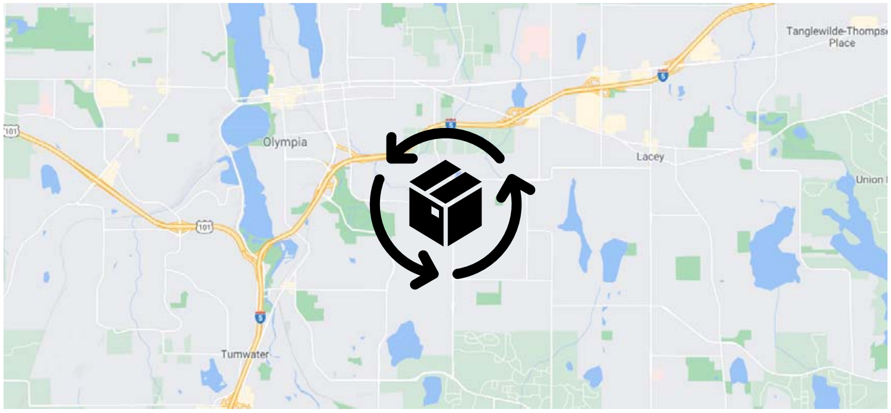


Separable Events

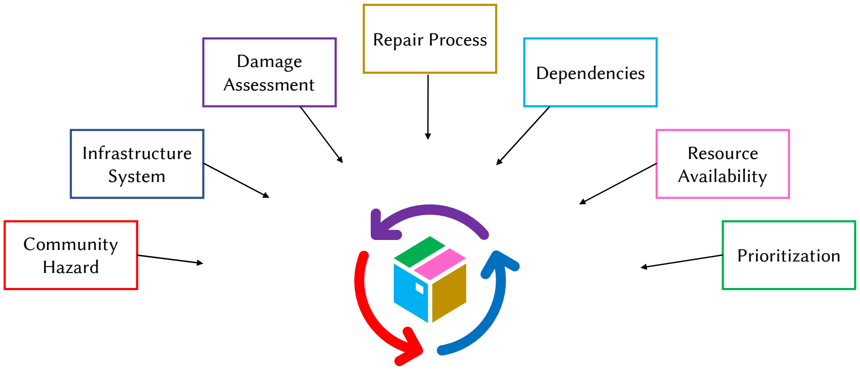
Resources

Dependencies

Hypothetical Case Study



Model Layout 1: required information



Repair Process

Damage Assessment

Dependencies

Infrastructure System

Resource Availability

Community Hazard

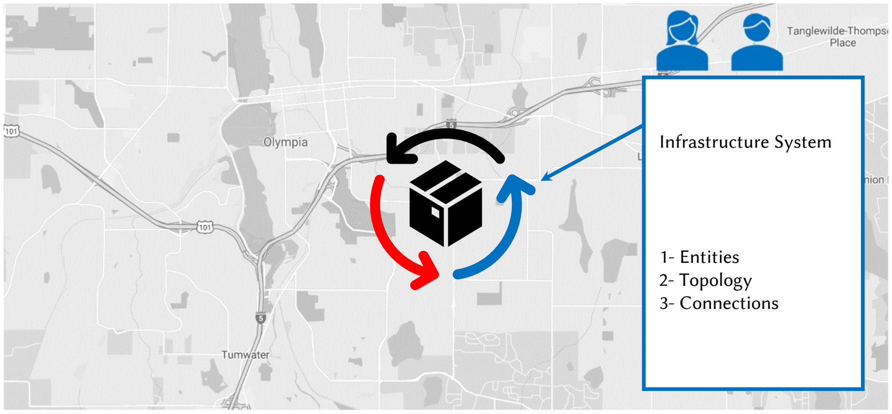
Prioritization

Community Hazard Identification

Community Hazard
(Type & Intensity)

1- Seismic Hazard
2- Liquefaction
3- Landslide
4- Lateral Spreading

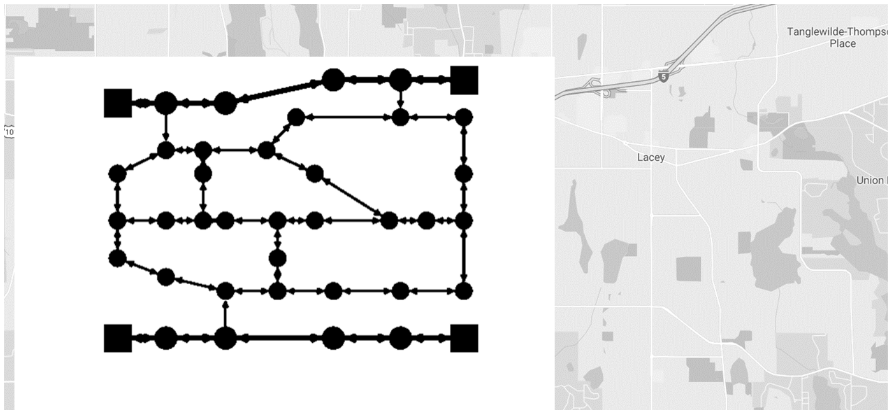
Infrastructure System



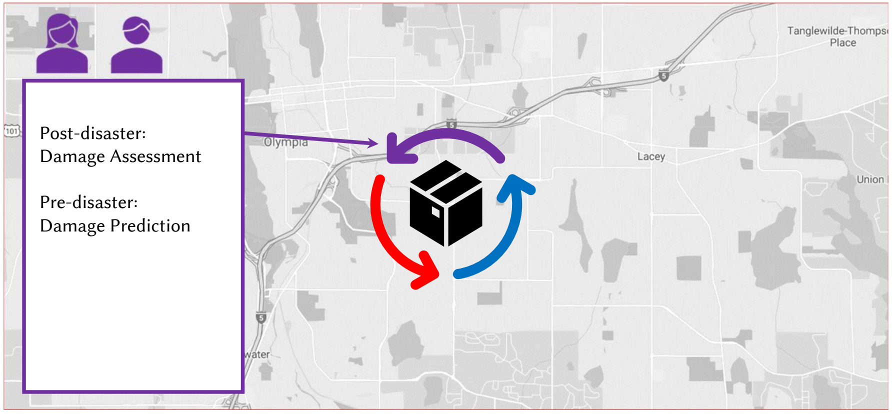
Infrastructure System

1- Entities
2- Topology
3- Connections

Infrastructure Network



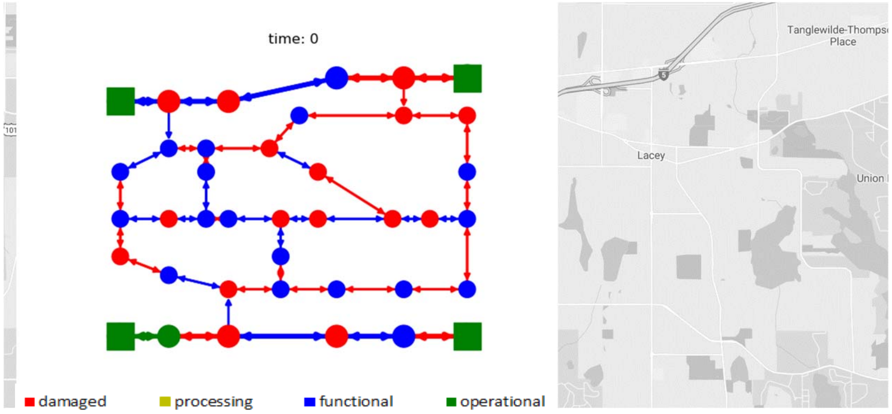
Damage Assessment/Prediction

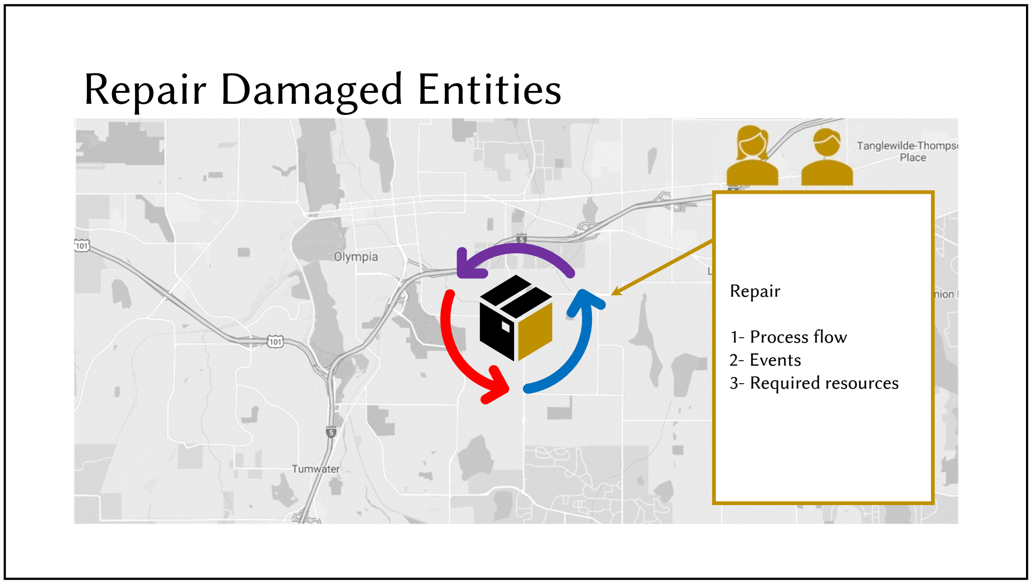


Post-disaster:
Damage Assessment

Pre-disaster:
Damage Prediction

Damage Assessment (Post-disaster)

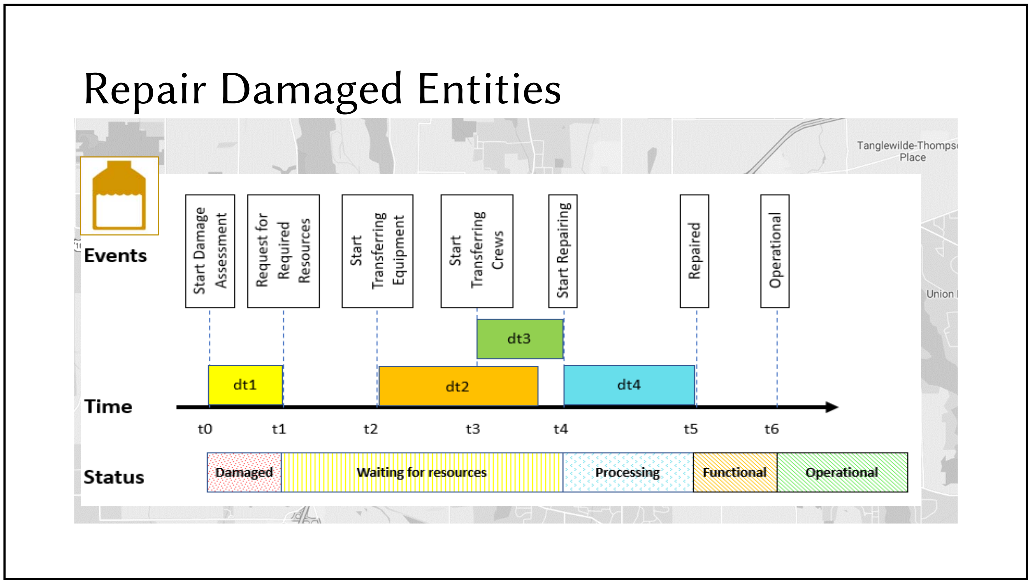




Repair Damaged Entities

Repair

1- Process flow
2- Events
3- Required resources



Repair Damaged Entities

Events

- Start Damage Assessment
- Request for Required Resources
- Start Transferring Equipment
- Start Transferring Crews
- Start Repairing
- Repaired
- Operational

Time

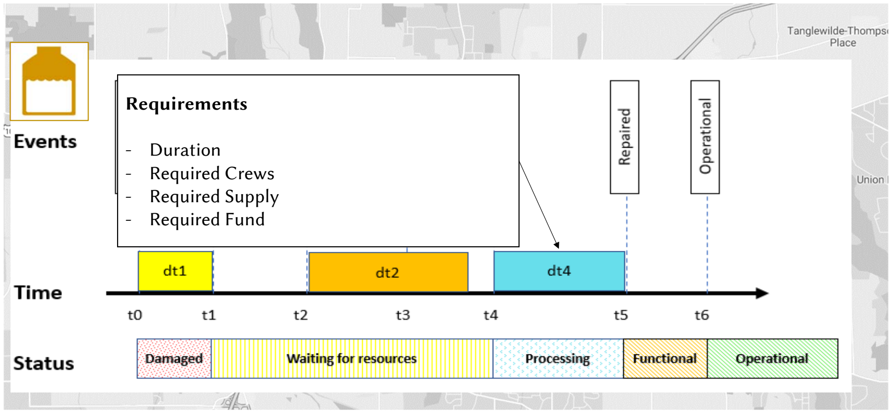
dt1, dt2, dt3, dt4

t0, t1, t2, t3, t4, t5, t6

Status

Damaged | **Waiting for resources** | **Processing** | **Functional** | **Operational**

Repair Damaged Entities



Events

Requirements

- Duration
- Required Crews
- Required Supply
- Required Fund

Repaired

Operational

Time

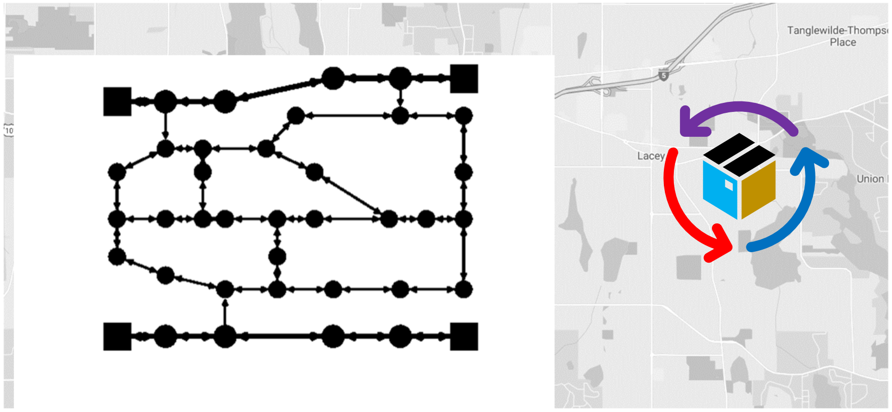
dt1 dt2 dt4

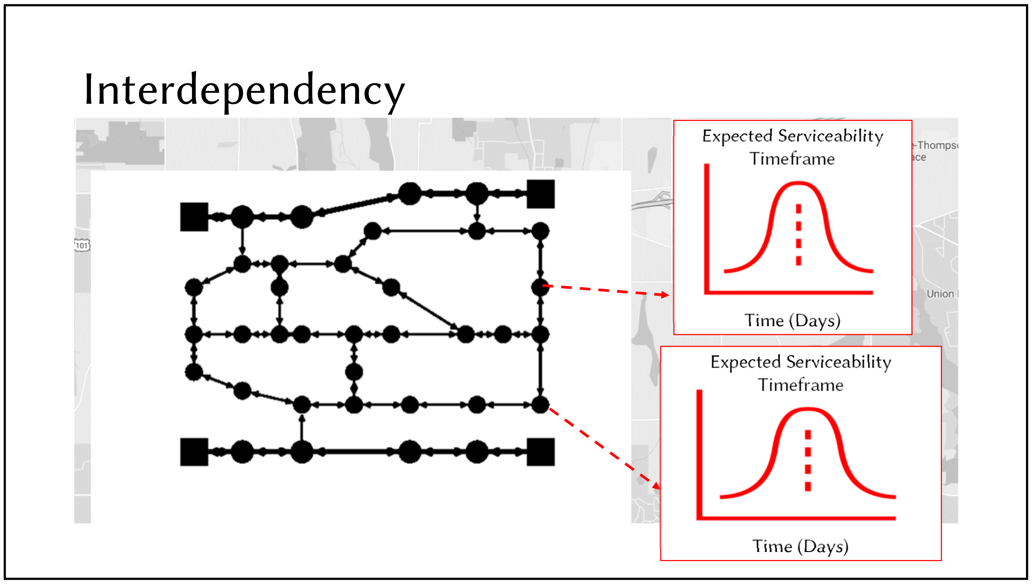
t0 t1 t2 t3 t4 t5 t6

Status

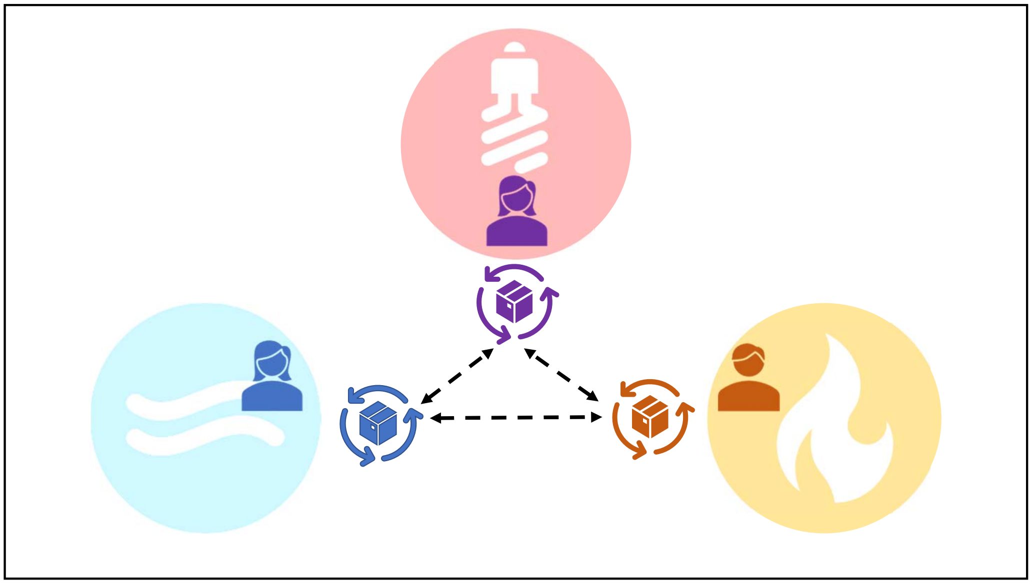
Damaged | Waiting for resources | Processing | Functional | Operational

Interdependency

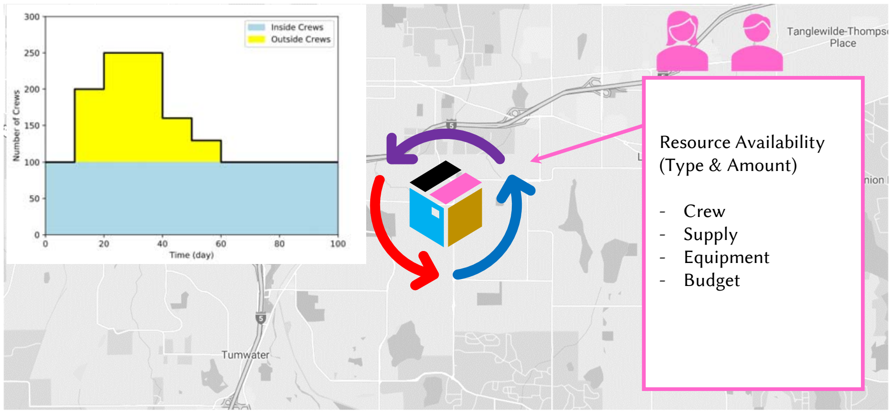




Interdependency



Resourcefulness



Resource Availability
(Type & Amount)

- Crew
- Supply
- Equipment
- Budget

Resourcefulness

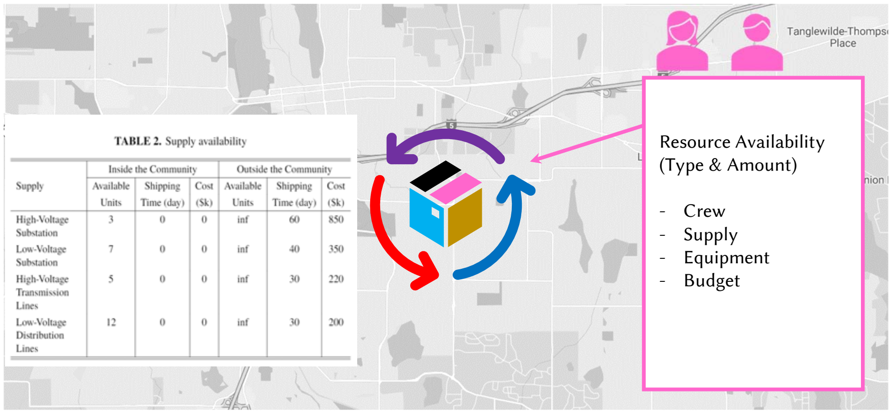


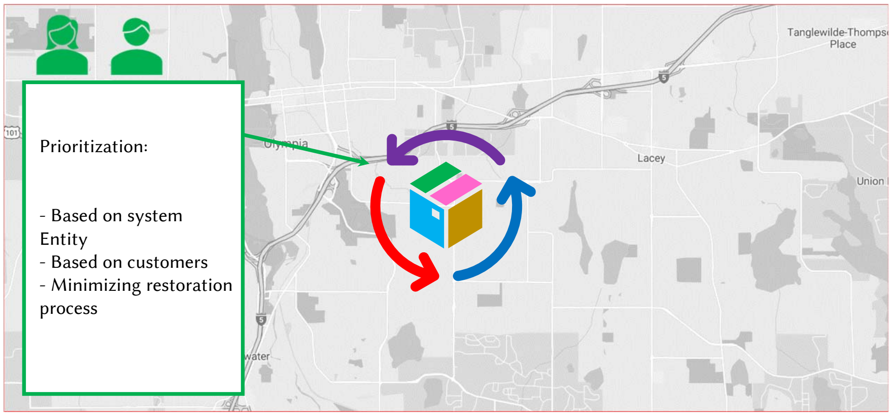
TABLE 2. Supply availability

Supply	Inside the Community			Outside the Community		
	Available Units	Shipping Time (day)	Cost ($k)	Available Units	Shipping Time (day)	Cost ($k)
High-Voltage Substation	3	0	0	inf	60	850
Low-Voltage Substation	7	0	0	inf	40	350
High-Voltage Transmission Lines	5	0	0	inf	30	220
Low-Voltage Distribution Lines	12	0	0	inf	30	200

Resource Availability
(Type & Amount)

- Crew
- Supply
- Equipment
- Budget

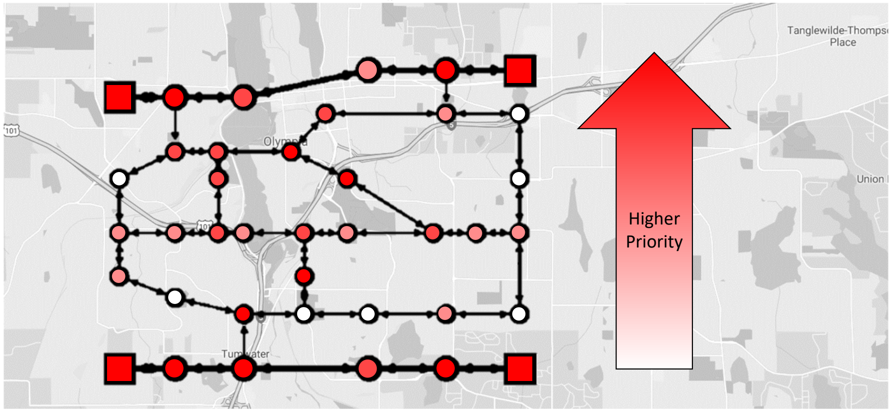
Prioritization



Prioritization:

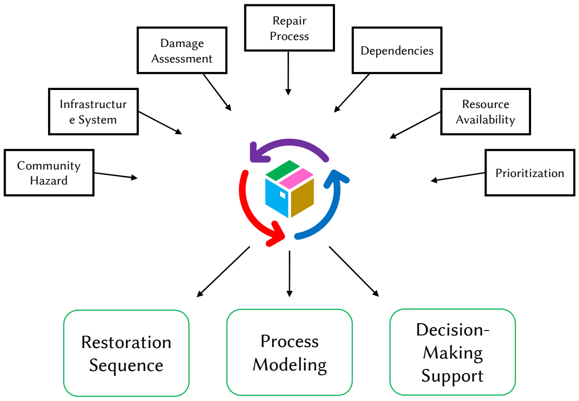
- Based on system Entity
- Based on customers
- Minimizing restoration process

Prioritization: Entity-based



Prioritization: District-based

Model Layout 2: Outputs



Damage Assessment

Repair Process

Dependencies

Infrastructur e System

Resource Availability

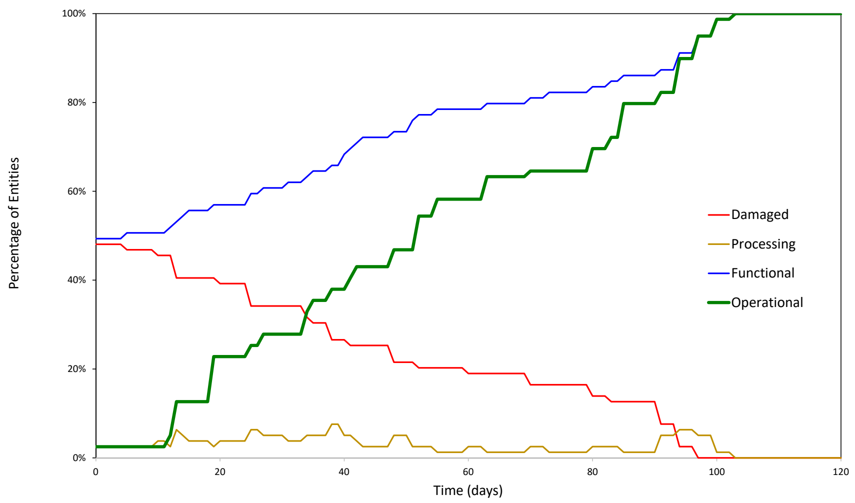
Community Hazard

Prioritization

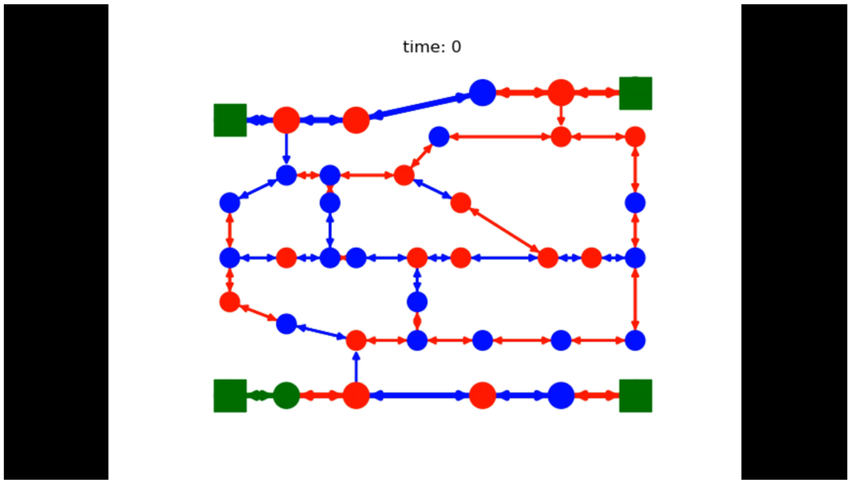
Restoration Sequence

Process Modeling

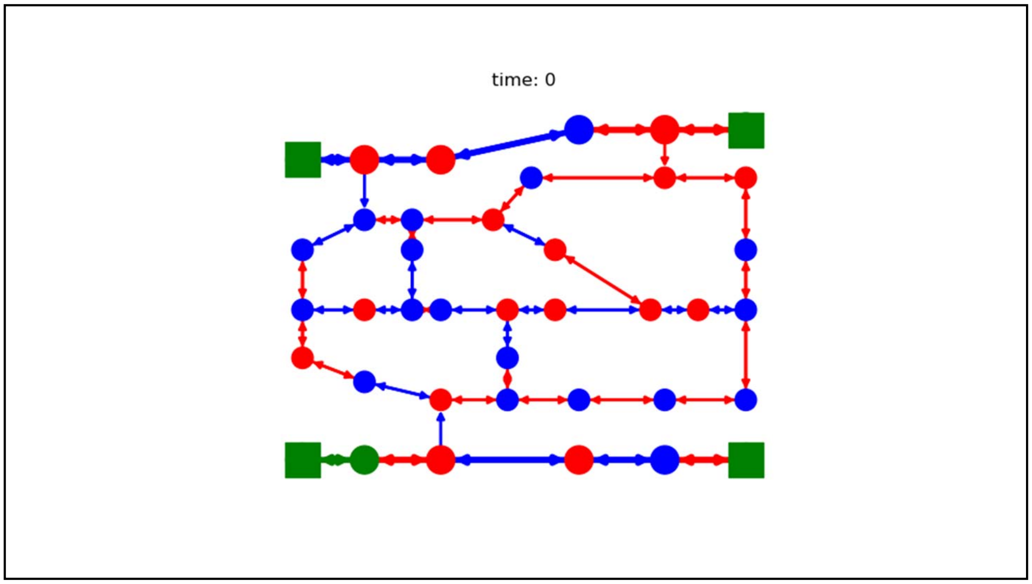
Decision-Making Support

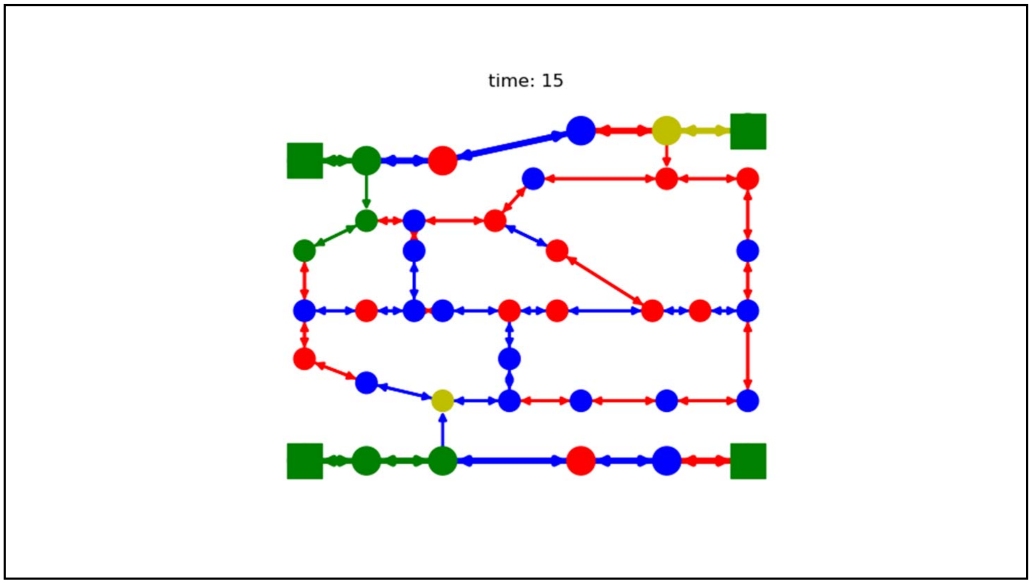

100%
80%
60%
40%
20%
0%
Percentage of Entities
0
20
40
60
80
100
120
Time (days)
Damaged
Processing
Functional
Operational

27

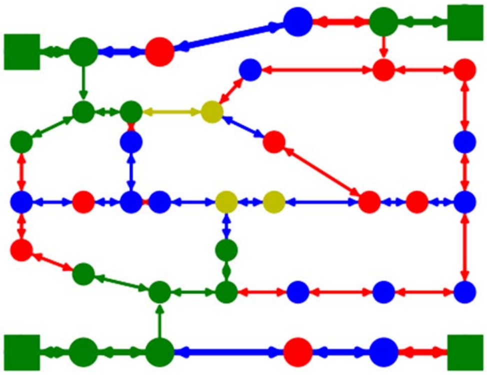

time: 0

28

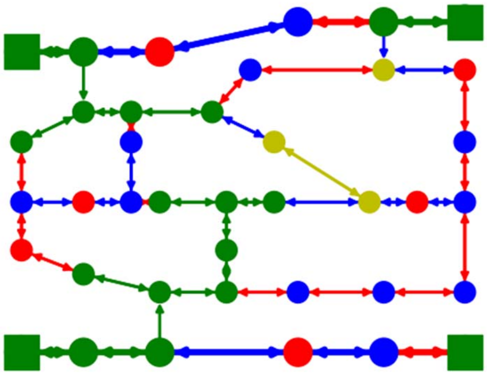

time: 0

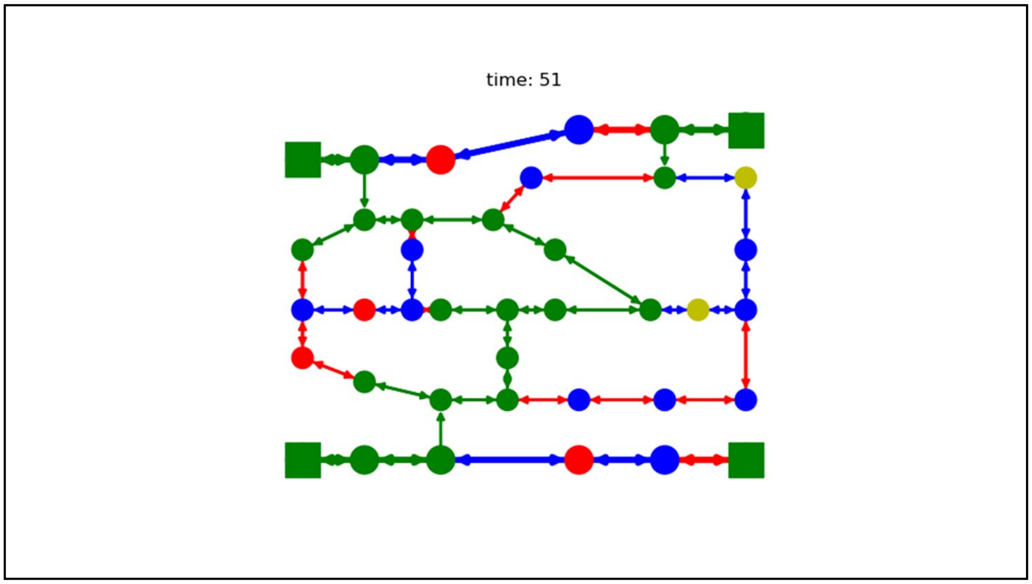

time: 15

time: 27

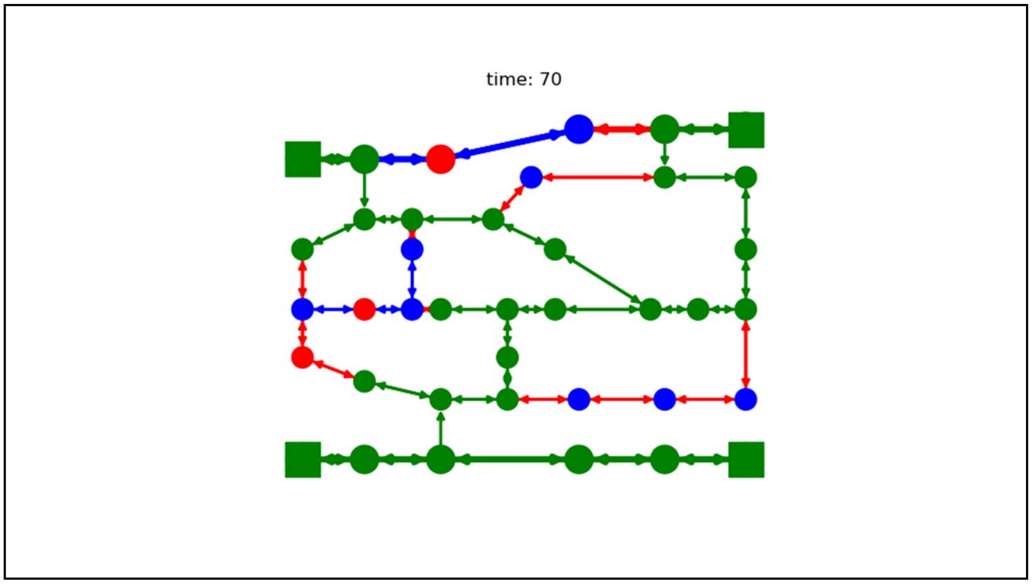


time: 40

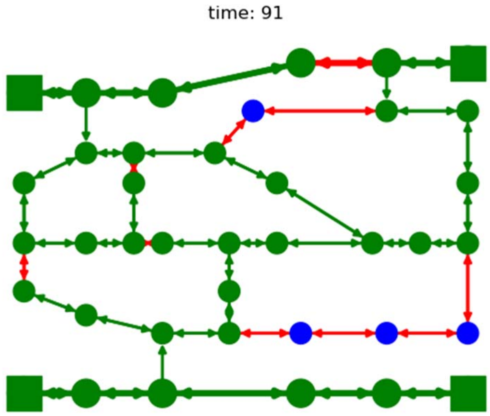




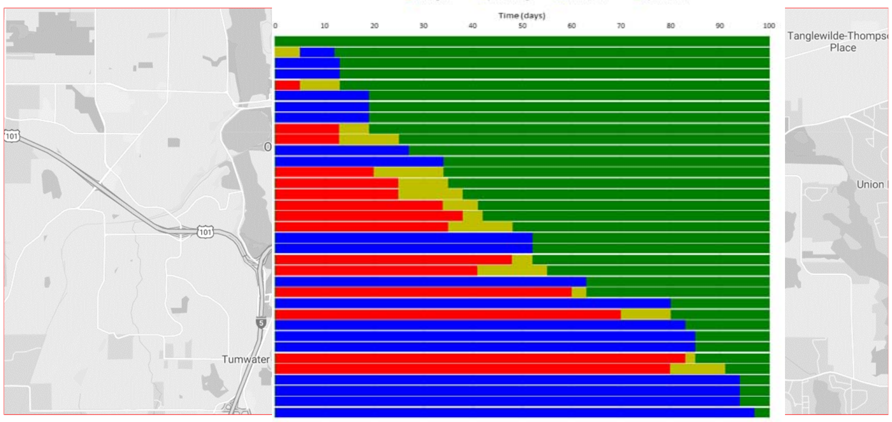
33



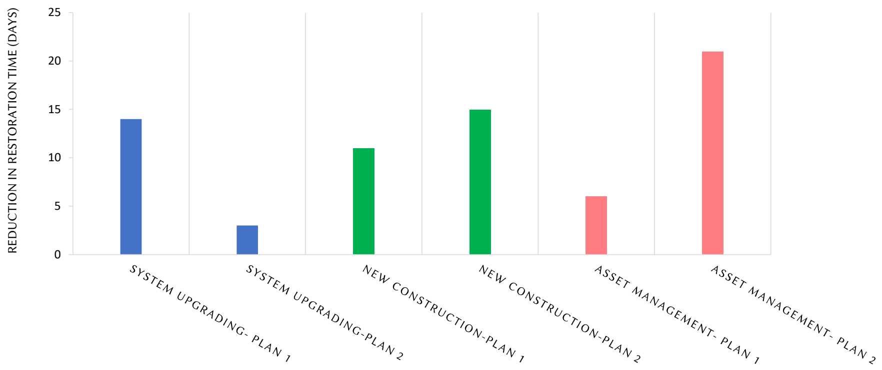
34


time: 91

Entities


damaged
processing
functional
operational
Time (days)
0
10
20
30
40
50
60
70
80
90
100
Tanglewilde-Thomps
Place
Union
Tumwater
101
101
5
O

Improvement Plan Comparison



Your Feedback

- Does this tool facilitate involved agents in envisioning post-disaster restoration? What's missing?
- Does this tool facilitate involved agents in envisioning post-disaster restoration? What's missing?
- Does it improve information sharing collaborations between emergency management and infrastructure agents to perform the planning?
- Does it improve communications and information sharing between infrastructure agents and non-expert community stakeholders?
- Is it worth implementing such tools to facilitate resilience planning in practice? What else should be included in such tools?