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Initial Framework to Design Lifeline Infrastructure for Post-earthquake Functional Recovery

Volume 1

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Initial Framework to Design Lifeline Infrastructure for Post-earthquake Functional Recovery

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Gina M. Raimondo, Secretary, National Institute of Standards and Technology
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This publication is intended to capture perspectives from external experts related to NIST efforts to enhance standards and measurement for disaster risk mitigation. These external perspectives can come from industry, academia, government, and other organizations. This report was prepared as a product of collaborative interactions; it is intended to document diverse perspectives and does not represent official NIST position on topics discussed herein.

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ABSTRACT

Services provided by lifeline infrastructure systems are critical to the recovery of social functions after an earthquake. Lifeline infrastructure includes water, wastewater, drainage, electric power, communications, gas and liquid fuels, solid waste, and transportations systems. They are large, complex, geographically distributed systems built with specialized components made of many different materials over long periods of time. The systems were not originally designed and built for resilience or functional recovery. It is difficult to prevent damage and potential service outages after earthquakes, but the loss and recovery of services can be managed to meet societal needs. The managing of lifeline infrastructure system service losses and recoveries requires (1) the establishing of practical objectives to ensure social needs can be met in a post-earthquake environment, and (2) efficient design and operation of the systems to allow basic service recovery times to meet societal needs. A lifeline infrastructure system is considered functionally recovered when all users have their basic services restored. The recovery objectives must first be defined in terms of when the basic services are needed by customers having different levels of importance to communities during a disaster. The recovery objectives are then used as input to an assets framework and an organizational actions framework. Both the assets and organizational actions frameworks target restoring the lifeline infrastructure system services being restored in a post-earthquake timeframe meeting the defined recovery-based objectives.

The assets framework is an 11-step process incorporating target performance and recovery time objectives at both the component and the system levels to identify, assess, and design the interlinking components and subsystems making up the built infrastructure.

The organizational actions framework is a 10-step process incorporating target performance and recovery time objectives at the group level and across the entire lifeline infrastructure organization to identify, assess, and create a lifeline infrastructure organizational structure populated with groups that can implement processes and perform a coordinated set of duties.

Lifeline systems provide services through the built infrastructure operated with human interaction. The assets and organizational actions frameworks are iterative and interactive and provide the following outputs:

- Component- and system-level designs enhancing ability to functionally recover
- Organizational group policies, plans, and strategies enhancing ability to functionally recover
- Target post-earthquake restoration objectives established consistent with asset designs and organizational policies, plans, and strategies
- Identifying potential measures to mitigate asset and organizational deficiencies to improve functional recovery
- Information for improving the system planning process and useful for decision makers to prioritize funding for mitigation measures

KEYWORDS

Functional recovery; infrastructure; interdependencies; lifelines; recovery objectives; restoration time; seismic design.

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PREFACE

In 2020, the National Institute of Standards and Technology (NIST) contracted with the Applied Technology Council (ATC) to "Develop a Framework for Design of Lifeline Infrastructure Systems for Functional Recovery." The purpose of this project is to develop a framework for functional recovery of lifeline infrastructure systems after earthquake events. More specifically, the goal is to develop a framework for water, wastewater, and electric power systems that considers their dependencies and interdependencies and is applicable to other lifeline infrastructure systems after earthquakes. This framework supports new development as well as upgrade to existing systems so that services can be restored within a targeted recovery time. It is applicable to the design of an entirely new infrastructure or organizational structure, expansion or additions to an existing infrastructure or organization, and replacements or modifications (component or group) in an existing system. The process is useful for the design of individual components as the need arises or a wholesale assessment of all components within the system to plan on-going extensions or replacements. Likewise, the framework is useful for developing policies and strategies to ensure individual organizational groups are adequately prepared or a wholesale assessment of all groups to plan organizational improvements.

The product of this work is a peer-reviewed NIST publication outlining steps for the design of lifeline infrastructure components and the development of groups at levels allowing the system to provide basic services within target recovery times. A second volume presents implementation of the framework to three lifeline infrastructure systems defined for the virtual testbed community of Centerville.

ATC is indebted to the leadership of Craig Davis, who served as the Project Technical Director, and to the members of the ATC-152 Project Team for their efforts in developing this document. The Project Technical Committee, consisting of Laurie Johnson, Anne Kiremidjian, Thomas D. O'Rourke, Ellis Stanley, and Kent Yu served as principal authors of the framework documented in the report. This work would not have been possible without the contributions from Alexis Kwasinski and Farzin Zareian who implemented the draft framework to two infrastructure lifeline systems, as documented in Volume 2. The project benefited greatly from Don Cutler, Bill Heubach, Katie Miller, and Ryan Kersting who provided technical review and advice at key stages of the work.

ATC gratefully acknowledges the input and guidance provided by Katherine "Jo" Johnson who served as Project Officer. Kiran Kahn (ATC) provided report production services.

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EXECUTIVE SUMMARY

Intended Use

Lifeline infrastructure systems include water, energy, communication, and transportation sectors and provide services to support communities, including life safety, public health, and social-economic factors. They require both built assets and the human agency necessary to operate them, but there are no known frameworks that integrate both the assets and the organizational actions needed to go along with the design assumptions to meet target recovery objectives. This document presents an initial framework that guides the reader through steps to achieve system-level functional recovery of lifeline infrastructure systems after earthquake events. The framework addresses how to provide the services that users need when they need them by considering the design of lifeline infrastructure system components, development of organizational policy and strategies, and evaluation of system capacity.

The framework is useful for the design of individual components as the need arises or as a guide for conducting a wholesale assessment of an entire system for retrofit upgrade, maintenance, extensions, or replacements. Likewise, the framework is useful for developing policies and strategies to ensure that organizations are adequately prepared or to guide the wholesale assessment of all groups in planning organizational improvements. The framework can be applied to all lifeline infrastructure systems and considers their dependencies and interdependencies. It is flexible and can be applied at full or partial system scales so that services can be restored after earthquakes within a targeted recovery time. Water, wastewater, and electric power systems were used to form the initial development of this framework, and the application to these three systems is illustrated in Volume 2, published as NIST SP 1311 [NIST, 2024].

The primary audience for the framework includes owner representatives who manage and operate lifeline infrastructure systems and analysts, designers, and others working in support. The framework applications to hypothetical water, wastewater, and electric power systems are presented in Volume 2 to benefit analysts and designers of these and other lifeline infrastructure systems.

Background

The NIST-FEMA [2021] Special Publication, *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Function Recovery Time*, defines functional recovery as: “A post-earthquake performance state in which a building or lifeline infrastructure system is maintained, or restored, to safely and adequately support the basic intended functions associated with the pre-earthquake use or occupancy of a building, or the pre-earthquake service level of a lifeline infrastructure system.” In particular, NIST-FEMA [2021] Recommendation 1 describes the need for a national framework to support functional recovery of critical infrastructure and improve the performance and coordination across multiple lifeline infrastructure systems in order to enhance community resilience. This report presents the results of a project to define tools that will support progress towards achievement of functional recovery goals.

Underlying Philosophy

Lifeline infrastructure across the U.S. encompasses large, complex, geographically distributed systems built with specialized components made of many different materials over long periods of time. Moreover, most lifeline infrastructure systems were not originally designed and built with resilience or functional recovery in mind. As a result, it is difficult, if not impossible, to prevent damage and potential service disruptions after an earthquake, but the disruption and recovery of services can be managed to meet societal needs. This means that new lifeline infrastructure systems can be designed and constructed, existing systems can be modified, and all portions of existing systems can be maintained and operated to limit disruptions and recover services for customers following an earthquake based on the critical nature of those services.

An earthquake not only can damage and disrupt the built infrastructure, but it can also damage or impair the organizational structure by disrupting the ability of groups that manage and operate the infrastructure to perform their functions properly. Further, disruption of the cyber domain can affect information and data exchange needed to recover infrastructure operations. Thus, an earthquake may require the recovery of both the built components and the organizational groups, as well as the ability to exchange information, to restore the system functionality. The recovery of components and information exchange requires group activities. At the same time, some group activities cannot be undertaken until the components and information exchange are recovered, which identify the interdependencies between the technical infrastructure and the organizational actions necessary for the lifeline infrastructure system to operate.

Preparing lifeline infrastructure to functionally recover involves designing physical properties making up the systems (assets) to an appropriate level and establishing pre-disaster recovery plans and organizational actions before and after an earthquake. An iterative process is needed to optimize the design of assets, development of organizational and group policies, and identification of restoration objectives that include considerations of cost and the probability of an earthquake and associated hazards occurring. The outcomes of this iterative process are the final designs, policies and plans, and post-earthquake restoration objectives that can support the functional recovery needs of communities and customers served by a lifeline infrastructure system.

The decision to incorporate recovery-based objectives in the design of a lifeline infrastructure system may come from a combination of external and internal influences on the lifeline infrastructure assets and organization. Once the decision is made to pursue functional recovery policy, planning is initiated. Management and governance establish functional recovery policy by setting system-level performance and recovery-time objectives that then drive the system planning process.

It is important to note that the goal of the framework is to help design systems to recover disrupted services within a timeframe based on the importance of the user to the community during a disaster. Thus, in addition to resulting in optimized designs, there may be a need to inform the lifeline infrastructure system customers and service users of the anticipated service disruption times when an earthquake occurs so they can prepare accordingly.

Framework Structure

The proposed initial framework has been designed to accommodate any form for the target performance and recovery time objectives. Recovery time objectives may differ for customers or users of different criticality. For this framework, the use of the FEMA P-2234 [2024] service recovery time methodology, which incorporates broader societal needs, is recommended as a starting point. Other system-level draft criteria may be used, such as Sattar et. el. [2022]. In addition, the framework aids in and also utilizes earthquake scenario planning. Guidance is provided for incorporating earthquake events as scenarios that includes all potential seismic hazards and their intensities. The framework addresses two types of objectives:

- **Performance Objective:** The planned damage or impaired state of assets and the organization for a specified hazard level.
- **Recovery Time Objective:** The planned duration to restore basic services for a specified earthquake event level.

The framework enables infrastructure system managers to define, iterate, and integrate post-earthquake performance and recovery time objective goals regarding the design of assets and the organizational actions needed to achieve functional recovery goals. The framework is structured with two constituent parts:

- **Assets Framework:** A series of steps are described for identifying, assessing, and designing the interlinking components and subsystems making up the built infrastructure so that lifeline system services are restored in a post-earthquake timeframe that meets the defined recovery-based objectives. The assets framework incorporates target performance and recovery time objectives at both the component and the system levels. This framework is presented in Ch. 4 and comprises 11 steps.
- **Organizational Actions Framework:** A series of steps are described for identifying, assessing, and creating a lifeline infrastructure organizational structure populated with groups that can implement processes and perform a coordinated set of duties to meet the defined recovery-based objectives. The organizational actions framework incorporates target performance and recovery time objectives at the group level and across the entire lifeline infrastructure organization. This framework is presented in Ch. 5 and comprises 10 steps.

The system-level objectives will apply to both constituent parts of the framework. Objectives for the components and groups in the constituent parts must be developed to ensure that system-level objectives can be met.

Framework Application and Outcomes

Assets are the physical properties making up the lifeline infrastructure system and involve each component or subsystem and how they are interconnected. The equipment used to create the cyber subsystems are assets. Assets also include the facilities and buildings that are a part of the lifeline infrastructure system. The assets framework may be used for the design of an individual component. Each component in a system may be designed or redesigned as necessary; the assets framework will help create a consistency for system-level design over time. The assets framework can also be used to layout and/or assess the entire infrastructure system and how it may perform during earthquakes.

Organizations are the body of people and processes having a purpose and structure to manage and operate a lifeline infrastructure system. The organization includes human activities and their interaction with the technical infrastructure, governing bodies, external agencies and organizations, and service users. Organizational actions are the coordinated activities for functional recovery that need to be undertaken by the lifeline organization. Organizations are made up of groups consisting of one or more people who must perform certain tasks necessary for the lifeline infrastructure system to operate.

The organizational actions framework may be used to establish policy, strategies, and procedures for an individual group. Each group in an organization may be structured or restructured as necessary; the organizational actions framework will help create consistency for system-level organization over time. The organizational actions framework can also be used to layout and/or assess an entire organizational structure and procedures to investigate how they may perform during earthquakes.

The performance objectives for assets are usually addressed at the component-level through existing codes and standards. The system-level recovery time objectives may be developed using processes described in FEMA P-2234 [2024], NIST [2015a, 2015b], Sattar et al. [2022], or others. The performance and recovery time objectives for organizational actions at the system-level are not commonly addressed in practice but are a part of this framework.

The system-level performance and recovery time objectives are used as inputs into the assets and organizational actions frameworks. The assets framework provides a process to design and assess the interlinking components and subsystems making up the built infrastructure so that the lifeline infrastructure systems can restore services in a post-earthquake timeframe that meets the recovery-based objectives. The organizational actions framework covers a set of processes for lifeline infrastructure systems to use for functional recovery with a focus on actions to be undertaken primarily by lifeline infrastructure organizational groups. The organizational actions framework provides a process for creating and assessing policies, strategies, and procedures to coordinate groups, including their interactions with the assets, to meet the recovery-based objectives.

The application of the framework is iterative and may result in the following outcomes:

- Component- and system-level designs enhancing ability to functionally recover
- Organizational group policies, plans, and strategies enhancing ability to functionally recover
- Target post-earthquake restoration objectives established consistent with asset designs and organizational policies, plans, and strategies
- Identification of potential measures to mitigate asset and organizational deficiencies to improve functional recovery
- Information for improving the system planning process and useful for decision makers to prioritize funding for mitigation measures

Furthermore, the lifeline infrastructure organization has the responsibility to help ensure that alternative emergency services can be provided to users within the service area during a disruption. It is appropriate for a lifeline infrastructure organization to inform the users of the potential service disruptions following an earthquake as well as help them obtain alternative emergency services along with other emergency response organizations.

1. INTRODUCTION

Lifeline infrastructure systems provide services to support communities, including life safety, public health, and social-economic factors. There is limited guidance on how to design and operate lifeline infrastructure systems for functional recovery. This document presents an initial framework that guides the reader through steps to design system components, develop organizational group policy and strategies, and evaluate lifeline infrastructure to achieve system-level functional recovery. The framework addresses how to provide the services that users need when they need them following an earthquake.

1.1. Background and Purpose

The NIST-FEMA [2021] Special Publication, *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Function Recovery Time*, outlines the needs for improving the functional recovery for lifeline infrastructure systems, with functional recovery defined as follows: “A post-earthquake performance state in which a building or lifeline infrastructure system is maintained, or restored, to safely and adequately support the basic intended functions associated with the pre-earthquake use or occupancy of a building, or the pre-earthquake service level of a lifeline infrastructure system.”

In particular, NIST-FEMA [2021] Recommendation 1 describes the need for a national framework to support functional recovery of critical infrastructure and improve the performance and coordination across multiple lifeline infrastructure systems in order to enhance community resilience. This report presents the results of a project to define the initial steps necessary to accomplish Recommendation 1 for lifeline infrastructure systems.

Lifeline infrastructure systems are often grouped into several principal systems: water, wastewater, stormwater drainage, electric power, gas and liquid fuels, telecommunications, solid waste, and transportation [Duke and Moran, 1975]. The development of this framework included implementation to water, wastewater, and electric power systems and concluded its applicability to these systems. However, the general framework is intended to apply to all lifeline infrastructure systems.

This report presents a framework for enhancing the functional recovery of lifeline infrastructure systems after earthquake events. The framework can be useful for the design of individual components as the need arises or to conduct a wholesale assessment of all components within the system in planning on-going extensions or replacements. Likewise, the framework is useful for developing policies and strategies to ensure that individual organizational groups are adequately prepared or to perform a wholesale assessment of all groups in planning organizational improvements. The framework considers dependencies and interdependencies among water, wastewater, and electric power systems and with other lifeline infrastructure and community systems. It supports new construction as well as upgrades to existing systems so that services can be restored within a targeted recovery time after earthquakes. It is applicable to the design of an entirely new infrastructure or organizational structure, expansion or additions to an existing infrastructure or organization, and replacements or modifications (component or group) in an existing system.

Lifeline infrastructure are large complex interdependent socio-technical systems. They require many aspects to be incorporated to achieve functional recovery [NIST-FEMA, 2021; Davis et al., 2022a]. This framework attempts to be comprehensive to show the numerous facets that need to be incorporated, and how they are interrelated. This is the first framework attempting to incorporate all the socio-technical facets in an integrated method. The framework is developed using a novel approach based on observed past earthquake basic service recoveries [Davis, 2014]. The proper background and information are provided so it can be used across all lifeline infrastructure systems. Input was obtained from a diverse range of experts to bring forth the perspectives within the multiple disciplines pertinent to the framework formulation. Each of these aspects add length and complexity to the reporting documents, which makes it difficult for smaller lifeline infrastructure systems to utilize (see Sec. 6.1.3 recommending future advancements to remedy this situation). Portions of the framework may be implemented independent of the rest, but the long-term goal should be to carry out the framework as a whole to develop lifeline infrastructure systems that are able to achieve service recovery time objectives and support community needs following earthquakes.

This initial framework to design lifeline infrastructure for post-earthquake functional recovery is expected to be modified as appropriate when enhancements and advancements are developed.

1.2. Intended Audience

The proposed framework improves the design of new lifeline infrastructure and retrofits to existing systems and the associated organizational actions needed to meet service recovery objectives. These characteristics require an ability to measure expected service losses and recovery times in order to determine if the recovery objectives can be met. Developing the method for measuring lifeline infrastructure service losses and recovery times requires procedures specific to the owners and operators of lifeline infrastructure, which are beyond the scope of this work.

The primary audience for the framework includes owner representatives who manage and operate lifeline infrastructure systems and those working in support. The supporting cast includes analysts, design engineers, system planners, emergency managers, system administrators, and others who play a role in the planning, analysis, design, construction, operation, and maintenance of infrastructure to ensure it can withstand and recover from earthquakes.

1.3. Outcomes

A key takeaway from this work is an overarching framework that uses target service recovery times for designing system components and related organizational actions. This framework is related closely to the framework published in FEMA P-2234 [2024] that results in establishing target service recovery time objectives. To apply these frameworks, acceptance of shared thinking and a common vocabulary across disciplines are important. More specifically, the following definitions have been developed as part of this project:

- The acceptable state of functionality needed to define a lifeline infrastructure system as functionally recovered (see Sec. 2.4)
- Common understanding of system function and functionality and relationship with the provision of basic services (see Sec. 2.4)
- Lifeline infrastructure system asset criticality categories and organizational essential functions, and critical customer/user categories that are associated with target recovery times (see Chapters 4 and 5)
- Documentation of transparent processes for designing lifeline infrastructure assets and the related necessary organizational actions to meet target service recovery times (see Chapters 3 to 5)

The framework creates a process usable for all lifeline systems of any size. It is to be applied to lifeline infrastructure systems addressing their local conditions. Key outcomes from using the framework include:

- Component- and system-level designs enhancing ability to functionally recover
- Organizational group policies, plans, and strategies enhancing ability to functionally recover
- Target post-earthquake restoration objectives established consistent with asset designs and organizational policies, plans, and strategies
- Identification of potential measures to mitigate asset and organizational deficiencies to improve functional recovery
- Information for improving the system planning process and useful for decision makers to prioritize funding for mitigation measures

1.4. Report Organization

This is Volume 1 of two reports. This volume is organized as follows:

- Chapter 2 presents background information including important concepts underlying the framework
- Chapter 3 presents an overview of the entire framework which has two constituent parts – an assets framework for the built lifeline infrastructure systems and an actions framework for lifeline infrastructure organizations
- Chapter 4 describes the 11 steps that comprise the lifeline infrastructure system assets framework
- Chapter 5 describes the 10 steps that comprise the lifeline organizational actions framework
- Chapter 6 describes application of the framework and necessary future work

A glossary and lists of references are provided at the end of this report. Application of the proposed framework to water, wastewater, and electric power using infrastructure systems within a fictitious city named Centerville is presented in Volume 2, published as NIST SP 1311 [NIST, 2024].

2. BACKGROUND

2.1. Framework Philosophy

Operation of lifeline infrastructure systems involves complex socio-technical relationships, and this framework addresses both the technical systems and the human agency necessary to operate them [Davis et al., 2022b; Davis, 2023]. The framework combines the technical infrastructure (physical, built, and cyber) and the human agency required to design, maintain, and operate the lifeline infrastructure system to meet specified earthquake performance and recovery time objectives. There are no other known frameworks attempting to integrate both the assets and the necessary organizational actions needed to go along with the design assumptions to meet the recovery objectives.

Lifeline infrastructure systems can be designed and operated to achieve post-earthquake target service recovery times to meet societal needs. Recovery time objectives may differ for customers or users of different criticality within a community. Lifeline infrastructures often involve large, complex, geographically distributed systems built with specialized components made of many different materials over long periods of time. Moreover, most lifeline infrastructure systems were not originally designed and built with functional recovery or resilience in mind. As a result, it is difficult, if not impossible, to prevent damage and potential service disruptions after an earthquake, but the total loss and recovery of services can be managed to meet societal needs. This means that new lifeline infrastructure systems can be designed and constructed, existing systems can be modified, and all portions maintained and operated to limit disruptions and recover services for customers following an earthquake based on the critical nature of those services.

Figure 2-1 is used to describe the rationale for and organization of the framework. It illustrates how the seismic design of lifeline infrastructure systems is driven by the consequences of service disruptions and based on providing post-earthquake services to meet societal needs.

Lifeline infrastructure is composed of built infrastructure, data and information (cyber), and organizational and management processes implemented through human action (boxes on the left of Fig. 2-1). The built infrastructure and cyber domains make up the technical systems and are the primary means through which services are delivered to customers [NIST, 2016a].

Lifeline infrastructure systems are developed based on planning, policy, and governance to establish the objectives for how the lifeline infrastructure systems function before and after earthquakes. This development initiates the clockwise flow of information from the upper left to the box holding the assets and organizations in the lower left of Fig. 2-1. The services provided by lifeline infrastructure systems are essential for communities to function (top right of Fig. 2-1). During times of service disruption basic service restorations are prioritized to the most critical users (lower right). Moreover, strategies are employed to reduce the societal consequences of service disruptions. Users will adapt to temporary service disruptions. Additionally, all basic services should be restored within a timeframe to meet community recovery objectives while satisfying public health, safety, and property protection objectives consistent with existing guidelines, standards, and codes. Service restoration goals are established to reduce the consequences resulting from disruptions. Customer and user priorities distinguish the more important parts of the lifeline infrastructure networks as well as the resources to support them (lower left).

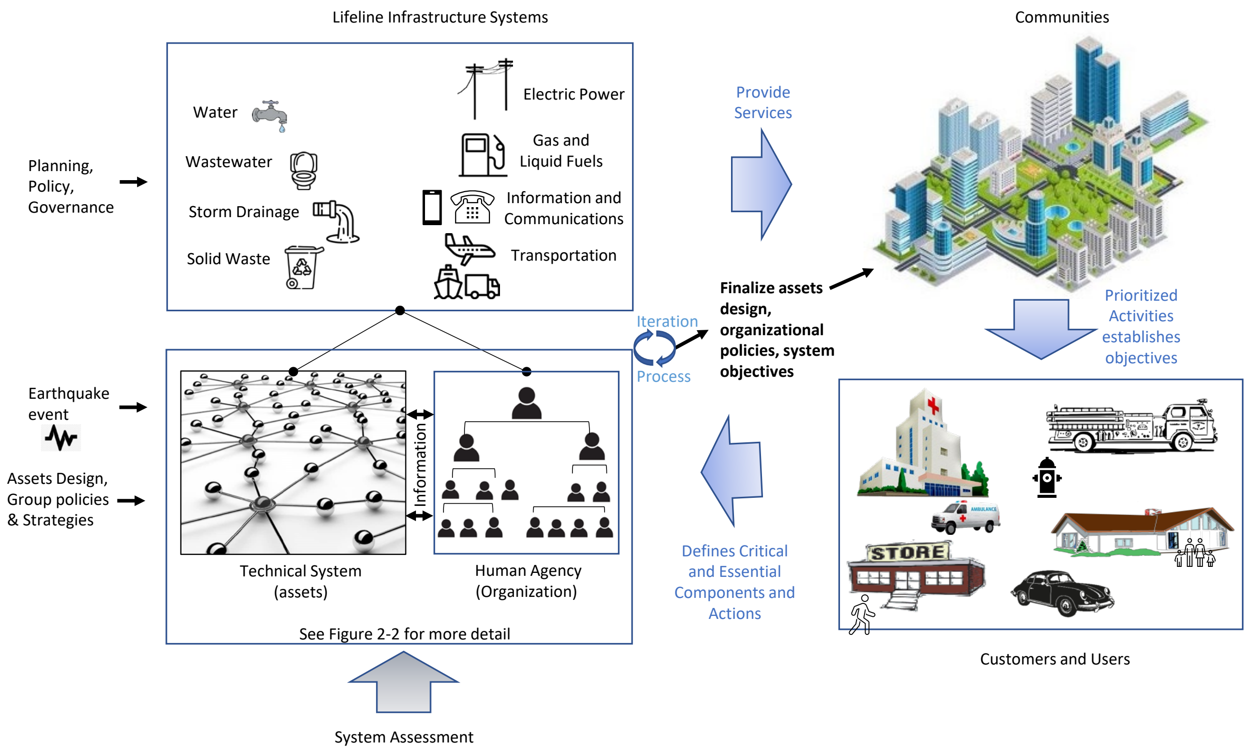

Figure 2-1. Framework philosophy schematic. (icons from www.flaticon.com, community from www.wallstreetmojo.com/public-infrastructure/).

The box containing assets and organizations in the lower left of Fig. 2-1 have additional injections from the left and bottom. The components are designed so the system can meet the service objectives. The more critical components are designed for higher earthquake hazard intensity levels, resulting in a lower likelihood of failure, than the components having a lower criticality level. Organizational groups having higher essential functions work under more detailed policies and strategies than those of lower level. The asset networks and organizational structure and activities are assessed (bottom inject) against earthquake event scenarios to confirm their capability to meet system-level performance and service recovery time objectives.

There is an iteration process to optimize the assets design, the organizational and group policies, and the service restoration objectives, which includes cost considerations and the probability of an earthquake and associated hazards occurring. The outcomes of this iteration process are the final designs, policies and plans, and post-earthquake service restoration objectives (center upward diagonal arrows in Fig. 2-1). These outcomes are applied to the lifeline infrastructure systems to support the communities they serve.

It is important to recognize how an earthquake not only affects the built infrastructure, but also the potential flow of information, and the groups of people making up the lifeline infrastructure system organizations, along with the communities they serve. As a result, there are deep inter-relationships between the lifeline infrastructure system functional recovery and the community resilience.

The service recovery objectives include targets for the lifeline infrastructure system to restore their basic services to customers. Section 2.4 describes how functional recovery is achieved for lifeline infrastructure systems when all the basic services are restored to customers and users. As each customer and user receives their basic services from the lifeline infrastructure systems, they can begin resuming normal activities relative to those amenities.

2.2. Lifeline Infrastructure Systems

Lifeline infrastructure systems have been identified in Ch. 1 as those critical to the functioning of modern society. They include water, wastewater, drainage, communication, electric power, gas and liquid fuels, transportation, and solid waste systems [Duke and Moran, 1975]. They are socio-technical systems made up of physical components (i.e., the physical assets) and human agency (i.e., the organizational actions). The components are interconnected and inter-related through physical and virtual links.

The socio part of the socio-technical system is the human domain which includes the organizational and management processes, procedures, policies, and corporate culture, as well as the compilation and utilization of data with the support of cyber systems. The technical part comprises the physical and cyber domains. The physical domain encompasses the manufactured and built infrastructure, which includes the equipment utilized as part of the cyber domain. The cyber domain includes data and information along with the needed control and operations algorithms [NIST, 2016a]. As a result, lifeline infrastructure can also be referred to as human-cyber-physical systems [NIST, 2016a], socio-ecological-technical systems, and digital-physical-social systems [Sinha et al., 2023]. This framework does not intend to contradict various taxonomies and methods categorizing infrastructure systems. As shown in Fig. 2-2, in this framework, the phrase lifeline infrastructure system refers to the social-technical system including the physical assets and organizational structure along with the information exchanged.

Figure 2-2 identifies how the lifeline infrastructure system is composed of the technical infrastructure and human agency. The technical infrastructure operates via assets through the physical and virtual interconnection of components to provide basic services. The human agency operates via organizational actions through the interaction of groups to provide essential functions. Functional recovery is achieved when the lifeline infrastructure system can support the basic intended functions associated with its pre-earthquake use. The basic intended functions require the assets to provide basic services to customers and users, mainly through the physical and cyber domains, which cannot be attained unless the organization can provide its essential functions. The effectiveness of assets and groups in Fig. 2-2 to provide basic services and essential functions depends on performance of the designs and plans, including information exchange, in the face of earthquake-induced damage and disruption.

Figure 2-2 illustrates how lifeline infrastructure systems are composed of two equally important categories – the technical portion and the human portion. Functional recovery cannot be achieved without incorporating both categories [NIST-FEMA, 2021]. This framework includes both the assets and organizational actions as shown in Fig. 2-2. A third critically important category is the control and command in cyberspace that use specialized assets to store and process data and information identified by the organization. The data and information are used by groups and potentially to automate the operation of other components. Figure 2-2 diagrams how the cyber domain works as a subsystem to provide services within the lifeline infrastructure system.

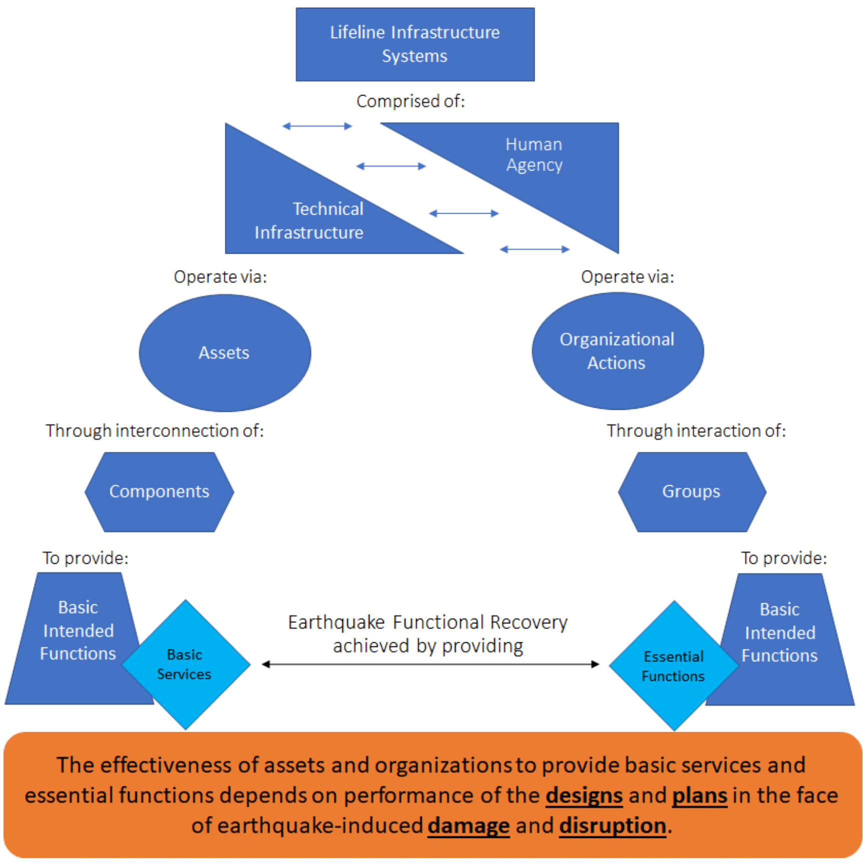

Figure 2-2. The structure of lifeline infrastructure systems comprises technical infrastructure and human agency.

2.2.1. Assets

Assets are defined as the physical properties making up the lifeline infrastructure system and involves each component or subsystem and how they are interconnected to make up the overall system. The equipment used to create the cyber subsystems are assets. Assets also include the facilities and buildings that are a part of the lifeline infrastructure system.

2.2.2. Organizational Actions

Organizations are the body of people and processes having a purpose and structure to manage and operate a lifeline infrastructure system. The organization includes human activities and their interaction with the technical infrastructure, governing bodies, external agencies and organizations, and service users. Organizational actions are the coordinated activities for functional recovery that need to be undertaken by the lifeline infrastructure organization. Organizations are made up of groups of people. A group is one or more people who must perform certain tasks necessary for the lifeline infrastructure system to operate. The people in a group commonly also make up portions of the community being served by the lifeline infrastructure system services.

2.2.3. Importance and Interaction of Assets and Organizational Actions

Functional recovery for lifeline infrastructure systems involves the designing of the assets to an appropriate level, pre-disaster recovery planning, and organizational actions before and after an earthquake. Designs are developed using engineering processes using guidelines, standards, and codes. Organizational actions are established through processes and procedures. The assumptions in selecting the design level and service recovery times for the built infrastructure assets are intimately integrated with organizational actions needed to properly address how those assumptions are enacted, or not, into the system itself and throughout the community being served by the lifeline infrastructure system. Further, independent of the seismic design for the assets, the built infrastructure cannot recover and operate without organizational actions. An earthquake not only can damage and disrupt the built infrastructure, but it can also damage or impair the organizational structure by disrupting the ability of groups to perform their functions properly. Further, disruption of the cyber domain can affect information and data exchange needed to recover infrastructure operations. Thus, an earthquake may require the recovery of both the components and the groups, as well as the ability to exchange information, to restore the lifeline infrastructure system functionality. The recovery of components and information exchange requires group activities. At the same time, some group activities cannot be undertaken until the components and information exchange are recovered, which identifies the interdependencies between the technical infrastructure and the organizational actions necessary for the lifeline infrastructure system to operate.

2.2.4. Networked Systems, Subsystems, and Components

The lifeline infrastructure systems are composed of multiple primary subsystems and specialized components having a direction of service flow as follows for water, wastewater, and electric power, as follows:

- Water subsystems include supply, treatment, transmission, and distribution.
- Wastewater subsystems include collection, conveyance, treatment, and disposal. Wastewater systems may also include water reclamation for reuse in coordination with water supply and distribution systems.

- Electric power systems include generation, transmission, and distribution.

Some examples of specialized components within these subsystems include dams and reservoirs, treatment plants and disinfection stations, and generation stations [NIST, 2016b], each of which can be a major subsystem. In this context, lifeline infrastructure is made up of multiple subsystems, where a subsystem is a system within the lifeline infrastructure system, which can be evaluated separately. Subsystems also include embedded communications and mechanical and electrical systems like supervisory control and data acquisition (SCADA).

A networked system involves interlinking and inter-related components. A set of components make up each of the primary subsystems to perform specific functions within the overall lifeline infrastructure system. The concept of a component is relative to the scale of the system or subsystem. Many components can arguably be defined as a subsystem. For example, a pipeline of defined length is normally considered a component within a water or wastewater system. However, the pipeline may be composed of a subsystem of interlinking pipe segments with different fittings to meet its purpose. Each pipe segment may also be described as a subsystem with specific jointing, corrosion protection, and gasketing functions. At the scale of a regional lifeline infrastructure system, a building making up a portion of the system is considered a component. However, if the building were addressed by itself, it would be considered a system; and many components making up the building would be considered subsystems (e.g., plumbing, electric power, lighting, HVAC, etc.).

In this framework, components are defined as lines, nodes, and site locations of facilities which make up a system or subsystem. The subsystems are spatially distributed networks of interlinked and inter-related components working together to serve a common purpose like those identified above.

2.3. Key Concepts

2.3.1. Performance and Recovery Objectives

Objectives are the targeted specific result from how the lifeline infrastructure systems should function and operate after an earthquake. They include human behavior, built infrastructure performance, and the ability of the system to operate and provide services to users. The objectives cover public health and safety, property protection, damage levels within the system, completing activities, and the lifeline infrastructure system services to be provided.

Performance objectives refer to the ability of the components and groups making up the system, as well as the system as a whole, to accommodate or withstand seismic hazards. Service recovery time objectives refer to providing services within a time duration after a service disruption has occurred because of damage resulting from an earthquake. The objectives need to be measurable. A concept addressing both performance and recovery objectives is recovery-based objectives [NIST-FEMA, 2021] which identifies the asset design level needed that allows recovery within a specific time frame. To achieve functional recovery, there also must be an associated set of personnel actions associated with the asset performance levels to accomplish a service recovery within a specified duration.

For the design of assets, safety and property protection are normally covered in common design guidelines, standards, and codes and therefore are not described in further detail in this framework; it is assumed safety and property protection are covered by other appropriate documents. Performance objectives can be addressed at the component-level and system-level. However, since the system is made up of the interlinking of all components making up the built infrastructure and groups within the organization, the performance objectives in this framework will only be addressed at the component and group levels. Service provision is provided at the system-level through the interaction of human activities and operating components. As a result, the service recovery time objectives will be addressed only at the system level. To achieve service recovery, there is a minimum duration for which repairs must be completed to some damaged components. Moreover, certain system adaptations may need to be completed. As a result, repair time objectives may be necessary for some components and require the interaction of the assets and organizational actions frameworks as described in Chapters 4 and 5, respectively. This framework uses the objectives as an input into the processes (e.g., from FEMA [2024], or Sattar et al. [2022]). However, describing the procedures for developing target objectives is beyond the scope of this framework.

Different objectives may be proposed for different earthquake events and intensity levels as further described in Sec. 2.5. Volume 2, published as NIST SP 1311 [NIST, 2024], presents example system-level objectives, respectively, for water, wastewater, and electric power systems.

2.3.2. Dependencies and Interdependencies

Dependencies are the reliance of infrastructure on services or the influence provided by other infrastructure or social systems. The services may be provided by permanent or temporary systems [NIST, 2017]. Under normal conditions, the supported infrastructure is reliant on services provided by the supporting infrastructure.

The influence of other infrastructure or social systems may be spatial or temporal. One system is dependent upon another to complete necessary tasks within a defined space and time. The spatial influence comes from impacts associated with damage and the interaction of resources as services from multiple lifeline infrastructure systems. The temporal influence is described by buffers in Sec. 2.3.5 and the sequential scheduling of repairs.

NIST [2016a] indicates that dependencies appear when a system, subsystem, or a component requires the provision of a service to perform its functions adequately. That is, dependencies are established with respect to services and not on specific systems or infrastructures providing those services. This is because, in general, it is possible that a given service could be provided by different providers. A common example of a dependence is water distribution networks requiring the provision of electricity to power their pumps. Although the electricity is often and normally provided by a local electric utility company, it could also be provided by a locally installed natural gas-fueled generator, without requiring an electric grid, and instead requiring a natural gas distribution network for receiving the electric power. Another example of a dependency is communication facilities requiring the provision of electric power, which is often primarily provided by an electric grid. However, during power outages, the service could originate from batteries or, if longer backup times are required, electric power could be provided by a diesel-fueled internal combustion engine driving an electric generator. As NIST [2016a] indicates, dependencies can also be established through human interactions with respect to social services (for example, by electric utilities requiring education services in order to have a well-prepared workforce; or, as indicated in Kwasinski et al. [2024], by requiring financial services to support their operations).

There are various classifications of dependencies (e.g., Rinaldi et al. [2001]; Yao et al. [2004]; Kwasinski et al. [2024]). This framework does not adhere to any specific published classification terminology but does generally use the following to understand the different types of dependencies:

- Functional dependencies are established when a system requires some function provided by another system to operate. Examples of functional dependencies are those included in the previous paragraph.
- Intra-dependencies are dependencies established within a given organization. For example, electric power grid operations depend on communications, sensing and control services provided by a private information and communications network that is part of the electric grid infrastructure. Because infrastructure systems provide their services through their physical domain, as defined in NIST [2016a], all services provided by the human operators and administrators of such infrastructure system also establish intra-dependencies.
- Conditional or substitute dependencies which often appear with backup systems are typically represented as adaptations. Conditional dependencies appear when a service is needed because of the lack of a primary service. For example, backup electric power generators are used to provide electricity during an electrical grid outage. The backup power generator establishes the need for refueling services. The refueling services are only necessary because of the condition resulting from the primary electric service provider having a service loss.
- Geographic or collocation dependencies appear when elements of multiple infrastructures are in close spatial proximity and an event can influence all of them. For example, a break in a buried water pipeline floods an electrical vault causing the electric line to short circuit and results in an electric power service disruption. In this case, the electric power is reliant upon the water line remaining in service without breaking; but it could also be decoupled from the dependency by construction of a vault and line that can manage the flooding. The dependency is associated with the spatial influence of one infrastructure upon another and the scheduling of operational changes and damage repairs.
- Physical dependencies are a special type of geographic or collocation dependency and appear when a system requires the use of a physical asset of another system. For example, a bridge (a physical asset belonging to a transportation network) could support electric cables, or a pipeline, to cross a river. Hence, the electric power, or water, or wastewater system needs the service to “bridge an obstacle” provided by an asset in a transportation network.

Other types of dependencies include cyber and logical [Rinaldi et al., 2001], and restoration [Yao et al., 2004]. The cyber and logical dependencies are embedded within the above outlined types by addressing lifeline infrastructure systems as socio-technical systems. The restoration dependency is addressed through the functional and geographic dependencies by the framework specifically incorporating recovery-based objectives.

When dependencies occur mutually between two systems, they are referred to as interdependencies [Rinaldi et al., 2001; NIST, 2016a].

Identifying dependencies is a critically important step when planning and designing for resilience because all dependencies have a negative impact on resilience [Kwasinski et al., 2024]. The main issue for identifying dependencies is to correctly identify the needed support service creating the dependence, i.e., first, the needed service is recognized and only then, as a second step, the ways in which the support service could be provided are identified. In some situations, identifying the support service is relatively simple, such as the provision of electricity or the provision of water. In other cases, identification of the support service is more complex, such as the service “provision of physical connectivity” provided by transportation networks or identifying the geographic proximity of vulnerable components which may harm the system being assessed.

Some additional dependency and interdependency examples pertinent to this framework include:

- Water is needed by electric power generation plants to generate steam for creating power.
- Gas leaks following an earthquake can delay the restoration of electric power service out of concern for electrical power switches found in buildings that may ignite fires.
- Reduction in transportation system capacity affecting fuel delivery for emergency generators, which can impact pumping of water and wastewater.
- Loss of telecommunications in a SCADA system affecting water storage and transmission.
- Reduced services of transportation and telecommunication systems negatively affecting emergency crews’ ability to restore water, wastewater, and electric power.

This framework considers interconnected infrastructure at the component and system levels. Unidirectional dependency relationships are commonly addressed at the component level. Bi-directional interdependency relationships are more commonly addressed at the system level.

2.3.3. Adaptations

Adaptations occur in response to a reduction in lifeline infrastructure system service levels. There are many adaptations possible that change by event and local conditions. The range of potential adaptations may change with local resources, climate, topography, time of year, duration of service disruption, and many other factors. Understanding adaptations and how they are used by the lifeline infrastructure system and service users is important for proper selection of performance and recovery objectives.

Studies have found the public is willing and able to manage service disruption in times of crisis [NIST, 2016b; Peterson et al., 2020]. Further, disaster-impacted individuals rarely passively wait around for someone else to take care of their needs. This means the public will actively adapt to the crisis and accommodate limited-service disruptions. Examples include the use of bottled water, portable toilets, and power generators. FEMA P-2234 [2024] provides more detailed descriptions of adaptations and how they are important for developing service recovery time objectives.

Adaptations can be classified in many different ways [Davidson et al., 2023]. In this framework, they are identified as user response actions and system adaptations. The following are examples of typical user response action adaptations. These adaptations either decrease, delay, or relocate demand or supplement supply or collection.

- Reduce consumption (e.g., skip showers)
- Delay consumption (e.g., reschedule manufacturing activities)
- Temporarily relocate (e.g., residents going to a hotel or to a friend’s or relatives house or a medical facility, working from home)
- Use a regionally redundant facility (e.g., alternate hospital, school, or grocery store)
- Use alternate equipment (e.g., use a portable space heater in place of central heating)
- Modify a facility for alternate use (e.g., using a recreation center as a heating or cooling center)

Adaptations can also be applied at the system level by the lifeline system operator to supplement system service levels, such as rerouting the system around damage and providing alternative emergency services to users by utilizing different ways of delivering or collecting product, possibly in coordination with emergency managers, (e.g., a water company delivering tanked water, an electric power company providing a portable generator, wastewater company deploying portable toilets).

Third-party community organizations or disaster relief agencies may also implement adaptations by providing alternative emergency services auxiliary to the lifeline infrastructure system supplies, such as providing bottled water and establishing warming/cooling centers for use by the general public.

The ability of users to implement adaptations is important when identifying realistic and cost-effective allowable service disruptions and recovery times. Although adaptations may be useful to the majority of users, the change in service level and associated need to implement adaptations may disproportionately impact some vulnerable lifeline infrastructure system service users. For instance, some users may be highly reliant on the quality of service normally provided. Examples include residents who have medical reliance on electric power or potable water for which adaptations may have limitations in their quality or duration of use. Some businesses require large quantities of high-quality product which cannot be supplemented with alternatives to the network (see FEMA P-2234). Some adaptations require a significant amount of effort or resources that may not be available. Some adaptations may require specialized equipment or natural resources that may not be available to all. Some adaptations may have side effects that draw more resources and effort than intended.

Adaptations have limited durations. Adaptations temporarily provide the basic services in alternative ways when the network cannot conventionally provide them. The duration limitation may result from the need to manage costs, scheduling, resources, communications, or societal risks. For example, electric power generators only last while fuel is available, and able to be replenished when used. Cellular phone service may be spotty during a disaster. While people are resilient, their patience is limited and temporary. After a certain period of having no power for heat or water for showers, the consequences may become too great resulting in eventually relocating out of the disaster area. This relocation can become permanent once they find a new residence and their kids are in a new school, creating broader societal consequences in the disaster-stricken area. There is also a time range or duration within which the use of adaptations becomes unmanageable.

2.3.4. Redundancy

Redundancy is an important strategy to reduce the probability of service disruption due to damage to an infrastructure component. The notion of redundancy is to have more than the minimum necessary number of a component having a design capacity of N serving a given function. There are different levels of redundancy. The level of redundancy to N is L_R and is denoted as $N + L_R$ redundancy. L_R is an integer. For example, when $L_R = 0$, then there are just enough components to provide the capacity for the system to meet the demand. If there is a failure, the system loses a component and cannot meet the demand until it is repaired. When $L_R = 1$, if there is exactly one failure then there is still N capacity for operation and, thus, service is not interrupted.

For example, assume a critical facility consuming a power level of P is powered by local diesel generators. Because of its criticality, these generators are engineered with (N + 1) redundancy. If $N = 1$, then each of the (N + 1) (i.e., two) generators is rated for a power output of P. The total capacity of the (N + 1) generators is then two times P. This solution requires an investment in multiple generators with a combined double capacity that exceeds the minimum needed by the facility. If, instead, $N = 2$, then each of the (N + 1), or three, generators are rated for half the power of the facility. Thus, the total capacity of the (N + 1) redundant arrangement of generators is one and a half times that of the facility. A simple analysis yields that, as N increases, the total cost of redundancy likely decreases because, in the provided example, the total capacity of the (N + 1) arrangement of generator converges to P. However, as N increases, so does the probability of having more than one of the (N + 1) components—i.e., in the example (N + 1) generators—being in a failed state simultaneously and, thus, having the entire (N + 1) system being unable to perform its function and experiencing a loss of service. Thus, the design of redundant systems involves a tradeoff between lowering costs and increasing chances of system failure. One alternative to the issue of increasing chances of system failure with increasing values of N is to increase the redundancy level to (N + 2) or higher redundant arrangements. However, higher redundancy levels also have higher costs, so the design challenges associated with the cost vs. loss of service probability remain.

In the context of this framework, it is also important to distinguish the concept of redundancy from that of geographical diversity. A potential issue with redundant components in a geographically dependent event, such as an earthquake, is that the earthquake could affect all redundant components to common-cause failures if they are collocated. For example, it could be possible to have redundant electric power lines serving a critical facility. But, if those lines are running along the same path, it is likely that the earthquake could affect the redundant lines in an equal way. Hence, wherever possible, it is necessary to preserve the advantages provided by redundancy by also implementing geographic diversity which implies locating the redundant components in different places. In the case of redundant electric power lines, geographic diversity implies having the redundant lines following different paths.

2.3.5. Buffers

Buffer is a generic term to identify alternative ways of providing a service on a temporary basis. Buffers are related to dependencies described in Sec. 2.3.2, system adaptations described in Sec. 2.3.3, and redundancy described in Sec. 2.3.4.

Buffers are normally applied to delay or prevent disruption of dependent services. It is a concept to supplement supply flow with storage or alternative sources. The simplest realization of buffers are batteries used to store electrical energy or water tanks used to store water. Like all buffers, batteries and water tanks have a storage capacity. The amount of time (called autonomy) a buffer can provide a given service depends on the buffer capacity and the rate of use of such service. Design capacity of a buffer depends on the expected restoration time for the service they are providing an alternative to and the criticality of that service. For example, if a customer Y requires no loss of water service after an earthquake, then it could install a water tank with a capacity providing an autonomy longer than the expected recovery time for the primary source of the water delivery service. Yet, it is important to indicate that expected recovery times are random variables and, thus, there is no complete certainty that a water tank providing an autonomy equal to the expected recovery time will prevent loss of water provision in the aftermath of the earthquake. The only theoretical way of ensuring certainty is to build the water tank with an infinite capacity. Since such a solution is, evidently, impossible to realize, it is up to the designer to calculate the water tank capacity assuming a given probability—which becomes a design parameter—that the recovery time would exceed the autonomy provided by the water tank. Still, as explained in Kwasinski et al. [2024] even when in practical terms buffers cannot prevent a loss of service, they do mitigate the negative effect of dependencies on resilience. In this context, when built into the system, buffers provide a level of redundancy, at least for a limited time. Further, buffers which are not a part of the normal system operations may also be considered a form of an adaptation. Thus, buffers are an important asset when designing for improved functional recovery and resilience. Sec. 2.4.4 graphically shows the application of buffers.

2.3.6. Lifeline Infrastructure System Owners and Operators

Lifeline infrastructure systems are owned and operated by many different types of organizations including public, private, federal, state, municipal, special districts, etc. This section covers ownership and operations as well as assessment and subsystem service recovery.

2.3.6.1. Ownership and Operations

Some lifeline infrastructure systems are owned and operated by a single organization. Some organizations own and operate subsystems or components making up portions of a lifeline infrastructure system. In some cases, a subsystem or component may be owned by one organization and operated by another. Regardless of the ownership and operating organization of each subsystem and component, in this framework lifeline infrastructure includes the entire set of subsystems from source to delivery for water, generation to delivery for electric power, and collection to disposal for wastewater systems.

2.3.6.2. Subsystem Service Recovery and Assessment

Assessments may cover individual subsystems, multiple interconnecting subsystems, or the complete set of subsystems making up the entire lifeline infrastructure system. Each subsystem provides services for customers and users. The customer or user may be another separately owned subsystem making up a portion of the entire lifeline infrastructure or an external consumer of the services in the case of distribution or collection subsystems. Key to the assessments is complying with the needs of the customer. All the individual subsystem objectives must meet the needs of the upstream and downstream subsystem customers.

Analyses must consider how all the subsystems and components work together as a whole for service provision. Each downstream subsystem is dependent on the flow of services from the upstream subsystems (an intra-dependency, see Sec. 2.3.2). Likewise, each upstream subsystem depends on the downstream subsystem receiving the flow. There are similar service dependencies on components upstream and downstream of other components. Each separately owned and operated subsystem must coordinate and interact with the other subsystems for the whole system to function and deliver services to end users. To do this, the subsystem owners and operators must each have their own performance and service recovery time objectives which meet the needs of the other subsystems to which they provide services. Each owner and operator of individual components must similarly have their own performance and service recovery time objectives which meet the needs of the other components to which they provide services. The goal of post-earthquake recovery is for all the lifeline infrastructure subsystems and components to coordinate and deliver basic services within an acceptable duration that allows the end users to undertake their societal activities in support of community resilience [FEMA P-2234].

The development of service recovery times for each asset which may be owned or operated by different organizations is not always straight forward. It is a function of the topology of each set of subsystems and how they connect and interact. Subsystems having redundant upstream services, like an electric power transmission line receiving services from multiple generation facilities, have less reliance on service restoration from any single generation plant. In contrast, the lack of redundancy places complete dependency on the services provided by a single upstream subsystem.

Lifeline infrastructure system service recovery time is commonly identified for the end user (e.g., FEMA P-2234) considering the system as a whole, but not for each subsystem. For a linear set of primary subsystems (e.g., generation, transmission, distribution for electric power) having no redundancy, the service recovery time for each, including operational transition time between each subsystem, must sum up to the system service restoration time. Where redundancies exist, the service recovery times of some subsystems may be longer than those identified for an equivalent liner set of subsystems. Some subsystems may not be able to make repairs without services from the upstream subsystem. For example, water distribution subsystems will be unable to locate leaks if there is no water to fill the pipelines. As a result, each subsystem owner and operator must coordinate with all upstream and downstream dependent subsystems and component owners within the iteration process described in Fig. 2-1. This needed coordination is part of each lifeline infrastructure system's organizational actions activities (see Step O3 in the Ch. 5 organizational actions framework).

2.4. Functional Recovery of Lifeline Infrastructure Systems

This section describes the concepts necessary to understand how functional recovery is applied to lifeline infrastructure systems. It provides background information used to develop the framework in Chapters 3, 4, and 5. A common understanding on how the concept of functional recovery is applied to lifeline infrastructure systems is critical for having consistent design and operation.

The NIST-FEMA [2021] definition of functional recovery is given in Ch. 1 and is repeated here using gray font to de-emphasize the portions intended only for buildings.

A post-earthquake performance state in which a building or lifeline infrastructure system is maintained, or restored, to safely and adequately support the basic intended functions associated with the pre-earthquake use or occupancy of a building, or the pre-earthquake service level of a lifeline infrastructure system.

NIST-FEMA [2021] goes on to say that basic intended functions are less than full pre-earthquake functionality, but more than what would be considered the minimum functionally sufficient for reoccupancy of buildings, or for temporary provision of lifeline services. Further, it is important to understand that functional recovery is defined as a state of the lifeline infrastructure system at some point in time after an earthquake.

2.4.1. Basic Services

A service is what is provided to fulfill a public need or customer demand. The term basic services is used to define and measure the fundamental services that a lifeline infrastructure system provides to customers to meet their basic needs following a natural hazard event, such as an earthquake. Basic services may be measured (e.g., volume or flow rate) and used as objectives for system service recovery. They also allow the functional recovery to be managed to a greater degree than by assuming a lifeline infrastructure system provides only a single service. The relationship between basic services and functional recovery is described below.

Before an earthquake strikes, customers receive a normal service. The normal service has multiple dimensions including all the basic services, a level of expected reliability, and enhanced service [IPWEA, 2015; LGAM, 2019]. An example of an enhanced service is treating water and wastewater to levels beyond those required by regulation. The basic services are necessities for any provision while all other levels of service are niceties to enhance value for customers. Basic services for water, wastewater, and electric power systems are described in Volume 2. FEMA P-2234 and Davis [2014; 2021] provide more details on basic service categories.

2.4.2. Basic Intended Functions

Basic Intended Functions (BIFs) are the actions to provide basic services. They are the purpose for which the built infrastructure of a lifeline system is used by the lifeline system operators to provide basic services. For example, a water system may use a pump (an action; the BIF) to provide sufficient pressure for firefighting purposes (a basic service). Also, a crew injecting chlorine (an action; the BIF) will provide water disinfection to ensure potable quality (a basic service).

Appendix A reviews fundamental definitions and assesses the results to provide an understanding of BIFs as applied to lifeline infrastructure systems and functional recovery. The following subsections describe how the BIF definition is developed for lifeline infrastructure systems and puts it into context for use with defining the state of functional recovery.

2.4.3. Functionality

Functionality is a system-level concept identifying how all components making up the infrastructure system interact. A system is functional if it can provide service at some level to customers, even in a damaged condition. The system achieves a state of full functionality when all post-event repairs are completed [Bruneau et al., 2003 pg 736], thus providing all levels of service to customers. Recovering to full functionality restores the system reliability to a level close to pre-event conditions. Functionality and system performance are often described synonymously (e.g., Tierney and Bruneau, 2007). However, this framework makes a clear distinction between function and services. As explained in Appendix A, function is what is done or used to provide a service; services are only provided when the infrastructure is functioning at a level sufficient to make them available.

Every system has a target performance level and intended purpose, which may vary slightly on a daily basis, under normal conditions, absent any significant or extreme event. Fig. 2-3 shows a conceptual diagram of system functionality over time before and after a significant earthquake event, normalized for deterioration effects. Three different post-earthquake trajectories are shown. Functionality, as a percentage of pre-event performance capability, is plotted as a continuous curve over time.

Before an earthquake (designated as pre-event level in Fig. 2-3), slight variations in functionality result from many reasons, for example, equipment or subsystems temporarily being removed from service for maintenance, employees unable to report to work, or materials supplies being insufficient to undertake certain work activities. Each of these will remove some, usually very small, level of reliability, operation, or service provision for a short time. In Fig. 2-3, this is expressed mostly as a straight line with one small temporary drop in functionality. As a result, the target purpose will not always be met at the intended level because from time to time there will be slight changes in system functionality. The target intended purpose sets the baseline definition of the full functionality state (i.e., the 100 % pre-event functionality level), that is, how all the lifeline infrastructure subsystems and components interact to provide services.

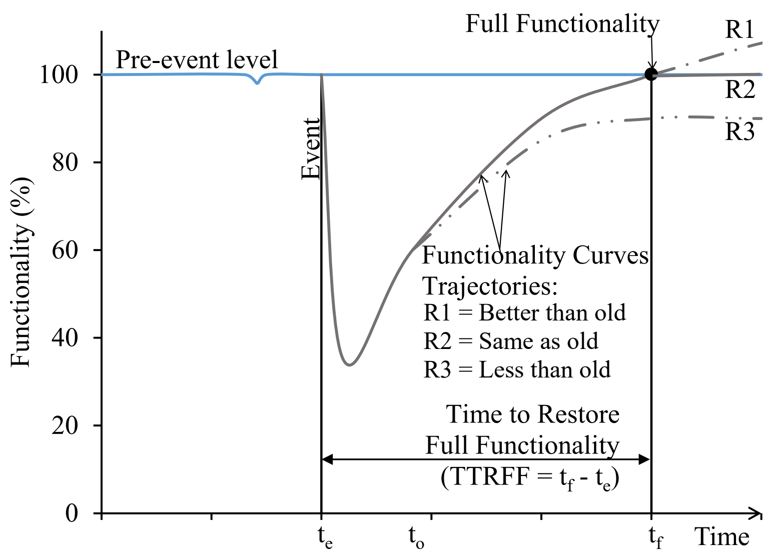

Figure 2-3. Illustration of lifeline infrastructure system functionality curve trajectories over time.

As shown in Fig. 2-3, an earthquake event can cause large abrupt deviations in measurable functionality at the time of the earthquake event, $t = t_e$. The time to restore to full functionality (TTRFF) occurs over the period $t_e < t \leq t_f$ by completing all construction and repairs resulting from damages caused by the event [Bruneau et al., 2003 pg 736; Cimellaro, et al., 2010; Davis, 2021]. At the state of full functionality, occurring at time t_f, the system is expected to achieve its target performance level and provide all levels of service.

After the time of an event t_e, the lifeline infrastructure system functionality curve may follow a number of different trajectories exemplified as R1, R2, and R3 functionality curves in Fig. 2-3. At time t_f or thereafter, the functionality curve may follow trajectory R1 in Fig. 2-3 and be rebuilt better than the original (better than old), trajectory R2 to be rebuilt to the same pre-event functionality, or trajectory R3 and rebuilt to a functionality level less than original (less than old).

2.4.4. Operability

Operability is the ability to provide basic services through the network to customer connections, allowing users to receive normal, or near normal services [Davis, 2021]. Operability is a continuous expression measurable over time. A system is operable if it is providing some basic services to customers, regardless of the state of the system (i.e., the system can be impaired with damages). The system achieves a state of complete operability when all basic services are provided to all customers. Each customer having complete operability restored to them can undertake their activities in a relatively normal manner with respect to the system providing the services.

Fig. 2-4 presents the conceptual difference between operability and functionality using a hypothetical case. The functionality curve in Fig. 2-4 is the same as R2 in Fig. 2-3 (rebuilt to the same pre-event functionality). Operability is achieved across the entire service area when the measure returns to 100 % at time to restore complete operability (TTRCO). Due to adaptability and/or pre-existing redundancies and isolation capabilities, which are important traits of functional recovery and resilience, having a functionality measure less than 100 % does not always require lifeline infrastructure system services to be lost nor prevent them from being restored. Shortly after an earthquake, Fig. 2-4 shows that functionality is lower than operability (lowest levels of 35 % functionality vs. 65 % operability) and TTRCO occurs before the TTRFF, the time to restore full functionality. For this case, functionality is only at 60 % of pre-event levels when system operability is completely restored.

To provide an example for a water system, a severely damaged component (e.g., pipeline) may require a lengthy timeframe for repair, but service may be restored to the degree users do not notice a difference in system performance using existing redundancies and/or temporary bypass of the system component. This state in which basic services have been restored, is considered operational. The system may not function as it did before the event, and has not returned to full functionality, but it is completely operable and able to provide water temporarily. This, in turn, allows users (e.g., a hospital) to provide their services as normal. A functionally recovered system is operable and can achieve the provision of the services needed by the community (100 % operability) prior to reaching a state of full functionality. From this, and as shown in Fig. 2-4, TTRCO is achieved sooner than TTRFF.

Fig. 2-5 presents the concept of buffers described in Sec. 2.3.5. The curves in Fig. 2-5 are the same as in Fig. 2-4 with the addition of the dashed operability curve, however the time scale is shorter in Fig. 2-5. The dashed operability curve shows the effect of a buffer that provides all basic services for a duration of t_B. When disruption of service is caused by a dependency on services provided by another lifeline infrastructure system, and a back-up is in place, the amount of time t_B is the autonomy (e.g., the time batteries can power a load). Buffers can delay the disruption of service by the amount of time t_B. If t_B is longer than TTRCO then buffers may prevent any disruption of service due to dependencies. Buffers can be applied to defer loss of a single, multiple, or all basic services.

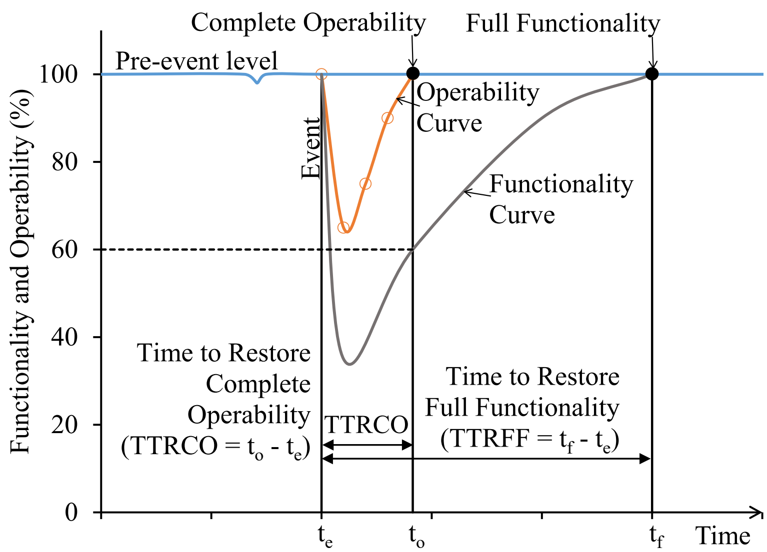

Figure 2-4. Conceptual representation of lifeline infrastructure system operability and functionality over time.

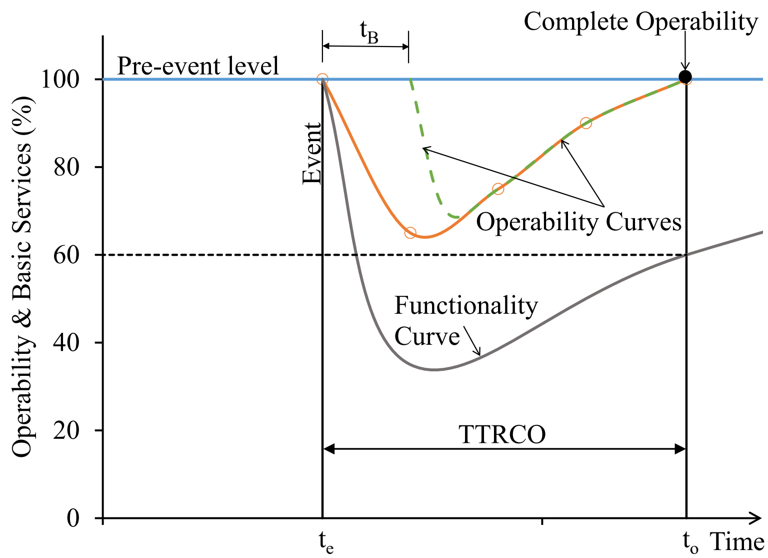

Figure 2-5. Conceptual representation of how buffers can influence operability.

2.4.5. Basic Service Categories

Basic services can be categorized to group similar qualities across multiple lifeline infrastructure systems. Basic service categories (BSCs) are descriptive terms or phrases classifying those most essential services provided, which are subsets of all the services a lifeline infrastructure system provides [Davis, 2014; 2021].

Table 2-1 presents BSCs for water, wastewater, and electric power systems [Davis, 2021]. Table 2-2 describes each BSC presented in the top row of Table 2-1. Volume 2 Chapters 3, 4, and 5 provide more detailed descriptions, respectively, for the water, wastewater, and electric power basic services.

Basic services allow customers and users to proceed with or resume activities in a relatively normal manner with respect to that amenity. For example, a customer receiving normal volumes of potable water can undertake normal household activities requiring use of that volume of water. They are the services users have become dependent and reliant upon for personal and community wide survival, safety, security, and well-being. Once a basic service category is lost, then some repairs or modifications are needed to increase the level of system functionality to restore the basic service.

Table 2-1. Basic Service Categories Provided by Lifeline Infrastructure Systems

	Basic Service Category				
Lifeline Infrastructure System	**Delivery**	**Collection**	**Quantity**	**Disposal**	**Fire Protection**
Water	X		X		X
Wastewater[a]		X	X	X	
Electric power	X		X		

[a] Some systems may also provide reclaimed water source services as a product for use by a water system.

Table 2-2. Lifeline Infrastructure System Basic Service Category Descriptions

Basic Service Category	Description
Delivery	The system can distribute product to customers/users, but the product delivered may not meet quality standards, pre-event volumes (may require rationing), or fire flow requirements for water systems.
Collection	The system can collect and remove waste, but may not be able to treat or properly dispose of collected materials at pre-event volumes.
Quantity	The product can be served (or waste/excess removed), at pre-event demand volumes.
Quality	The product can be served, or waste/excess removed, meeting pre-event quality standards.
Disposal	Entire collected volumes can be properly disposed, protecting the environment and meeting public health standards.
Fire Protection	The water system can provide pressure and flow of a suitable magnitude and duration to fight fires.

The operability curve in Fig. 2-4 involves the restoration of BSCs. As shown in Fig. 2-6, operability is the fulfillment of all the respective BSCs. The TTRCO across a system can be viewed through the incremental restoration of each BSC provided by the system. It therefore serves as a descriptive milestone delineating when customers resume receipt of their accustomed services. The measure of operability is increased as each BSC is restored to customers. Once a lifeline infrastructure system has restored all basic services to all customers, then complete operability is accomplished throughout a service area, and user activities can essentially resume in a relatively normal manner with respect to services provided by that system. Improvements would continue to restore the lifeline infrastructure system functionality. Once full functionality is accomplished, all pre-earthquake normal levels of service would be restored, or rendered as close as possible, to pre-event normal service levels, including the enhanced services described in Sec. 2.4.1.

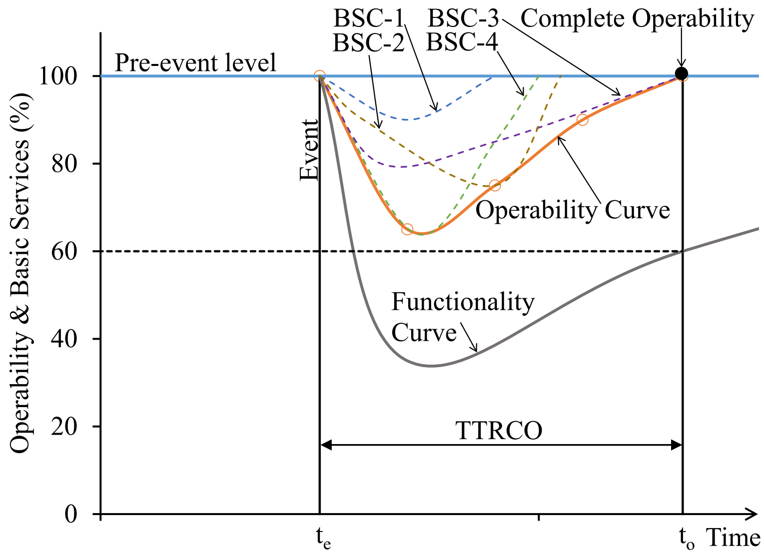

Figure 2-6. Illustration of Basic Service Categories (BSC-1 to BSC-4) defining the operability curve.

2.4.6. Basic Intended Functions (BIFS) and Lifeline Infrastructure System Functional Recovery

As previously defined, BIFs are the actions through which lifeline infrastructure systems provide basic services. There is a distinction between a function and a service; they are not the same. A service is provided by a functioning lifeline infrastructure system. Therefore, each asset or portion of the organization (e.g., group) within the system has reached the state of functional recovery when it can be returned to use or when its function has been replaced using a system-adaptation to provide the BSCs. Figures 2-6 and 2-7 show how restoration of the basic intended functions, which allow the BSCs to be restored, also increases the functionality measure of the system. The BIFs of multiple components may be necessary to recover basic services.

Each asset or portion of the organization (e.g., group) within the system has reached the state of functional recovery when it can be returned to use or when its function has been replaced using a system adaptation to provide the basic service categories.

As illustrated in Fig. 2-7, the functionality measure is depicted to be less than 40 % when BIFs are sufficiently restored to return BSC-1. The functionality measure is a little above 40 % when BIFs are sufficiently restored to return BSC-4. The functionality measure is less than 50 % when BIFs are sufficiently restored to return BSC-2. The functionality measure is at 60% when BIFs are sufficiently restored to return BSC-3, this is the level at which complete operability is restored. Figure 2-7 identifies how a functionality level can be determined when the lifeline infrastructure system is able to provide its basic services to customers. This illustration is for descriptive purposes only and does not apply to any specific lifeline infrastructure system.

Complete operability of the system is restored when the appropriate set of components have their BIFs restored. The state of 100 % operability defines the level of functionality when functional recovery has been met or exceeded because the BIFs are recovered to support the pre-earthquake service level (i.e., all BSCs are provided to all customers).

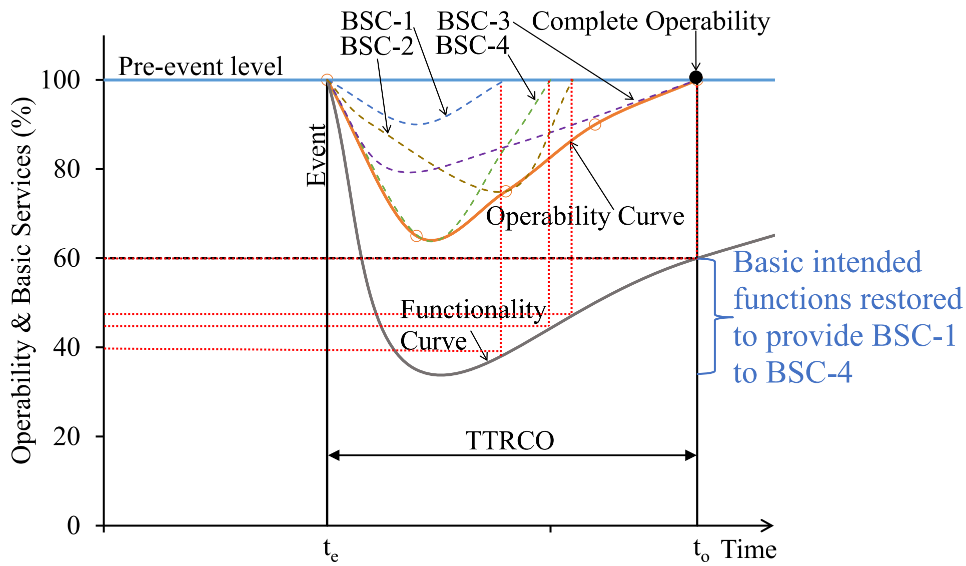

Figure 2-7. Illustration of basic intended functions and relationship with basic service categories (BSCs).

The state of complete operability defines the level of functionality when functional recovery of a lifeline infrastructure system has been met or exceeded.

The time to restore BIFs (time to functional recovery) varies based on user needs and location. Although the system can provide basic services, the customers themselves may not be functionally recovered because of their dependencies on other services which are not restored. Additionally, each customer may functionally recover with respect to a given lifeline infrastructure system at different times based on their individual needs. For example, one customer may only need BSC-1 (e.g., water delivery) to undertake normal activities, while a neighboring business owner may require BSC-1 and BSC-3. Another neighboring business may require the restoration of all BSCs to undertake their activities, and so on. Further, in large geospatially distributed systems, BSCs may not be returned to all users at the same time.

The state of complete operability defines when functional recovery has been achieved by the lifeline infrastructure system. At the time when complete operability is achieved by the lifeline infrastructure system, functional recovery may have already occurred for some customers and users.

The main points in this Sec. 2.4 applicable to the framework are:

- Implementing the framework starts with defining the basic services the infrastructure provides to users
- Operability is defined by restoration of the basic services
- The BIFs needed to reach functional recovery are defined by the level of functionality needed to restore operability
- Functional recovery is achieved when or before the infrastructure system reaches complete operability (i.e., all BIFs are recovered to support provision of all BSCs).

These points are applicable to every asset and group making up the lifeline infrastructure system. Therefore, as indicated in Sec. 2.2.4 these points are also applicable to every subsystem making up the lifeline infrastructure system, including buildings. An approach to applying these main points to the framework is to use basic services to establish performance and recovery time objectives, then identify the components and BIFs needed to provide the basic services. For example, in a building making up a component within the lifeline infrastructure system, the basic services may include a safe and re-occupiable shelter for people and equipment, lighting, and ventilation [Davis, 2021] among others. The building reaches complete operability when all these basic services are provided and approved by the authority having jurisdiction (AHJ). If an earthquake damages the building and removes the ability to provide these basic services, the BIFs must be repaired to a level they can be used to recover the basic services (for example repairing the electric cabinets to restore lighting), and in doing so increases the building's functionality. Once all the building's basic services are recovered and approved by the AHJ, it has reached complete operability and a state of functional recovery. The building functionality has reached a level capable of meeting all the user's basic needs so that the lifeline organization groups can perform their duties. However, it is not in a state of full functionality and some additional repairs may be required.

The following describes the relationship between BSCs, operability, BIFs supporting the BSCs, and functionality. The distinction between BIFs and basic services (i.e., a function is not a service) holds true even though in many cases the restoration of a BIF may directly result in recovering a basic service, at least to some users. As indicated in Figures 2-3 to 2-7, the recovery of functionality and operability can follow different paths. In some cases, the operability curve will only track along, or closely to, the functionality curve if all repairs must be completed to recover the basic services (e.g., there are no redundancies or system adaptations), resulting in no significant difference between recovering a BIF and a basic service. However, important resilience and functional recovery concepts are to utilize redundancies and system adaptations and make just enough repairs to achieve complete operability in advance of full functionality. When doing this, there should be no confusion with the role of BIFs and how they affect the functionality curve, which is derived from the authoritative definitions given by Bruneau et al. (2003) and Cimillero et al. (2010) for achieving full functionality. Figure 2-7 shows how the BIFs are measured along the functionality curve and relate to the operability curve.

The recovery of BIFs is achieved by making the minimum repairs and adaptations necessary to restore the BSCs. Therefore, conceptual plots of BIFs over time may closely resemble the BSC curves in Fig. 2-6. BIF curves are developed from progress making up the lower portions of the functionality curve up to TTRCO. Conceivably, the combined BIFs loss and recovery leading to the state of functional recovery can also be plotted as a continuous expression, which would result in a curve bounding all the BIFs needed to recover the BSCs; this curve would resemble the operability curve presented in Fig. 2-4 but is clearly different than the functionality curve. This explains how the concepts of BIFs and operability are closely tied and represent two related aspects important for community recovery; operability being the measure of all basic services to end users and the BIFs are needed to provide those basic services.

The main points itemized above can be applied to any lifeline infrastructure system and buildings within it. Building users commonly all need a consistent or similar set of basic services provided by the same set of subsystems, which resides at a single site (i.e., an office building with defined location). Thus, once the BIFs for the subsystems are restored and approved by the AHJ, all building users receive their basic services and can then resume their activities. In contrast, lifeline infrastructure systems serve many users over a large area (i.e., residential, offices, hospitals, and multiple site locations) each having different demands for basic services which may be provided by different components and groups. This sometimes may result in users receiving their basic services from the lifeline infrastructure at different times. If a building has multiple occupancy types needing different basic services (e.g., main office, customer service, banking, material storage), then it is possible for the various users to have their basic services provided within the building at different times because the BIFs that provide those basic services are recovered at different times. As a result, the concept of different users reaching functional recovery at different times may apply to both the lifeline infrastructure system, and some buildings within the system.

Every component making up the lifeline infrastructure has a set of BIFs to provide the BSCs. Many organizational groups within the system have essential functions that must be coordinated to recover service disruptions. The number of functions increases with increasing distribution area. The importance of different functions changes with service user types. As a result, there are a very large number of functions that must be coordinated with varying importance throughout a lifeline infrastructure system following a damaging earthquake. The wide array of conditions to make these restorations and combinations for organizational groups and component repairs are difficult to manage. When there are many different functions covering large areas for many different user types it is important to identify which functions to focus on and why. Using the limited number of basic services to identify which functions to recover to meet customer needs helps to optimize activities to meet recovery-based objectives. This is opposed to attempting to coordinate large sets of BIFs to identify the services that can be recovered. As a result, basic services are utilized as a fundamental measure for developing this framework.

The difference between BIFs and BSCs in systems containing limited redundancies, covering small service areas, and having few user types may be a minor distinction, except where dependent services are addressed as explained in Sec. 2.3.2. However, the distinction becomes increasingly important for large, complex, geographically distributed systems serving many user types.

2.5. Earthquake Event Scenarios for System-Level Assessment

As shown in Fig. 2-1 (lower left box), earthquake event scenarios are needed to assess lifeline infrastructure system performance and identify expected service recovery times. Assessments performed for component-level design follow current practice as applied in codes and standards (e.g., ICC [2022]; ASCE [2022]) where emphasis is on the evaluation and design of a building or component for intensity measures at a specific location without regard to the geospatial distribution of all other interconnected parts that are needed to allow the system to operate. This is incorporated in the framework in Secs. 4.4 and 4.8. However, a systems approach is needed for the proper design of the entire lifeline infrastructure. The objectives for the system-level design are to limit damage and meet target service recovery times after an earthquake. To do this, each component in the system is designed to ensure that the system can achieve its recovery-time objectives. The expectation for meeting the service recovery time objectives is checked using a system-level assessment. This requires the identification of earthquake sources and associated event levels that can be used to identify the associated spatially distributed hazards. The hazards may have the potential to damage lifeline infrastructure which would limit the ability of the system to provide services to customers and users.

FEMA P-2234 Appendix H presents a consequence-based method to identify the potential earthquake event recurrence intervals that may be used by lifeline infrastructure systems to achieve target water service recovery times. The target recovery times identified in FEMA P-2234 correspond to societal impact of expected lifeline infrastructure system performance. The societal impacts range from a small disruption that does not activate the need to use adaptations, to the maximum duration of outages when significant long-term consequences may result and potentially prevent full recovery.

For the purpose of assessing a lifeline infrastructure system an earthquake event is a scenario that includes all potential seismic hazards and spatial distribution within the system's service area including fault rupture surface displacement, ground shaking, landslide, liquefaction, and tectonic deformation. In some cases, it may also include tsunamis and seiches. Methodologies can evaluate region-specific multihazards [Soleimani et al., 2021] using the National Seismic Hazard Model [USGS, 2022] to develop a suite of maps that can be used to assess lifeline infrastructure systems consistent with known seismic conditions surrounding a given network. These methods provide hundreds to thousands of maps that aggregate the regional seismic hazard curve [USGS, 2019] and are useful in a fully probabilistic seismic assessment of a lifeline infrastructure system. In most practical cases full probabilistic assessments may not be viable and only one to a few maps may be feasibly applied for this framework. Additional research is needed to identify a reasonable set of earthquake event scenarios for application to lifeline infrastructure systems (see Sec. 6.2.6). Table 2-3 presents suggested earthquake events to utilize for this framework based on preliminary work presented in FEMA P-2234 Appendix H. The earthquakes in Table 2-3 bound the range of event frequencies used in current practice to approximate the regional risk or consequence. FEMA P-2234 presents a methodology to develop target basic service recovery times for different lifeline infrastructure systems to correlate with the earthquake event levels listed in Table 2-3.

For each event, the ground motions vary in intensity by location and dissipate with distance depending on the fault selected to construct the earthquake scenario and the hypocenter (or epicenter) location. These variables also influence the potential surface fault rupture and location. The shaking intensity variation can influence the potential for landslide deformation, liquefaction triggering, differential settlement and lateral spreading, as well as other earthquake hazards. Reasonable professional judgement is necessary to develop the scenarios to make them applicable to individual lifeline infrastructure systems.

For application in the framework, assessments using all four earthquake event levels in Table 2-3 with corresponding service recovery times are recommended (e.g., FEMA P-2234). However, if there are practical limitations to the number of assessments that can be made, then the framework is recommended to be applied using at least earthquake event Levels II and/or III.

Table 2-3. Suggested System-Level Target Earthquake Events for Scenarios (from FEMA P-2234)

Level	Target Event Return Period[1]	Philosophy
I	100 years or less	Relatively small event, limited damage, no significant adaptations needed
II	500 years	Large event causing significant damage requiring adaptations
III	2,500 years	Very large event causing serious damage requiring extended use of adaptations
IV	>2,500 up to 100,000 or more years	Rare and very extreme, but plausible, event. System response is to contain losses in support of community recovery. Recovery planning needs to be developed for the plausible but unknown event.

[1] The number of years is a qualitative estimate to give a rough figure (order of magnitude) and may change with more detailed studies and risk analysis. These values also represent the consequence return period (i.e., this assessment assumes a 1:1 correlation between the consequence return period and the event return period).

3. FRAMEWORK OVERVIEW

3.1. Introduction

Lifeline infrastructure systems are not currently planned, designed, constructed, operated, or maintained to recover services within a defined time after an earthquake. Current design procedures instead focus primarily on life safety and property protection [NIST-FEMA, 2021].

This report offers a preliminary framework to help ensure functional recovery of lifeline infrastructure systems after earthquake events. The goals of the framework are to define and implement assets and organizational actions necessary for lifeline infrastructure systems to achieve post-earthquake performance and service recovery time objectives that meet societal needs. The two key constituent parts of the framework are as follows.

- **Assets Framework:** Identify, design, and assess the interlinking components and subsystems making up the built infrastructure so that lifeline systems can restore services in a post-earthquake timeframe to meet the recovery-based objectives. The assets framework incorporates target performance and recovery time objectives at both the component and the system levels. The assets framework is explained in Ch. 4.
- **Organizational Actions Framework:** Create a lifeline infrastructure organizational structure populated with groups that can implement processes and perform a coordinated set of duties to meet the recovery-based objectives. The organizational actions framework incorporates target performance and recovery time objectives at the group level and across the entire lifeline infrastructure organization. The organizational actions framework is explained in Ch. 5.

To be effective, there must also be proper connections between the assets and the organizational actions constituent frameworks.

For these constituent frameworks to be utilized, there must first be a commitment to functional recovery made by those who govern and manage the lifeline infrastructure systems. Once a commitment is made, then functional recovery can be planned, designed, and implemented into the system assets and organization. System planning is essential to implement the proper designs. Designs are made at the system level, as well as the component and group levels, for the assets and organization. In the context of this framework, designs provide the basis for constructing and developing components and organizational groups to meet planned objectives. Planning is a continual process needed to identify the resources and activities so that the system assets and organization can be designed and implemented to meet defined objectives. Assessments and evaluations are a part of the design process. Results of the system-level assessments are used to feed back into the system planning process, which can then identify where new and improved designs (e.g., mitigations) are needed to enhance functional recovery. This feedback should also be used to inform the broader community the lifeline infrastructure systems operate within and decision makers, within the system and the broader community, to help them decide on priorities and funding for improving system-level performance and community-wide resilience.

The following sections describe how the decision to implement functional recovery influences the system planning process and development of performance and recovery-based objectives. This is followed by an overview of the framework to design lifeline infrastructure system assets and organizations for functional recovery. Lastly reporting the outcomes of the framework are described for implementation and to be used as feedback to the planning and decision-making process at the system and community levels.

3.2. Initiating the Framework towards Functional Recovery

Undertaking the framework development efforts described in Chapters 4 and 5 first requires an organizational commitment to a functional recovery policy that integrates recovery-based objectives into lifeline infrastructure system planning, design, and operations. Fig. 3-1 presents a governance and management schematic of the decision making, policy, and planning process necessary to develop system-level objectives and implement the assets and organizational actions frameworks. The governance and management levels for each part of the process are identified on the right side of Fig. 3-1.

Governance is the role of leading an organization and management is its day-to-day running or operating. Making the decision to commit to designing a system to meet functional recovery objectives is a policy choice influenced by governance. Governance includes activities and processes to achieve collaboration on behalf of the common interest to ensure societal needs are met [Davis, 2023]. It requires leadership and interaction among lifeline infrastructure organizations and the communities they serve. Leadership from outside the lifeline infrastructure system includes regulation and elected bodies on behalf of the lifeline infrastructure customers and users. The decision to incorporate recovery-based objectives may come from a combination of external and internal influences on the lifeline infrastructure assets and organization.

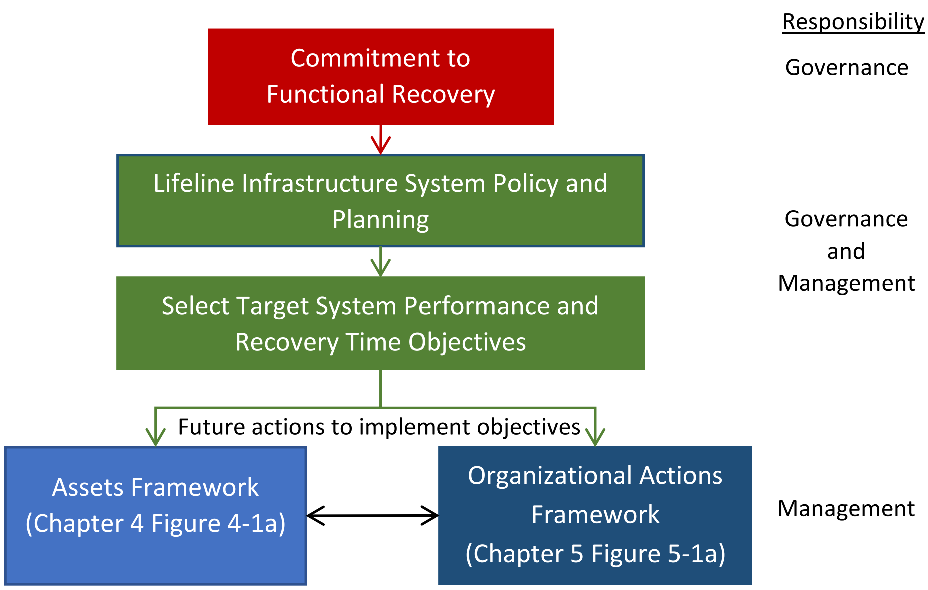

Figure 3-1. Process for framework initiation.

3.3. System-Level Policy and Planning

Policy development, planning, and implementation are central actions that will result in enhanced functional recovery performance after an earthquake. Management and governance establish functional recovery policy by setting system-level performance and recovery-time objectives that then drive the planning process. The system-level objectives are used in completing the assets and organizational actions frameworks described in Chapters 4 and 5. Additionally, plans are prepared to establish the future actions and accompanying procedures to implement the resulting frameworks.

3.3.1. Policy

System-level policy is necessary to plan, design, construct, operate, and maintain lifeline infrastructure system assets to meet post-earthquake recovery objectives. Additionally, procedures are required to ensure organizational activities are prepared and coordinated to achieve the recovery objectives. These policies and procedures should originate through proper governance at jurisdictional levels within which the lifeline infrastructure systems operate so that regulators can ensure lifeline infrastructure operators provide their services to users when needed. However, in the absence of any jurisdictional level guidance, the lifeline infrastructure organizational leadership can create their own system-level policies and procedures. This may require the establishment of post-earthquake performance and recovery time objectives in a documented system-level policy to govern and guide organizational decisions and activities for functional recovery.

3.3.2. Planning

Plans provide a roadmap for achieving policy objectives. Planning for functional recovery requires assessing the types of earthquake events and the seismic hazards within each event that may impact the system performance, the dependencies and interdependencies with other lifeline infrastructure system services and with other community systems, budgeting for pre-event mitigation activities, budgeting for responding and recovering to an event, communicating with the communities and service users within the service areas about potential outage durations after each type of event. Thus, system planning for functional recovery may draw upon or even require development of several plans. Some of the key plans that lifeline infrastructure organizations may have or need to develop are briefly described below. Most of these are all-hazards plans and not specific to earthquakes, but earthquake hazards may be addressed as a specific chapter or annex to the plan. Depending on the size of the lifeline infrastructure system, different parts of the organization or different geographic areas may maintain their own versions of these plans that are then referenced in the overall organization plan.

- **Emergency Management or Emergency Operations Plans:** These describe who does what, as well as when, with what resources, and by what authority before, during, and immediately after an emergency [FEMA, 1996]. These plans are the centerpiece of an organization’s comprehensive emergency management efforts identifying how the organization will work in a coordinated manner with the broader emergency management structure having jurisdiction in their service area(s), as well as their mutual aid and assistance plans with other lifeline infrastructure organizations. Mutual aid and assistance are the common mechanisms for jurisdictions to obtain critical resources during a disaster to help with infrastructure response and recovery. It will also describe how the organization's normal operating managerial structure will transform into an incident command system (ICS), or similar organizational crisis management structure, such as described by the National Incident Management System, with actions that follow pre-specified plans, procedures, and processes (e.g., FEMA, 2023). This transformation aids emergency management but modifies, and at times may inhibit, normal operations by pulling resources to manage the event response and ensure the organization can at least focus on its most essential functions.

- **Continuity Plans:** Sometimes referred to as continuity of operations or business continuity plans, these describe how the organization will provide uninterrupted critical services, essential functions, and support, while maintaining organizational viability, before, during and after a wide range of emergencies, including localized acts of nature, accidents and technological or attack-related emergencies that disrupt normal operations [FEMA, 2018]. Continuity planning enables the successful implementation of emergency management plans during and after an emergency by ensuring that essential functions, critical services, and visible leadership are readily available when normal operations are impacted, or necessary resources are unavailable. One of the greatest uncertainties for this framework is the time it may take for personnel to report for duty following an earthquake event. Continuity planning can help reduce the uncertainty by identifying potential risks for key individuals to report to work and ensuring personnel are prepared at home so they can return to work rapidly. Business continuity plans also address key variables that minimize losses and allow for the continued functioning of business following an incident.
- **Assets Management Plans:** These provide integrated, multidisciplinary set of strategies in sustaining infrastructure assets. Generally, the planning process focuses on the physical life cycle of assets, specifically maintenance, rehabilitation, and replacement with the goal of preserving and extending the service life of long-term infrastructure assets that are vital to maintaining the quality of life in society and efficiency in the economy. These plans identify the need for improving or replacing the assets/components, and when this should be put in the capital investment strategy and budget.
- **Seismic Mitigation Programs and Plans:** Identify infrastructure modifications needed to improve seismic performance and service recovery. The planning process typically includes risk assessment and prioritization of all infrastructure assets/components and establishment of a series of strategies and timetables to retrofit, upgrade or replace the "most vulnerable" elements of the lifeline infrastructure system. This information also informs an organization's capital investment strategy and budget.
- **Capital Investment Strategy or Plans:** Provides a long-term roadmap for lifeline organizations to align capital expenditures with larger business, system, and service

objectives. Results of asset management and seismic mitigation planning will inform an organization's broader capital investment strategy and budget.

None of the listed plans are new concepts. They are, and have been, recognized as necessary plans needed for infrastructure and disaster management. Many include procedures to ensure coordination across the organization and with other organizations. Policies within some or all the plans may be integrated to improve organizational coordination of response and recovery. These plans will influence both the assets and organizational actions defined in this framework and consistency in policies and procedures across these plans will help to achieve functional recovery.

The planning process should also interact with broader community-level plans. Some of the key community-level plans that may affect lifeline infrastructure policy and planning for functional recovery are briefly described below. Some lifeline organizations may have their own versions of these plans that should be referred to in planning for functional recovery.

- **Comprehensive or Master Plans:** These take a long-range look (typically 20 to 30 years) at a community and provide general concepts and a vision of a community's future, how the community should develop and how proper land use and zoning designations can affect the health, safety, and welfare of the community. These plans are an expression of citizen preferences, and a participatory planning process offers the opportunity to assess community expectations of the post-disaster performance and functional recovery standards of infrastructure.
- **State and Local Hazard Mitigation Plans:** The Disaster Mitigation Act of 2000 (Public Law 106-390) requires that every state and local government prepare, adopt, and maintain a state or local hazard mitigation plan to be eligible for FEMA post-earthquake aid for public and non-profit facilities. These plans assess hazards, risks, and vulnerabilities; identify actions for risk reduction; and focus state and local resources on the greatest risks while communicating priorities to state and federal officials [FEMA, 2021]. The mitigation planning process encourages communities to integrate mitigation into their day-to-day decision making about land use planning, hazard management, site design, and other functions.
- **Capital Improvement Programs and Plans:** These describe a multi-year schedule of public physical improvements, such as the proposed expenditures for constructing, maintaining, upgrading, and replacing a community's physical plant. These expenditures are quite often the implementation proposals for policies defined in a local comprehensive or master plan, such as the construction of infrastructure to serve a new industrial park, or upgrades to existing infrastructure to accommodate increased housing and commercial densities in an older downtown area. The planning schedule usually covers a period of five or more years. The first year of the plan is typically called a capital budget and includes all capital projects to be appropriated by the governing body. The preparation and adoption of capital improvement plans and budgets typically have a participatory planning component which can provide the opportunity to assess community expectations of the post-disaster performance and functional recovery standards of infrastructure.

- **Recovery Plans:** The National Disaster Recovery Framework (NDRF) [FEMA, 2016] defines recovery principles, roles, and responsibilities of recovery coordinators and others, a coordinating structure and series of recovery support functions that facilitate communication and collaboration among all stakeholders, guidance for pre- and post-disaster recovery planning, and the overall process by which communities can capitalize on opportunities to rebuild stronger, smarter, and safer. The Infrastructure Systems Recovery Support Function within the NDRF provides a collaborative forum for federal government engagement with states, local governments, tribes, and territories as well as private sector representatives to focus on public engineering services that can reduce risks from disasters and expedite recovery. State and local governments are encouraged to develop recovery plans consistent with the NDRF coordinating structure that enables disaster recovery managers to operate in a unified and collaborative manner.
- **Community Resilience Plans:** These focus on helping communities prepare for anticipated hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions. Activities, such as disaster preparedness, which includes prevention, protection, mitigation, response and recovery—are key steps to resilience. The NIST Community Resilience Planning Guide [NIST, 2015a; NIST, 2015b] defines a six-step resilience planning process to enhance the resilience of a community's buildings and lifeline infrastructure that includes working with community stakeholders to identify performance-based recovery objectives for community buildings and lifeline infrastructure systems.
- **Climate Adaptation and Resilience Plans:** Some states are now requiring local governments to address issues of climate change, mitigation, and/or adaptation as part of their comprehensive plans. Other local and state governments are electing to develop climate resilience plans. The planning process is likely to involve a climate change vulnerability assessment, measures to address vulnerabilities, and the development and prioritization of a series of adaptation and resilience objectives, strategies, programs, and projects. These plans will include adaptation and resilience measures for infrastructure systems.

Planning involves considering the future and dealing with uncertainty. Plans, even comprehensive ones, are completed despite lacking some level of information. In some cases, the planners and stakeholders involved in the planning process may not even know what information may be missing. For performance and recovery-based seismic planning and design, it is important that all planning processes incorporate the most pertinent information needed for decision making, which includes the uncertainty of potential earthquakes, and the potential range of associated impacts, losses, and costs.

The planning process is a continuous cycle of developing, implementing, monitoring and evaluation, and modifying the plans. The outcome of monitoring and evaluation efforts can provide new information to revise plans and programs. As an example, the planning should use results of the system seismic evaluation undertaken as described in the Ch. 4 asset and Ch. 5 organizational actions portions of the framework, but initial planning or even an initial planning cycle may need to be undertaken to complete the evaluation. As a result, this is an iterative process. Also, as things change over time, the plans need to be modified as part of the continuous process.

3.4. System-Level Performance and Recovery Time Objectives

Recovery time objectives may be needed for each subsystem regardless of the subsystem owner or operator. Commonly target service recovery time objectives focus on the end customers or users (e.g., FEMA P-2234), which are applicable to the collection or distribution subsystem. However, the other upstream and downstream subsystems must also have target recovery time objectives in order to meet the service objectives for end customers and users. Developing multiple sets of synchronized recovery time objectives requires coordination among all the subsystem owners and operators, even if all subsystems are internal to a single system. Sections 4.2, 4.11.2 and 5.5 also address the coordination of recovery time objectives needed for different subsystems, owners, and operators.

The target performance and recovery objectives are created through management and governance and established through policy within the lifeline infrastructure system. System-wide policies help ensure good governance allowing the system to be better managed to provide critical services. Establishing lifeline infrastructure system objectives is also part of a broader process needed for developing seismic resilience in coordination with the community goals (e.g., NIST, 2015a; Davis, 2023).

It is important to focus first on establishing system-level performance and recovery time objectives. The system-level objectives will apply to both constituent parts (i.e., the assets and organizational actions) of the framework. Objectives for the constituent parts must be developed to ensure that system-level objectives can be met. The constituent parts will be addressed using components for the assets framework and groups for the organizational actions framework as shown in Fig. 2-2. The assets and organizational actions frameworks in Chapters 4 and 5 provide guidance on how to develop the component and group objectives, respectively, that are intended to meet the system-level objectives.

The framework can accommodate any form for the target performance and recovery time objectives selected in Fig. 3-1. FEMA P-2234 [2024] presents a framework for defining lifeline infrastructure system-level service recovery time objectives. For this framework, the use of the FEMA P-2234 [2024] service recovery time methodology, which incorporates the broader societal needs, is recommended as a starting point. Other system-level draft criteria may be used, such as Sattar et. el. [2022].

The framework addresses two types of objectives:

- **Performance Objective:** The planned damage or impaired state of assets and the organization for a specified hazard level.
- **Recovery Time Objective:** The planned duration to restore basic services for a specified earthquake event level.

Earthquake events are described in Sec. 2.5. Recovery time objectives may differ for customers or users of different criticality.

The objectives are developed using policy and planning processes and used as input to the framework (e.g., FEMA P-2234). Chapters 4 and 5, respectively, describe these objectives in detail for the assets and organizational actions frameworks.

Designing, developing, and/or modifying lifeline infrastructure for functional recovery requires the establishment of performance and recovery time objectives to be used for assets and organizational actions as shown in Fig. 3-1. The performance objectives for assets are usually addressed at the component-level through existing codes and standards. NIST [2016b] identifies a few cases where system-level objectives have been created and utilized, but their application in practice is not widespread. The system-level service recovery time objectives may be developed using processes described in FEMA P-2234 [2024], NIST [2015a, 2015b], Sattar et al. [2022] or others. They are necessary to establish the system-level organizational objectives together with the component-level and group-level recovery time objectives. The performance and recovery time objectives for organizational actions at the system-level are not commonly addressed in practice. Continuity programs address performance objectives for organizational essential functions, which are associated with group-level actions. Ch. 5 shows how recovery time objectives can enhance continuity programs.

There is the need to inform the lifeline infrastructure system customers and service users of the anticipated service disruption times when an earthquake occurs so they can prepare accordingly. Also, the lifeline infrastructure organization has the responsibility to help ensure that alternative emergency services can be provided to users within the service area during a disruption. It is appropriate for a lifeline infrastructure organization to inform the users of the potential service disruptions following an earthquake as well as obtain alternative emergency services. Alternative emergency services may include the distribution of potable bottled or tanker truck water, emergency generators, heating and cooling centers, portable toilets, and other provisions. Lifeline infrastructure organizations may not be responsible for providing all the alternative emergency services but should be responsible for engaging with officials in their service areas, hopefully in advance of a disaster, to ensure there are mechanisms for providing them during times of service disruption.

3.5. Assets and Organizational Actions Frameworks

As shown in Fig. 3-1, the system-level performance and recovery time objectives are used as inputs into the assets and organizational actions frameworks. The assets framework in Ch. 4 provides a process to design and assess the interlinking components and subsystems making up the built infrastructure so that the lifeline infrastructure systems can restore services in a post-earthquake timeframe to meet the recovery-based objectives. The organizational actions framework in Ch. 5 covers a set of processes for lifeline infrastructure systems to use for functional recovery with a focus on actions to be undertaken primarily by lifeline infrastructure organizational groups. The organizational actions framework provides a process for creating and assessing policies, strategies, and procedures to coordinate groups, including their interactions with the assets, to meet the recovery-based objectives. The processes and steps in the assets and organizational actions frameworks are interconnected. Each framework influences the other. They can be undertaken independently and doing so improves the ability to functionally recover. However, to achieve functional recovery by meeting the recovery-time objectives, both frameworks and their interactions need to be addressed.

The assets framework may be used for the design of an individual component. Each component in a system may be designed or redesigned as necessary; the assets framework will help create a consistency for system-level design over time. The assets framework can also be used to layout and/or assess the entire infrastructure system and how it may perform during earthquakes. The assessment may be used to design each component to common standards or identify which components may need to have improved performance levels. The design of a single component within a system may trigger the need for modifications of many other components and/or groups within the organization. The use of the assets framework does not necessarily require the use of the organizational actions framework, especially with the design of a single component within a network which does not necessitate application of the organizational actions framework.

The organizational actions framework may be used to establish policy, strategies, and procedures for an individual group. Each group in an organization may be structured or restructured as necessary; the organizational actions framework will help create consistency for system-level organization over time. The organizational actions framework can also be used to layout and/or assess an entire organizational structure and procedures to investigate how they may perform during earthquakes. The assessment may be used to develop each group to common procedures or identify which groups may need to have improved performance levels. The review of a single group within a system may trigger the need for modifications of other groups and/or components within the infrastructure. The use of the organizational actions framework does not necessarily require the use of the assets framework. That is, improving the policies for a single group within an organization does not necessitate application of the assets framework.

3.6. Seismic Design Process Based on Performance and Recovery

The objectives selected in Fig. 3-1 are used as the starting point for the performance and recovery-based seismic design process shown in Fig. 3-2. Services are provided by the infrastructure system through a combination of assets and organizational actions like those shown in Fig. 2-2 (i.e., the light blue box in upper right of Fig. 3-2 is analogous to the top box in Fig. 2-2). The system-level objectives determine how services are provided through the system and through adaptations when the system may be impacted by an earthquake and unable to provide the services as normal.

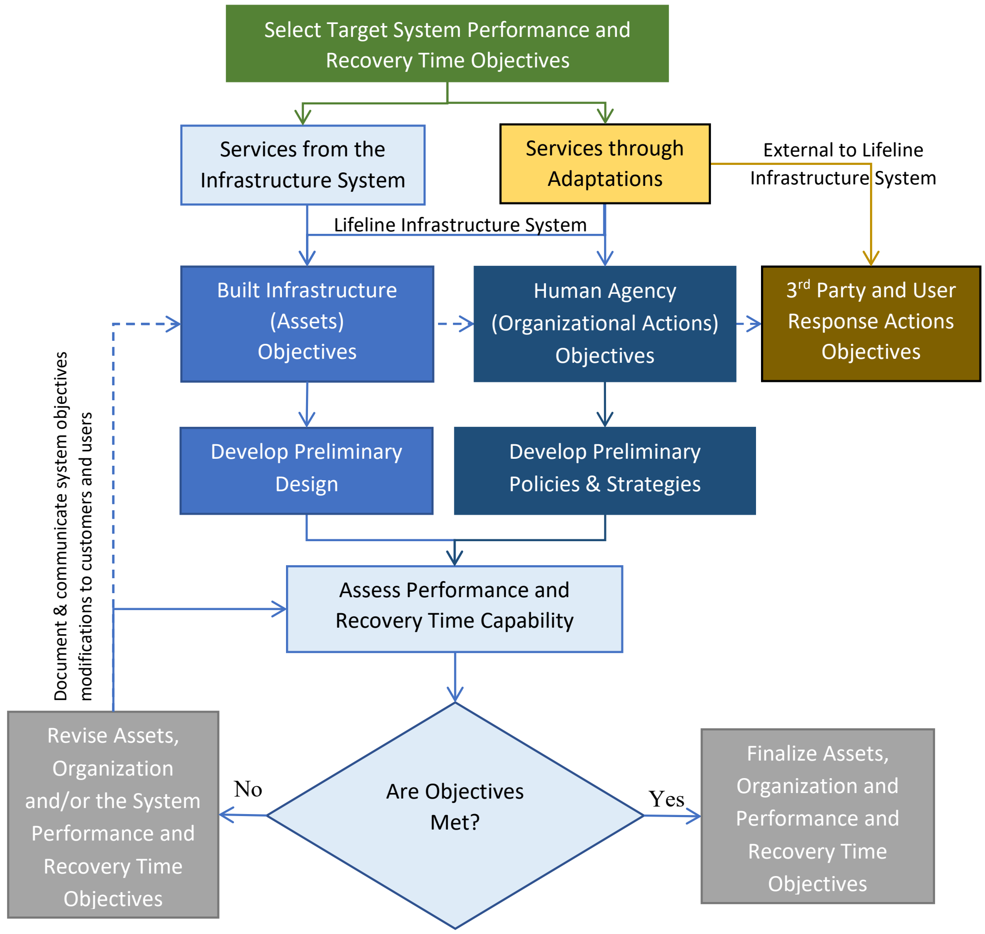

Figure 3-2. Performance- and recovery time-based seismic design flow diagram for the lifeline system built infrastructure (assets) and human agency (organizational actions). Light blue color represents processes covering both the built infrastructure and human agency.

3.6.1. Adaptations

The second row in Fig. 3-2 shows how post-earthquake services are provided either through the network or through adaptations. The flow process to the third row in Fig. 3-2 shows how the services provided through adaptations may come from adapting the infrastructure, the lifeline organizational actions, and/or third party and user response actions.

Adaptations may be implemented by the lifeline infrastructure organization, service users, or third-party organizations. The adaptations implemented internal to the lifeline infrastructure organization influence the asset and organizational actions objectives. A lifeline infrastructure organization may undertake actions to aid users in implementing adaptations, examples which have been listed above. The adaptations implemented that are external to the lifeline infrastructure organization require objectives to be developed and met by customers and users and other third-party organizations. As a result, the performance and recovery time objectives of lifeline infrastructure completely influence the post-earthquake behavior of their customers and users as well as third-party organizations. An example of this is described for the application of buffers in Sec. 2.3.5. Proper planning requires a set of transparent service recovery objectives that allows for the development of objectives for the customers and users and third-party organizations. The objectives of users and third-party organizations are important for functional recovery. Details of objectives specific to different users and third parties are beyond the scope of this framework.

3.6.2. Iterating the Process

The process in Fig. 3-2 covers the broad aspects of a lifeline infrastructure system from the entire built infrastructure network to single components and from the entire organization to individual groups. This section addresses the process at the system-level and is applied to the two constituent frameworks.

3.6.2.1. Assessing Assets and Organizational Actions

When assessing the assets in Fig. 3-2, using the target performance and service recovery time objectives, a preliminary system layout (e.g., the entire system or a portion of a service area) or asset design (e.g., water tank, transformer, or building) is prepared. This step could also entail evaluating the vulnerability to defined earthquake hazards of an existing system layout or an existing component. The hazards are to include, but not be limited to, ground shaking intensity and permanent ground deformations. Permanent ground deformations include fault rupture, liquefaction-induced settlement and lateral spreading, landslides, ground settlement, soft clay cyclic mobility, and other potential movements that may affect the system or components.

When assessing the organizational actions in Fig. 3-2, using the target performance and service recovery objectives, a preliminary organizational structure and processes (e.g., the entire organization or a portion of it) or specific group will be defined along with their policies, strategies, and procedures. This step could also entail evaluating the response capabilities of the existing organizational structure or an existing group to potential earthquake effects. Personal repercussions to a percentage of the lifeline system personnel may prevent them from undertaking their duties. Consideration should also be given to factors such as a bridge vulnerable to earthquake motion being damaged, which prevents personnel from traveling to work. Other aspects are described in Ch. 5. It is important to recognize that the organization undertakes the steps shown in the blue boxes in Fig. 3-2, which includes the assets portion of the framework (Ch. 4). The organization must be able to make reasonable and justifiable value judgements of the assessment results to determine if the system assets and the organizational actions are able to meet the target performance objectives.

The assets and organizational actions frameworks, in Chapters 4 and 5 respectively, each include the systems-level assessment identified in the last rectangular blue box in Fig. 3-2. The system-level assessments should be performed using earthquake event scenarios as described in Sec. 2.5. The system-level assessment in Ch. 4 for the assets framework focuses on identifying how the built infrastructure performs when subjected to an earthquake event and how it recovers in the aftermath. Key organizational actions are included like assessing the components making up the lifeline infrastructure system. The system-level assessment in Ch. 5 for the organizational actions framework focuses on identifying how the organizational structure and procedures perform when subjected to an earthquake event and recover in the aftermath. Key assets are included like the performance of buildings used by the groups. Addressing each constituent framework separately is necessary to simplify the socio-technical system assessment. The overall goal is to ensure that lifeline infrastructure system service recovery times can be met.

3.6.2.2. Comparing Assessment Results to Target Objectives

Results of the assessments, including recovery time analyses, are compared to the lifeline infrastructure system objectives (blue boxes in Fig. 3-2) to determine if the anticipated performance and service recovery time meet or exceed the target criteria. The process is iterative. If the evaluated performance or recovery time falls short of the target lifeline infrastructure system objectives (path “No” in Fig. 3-2), then modifications are required. For the assets, modifications may need to be made to the design or system layout. For organizational actions, modifications may need to be made to processes, the system organizational structure, and/or activities. Modifications can be optimized through the integration of options in the assets and organizational actions frameworks, and through the interaction with other lifeline infrastructure systems, to meet the target objectives. The identified modifications should be used as feedback into the planning process and to decision makers as described in Sec. 3.1.

The process is also interactive since the performance and recovery of assets are not independent of those for the organizational actions, and vice versa. Additionally, the performance and recovery of assets and organizational actions in any specific lifeline infrastructure system are not independent of other lifeline infrastructure systems. Within any lifeline infrastructure system, modifications and changes to the components using the assets framework will influence the organizational actions. At the same time, modifications and changes to the groups using the organizational actions framework will influence the assets. Additionally, modifications and changes to the assets and organization in one lifeline infrastructure system potentially influences all lifeline infrastructure systems. The interaction among lifeline infrastructure systems is addressed in steps within the assets and organizational actions frameworks (specifically in Steps A5 and O3 in Chapters 4 and 5, respectively). The integration of the assets and organizational actions frameworks is shown in Fig. 3-2 in the last rectangular blue box titled “Assess Performance and Recovery Time Capability”.

If the performance or recovery time fall short of the system-level objective, and design cannot be cost-effectively or physically modified, then the iteration may focus on potential changes to organizational actions and the response and repair assumptions to meet the same objectives. If the performance or recovery time falls short of the system-level objective, and the organizational activities cannot be logistically or cost-effectively modified, then the iteration may focus on potential design changes to reduce the possibility of damage and service disruptions during a post-earthquake response.

In some cases, the conditions may impose such large demands that the system-level objectives may not be feasibly met for either logistical, technical, or economic reasons (e.g., a fault rupture displacement far exceeding what a design can accommodate or the devastation throughout a community may far exceed what an organization can manage for the target recovery time). In such cases, the target system-level objectives may need to be revisited and in special situations modified. These modifications should be accounted for in system-level response and recovery plans. They should also be incorporated into community-level response and resilience plans to ensure the public is prepared for certain extreme situations.

It is possible for the constituent parts of the framework to exceed their target performance and recovery time objectives, while still not meeting the system-level objectives. In such cases, all attempts should be made to modify the asset designs and/or organizational actions to meet the system-level objectives. Because a lifeline infrastructure system is built by developing one or a few components and groups at a time, and since every system is different, the assets and organizational actions objectives defined in Chapters 4 and 5, respectively, will focus first on the constituent parts. Having these intermediate target objectives allows for each component or group to be addressed individually while targeting the overall system performance, without the need to always address the entire system when developing a single constituent part.

As shown in Fig. 3-2 with the dashed arrow, if the lifeline infrastructure system-level and/or objectives for the constituent parts are modified, this will influence the third-party and user response action objectives, which may need to be modified accordingly. Once the component designs and the group policies and strategies meet or exceed the performance objectives (path "Yes" in Fig. 3-2), the objectives, system layout and/or component design, together with the system organizational structure and planned group activities are finalized. The recovery time objectives need to be made available to customers, users, and third-party organizations.

3.7. Reporting

The findings and results obtained by implementing the assets and organizational actions frameworks should be documented and implemented into the plans described in Sec 3.3.2. The process then proceeds with implementing the plans and incorporating findings from the framework process into practice. The reported results should be used as feedback for decision makers and the planning process as described in Sec. 3.1. Results from the assets framework should be integrated with the organizational actions framework. The reporting may need to be provided in various forms to meet the needs of different stakeholders, such as system leadership and decisionmakers, elected officials, emergency managers, planners, high and mid-level managers, engineering designers, customers and users, and non-government organizations. The resulting policy-level recovery time objectives should be transparently available to users and third-party organizations through active engagement so that they can properly prepare for their own functional recovery as shown in Fig. 3-2.

4. LIFELINE INFRASTRUCTURE SYSTEM ASSETS FRAMEWORK

4.1. Overview

The lifeline infrastructure system assets framework provides a process to design and assess the interlinking components and subsystems making up the built infrastructure so that services can be restored in a post-earthquake timeframe to meet the recovery-based objectives. The assets framework is based on the following features:

- Identify the components within a lifeline infrastructure system that are necessary and identify their dependencies and interdependencies with other systems to provide the basic services to customers of different criticality.
- Design lifeline infrastructure system components and subsystems for reduction in seismic risk given the needs of customers of different criticality.
- Assess the entire lifeline infrastructure system for earthquake events. Balance the needs of customers, performance level, recovery time, risk, and cost to provide services that meet functional recovery goals.

These features include interaction with other dependent and interdependent systems. They apply to the design of new systems or the improvement of existing systems. The process incorporates system redundancy, isolation capabilities, and ability to adapt. These resilience traits and the above identified features apply to all lifeline infrastructure systems of any size and location.

4.2. Framework for Assets

The goal of the lifeline infrastructure system assets framework is to create a process to identify, design, and assess the interlinking infrastructure components so that services are restored in an appropriate post-earthquake timeframe to meet recovery-based objectives.

This assets framework was originally developed for a large water system [Davis, 2019a]. It has been adapted to include dependencies and interdependencies. Moreover, it can be used for wastewater and electric power, and other lifeline infrastructure systems [Davis, 2019b] of any size. The assets framework provides a hierarchy for both system-level and component-level target performance and recovery time objectives. It is important to focus first on establishing system-level performance and recovery time objectives. Component-level objectives are developed to ensure the system-level objectives are met. Therefore, the initial step in the framework requires the system planning function in Fig. 3-1 to establish the system-level performance and recovery time objectives consistent with the organizational governance and policy as described in Ch. 3. The system-level objectives are common for both the assets and organizational actions frameworks. The component-level objectives also need to be established. The assets framework presented in this chapter provides guidance on how to develop component-level objectives that are intended to meet the system-level objectives.

Volume 2, published as NIST SP 1311 [NIST, 2024], presents example applications of the assets framework to water, wastewater, and electric power infrastructure for an example community.

As presented in Ch. 3, this assets framework addresses two types of objectives:

- **Performance Objective:** The planned damage state of assets at a specified hazard level.
- **Recovery Time Objective:** The planned duration for restoring a component or system to a defined operational or functional level for a specified hazard or earthquake event level. Section 2.4 describes earthquake events for use with this objective. Recovery time objectives may differ for customers or users of different criticality. A system service recovery time objective for functional recovery is the duration that it takes after the earthquake for services to be restored to users through the network. A component recovery time objective for functional recovery includes the time for repairs or system adaptations (e.g., installing a temporary bypass line) to reinstate operations. The component repairs and system adaptations may be temporary or permanent. Coordinated and synchronized recovery time objectives may need to be developed for each subsystem as described in Sec. 3.4.

Lifeline infrastructure systems are composed of numerous specialized physical components, such as pipelines, pumping stations, and treatment plants for water and wastewater systems or transmission towers and lines, substations, and generation facilities for electric power systems. The component-level objectives include life safety, property protection, and recovery time. Life safety and property protection are commonly addressed in current guidelines, standards, and codes. The assets framework addresses the component recovery time objective. The design for a recovery time objective should not be lower than that needed to meet safety or property protection.

Figure 4-1a presents a flow diagram for component-level designs to meet the performance and recovery time objectives in Steps A1 to A7. The system-level recovery time objectives are used as input to utilize the framework. Step A4 in Fig. 4-1a establishes component level performance objectives to be utilized along with any other performance objectives which may be specified in existing codes and standards (this framework does not supersede the objectives in existing codes, standards, or guidelines and instead should be implemented along with them). System-level performance objectives may be identified and implemented for use as part of the framework (examples are described in Volume 2 Chapters 4, 5, and 6). Figure 4-1a is intended for use by components in all lifeline infrastructure systems but is applied to only one system at a time. The diagram is intended for use for one component at a time, multiple components and/or subsystems in sequence, and the system as a whole. The process in Fig. 4-1a is an expansion of the lower left box in Fig. 3-1. Figure 4-1b presents a design validation process in Steps A8 to A10 intended to ensure the component-level design can meet the system-level recovery objectives. Step A11, which describes reporting the system assessment results is not shown in the flow diagram.

The component recovery time objective helps to meet the system-level recovery objectives in a cost-effective way. Costs balanced with needs as well as performance and recovery are addressed in Step A6. Figure 4-1a is separated into upper and lower portions identified by dashed boxes. The upper portion of Fig. 4-1a presents a process to establish component-level performance and recovery time objectives. The lower portion of Fig. 4-1a duplicates a portion of the flow diagram in Fig. 3-2 but provides more details for the component-level design process.

There are three parallel vertical processes shown in Fig. 4-1a. The primary process is the one to the left containing the seven blue rectangular boxes starting with Step A1 and ending with the diamond in Step A7. The parallel processes in orange-colored (Step A5) and yellow-colored boxes are described in relation to the blue boxes.

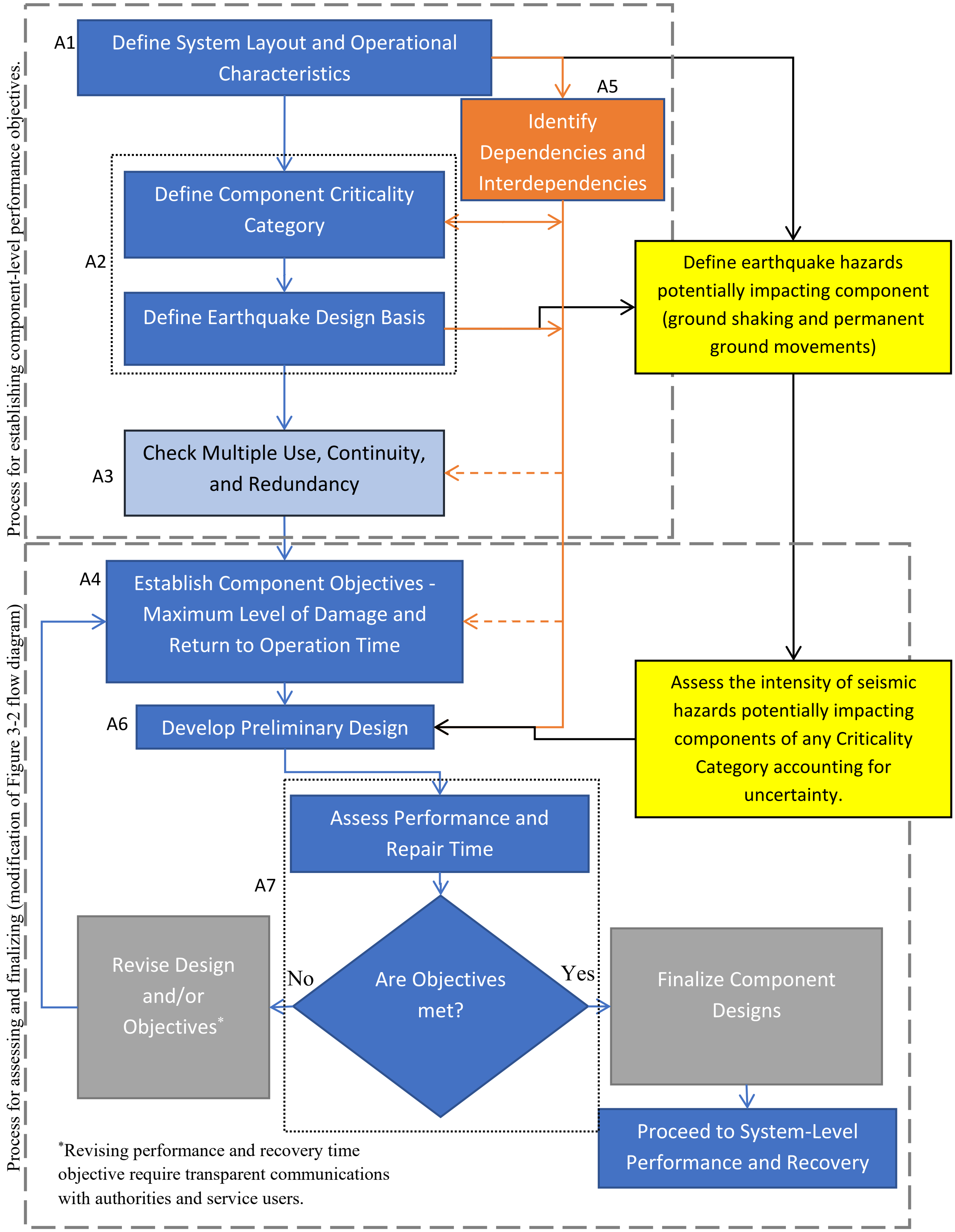

Figure 4-1a. Assets framework component-level design process flow. The steps are identified by the numbers A1 to A7.

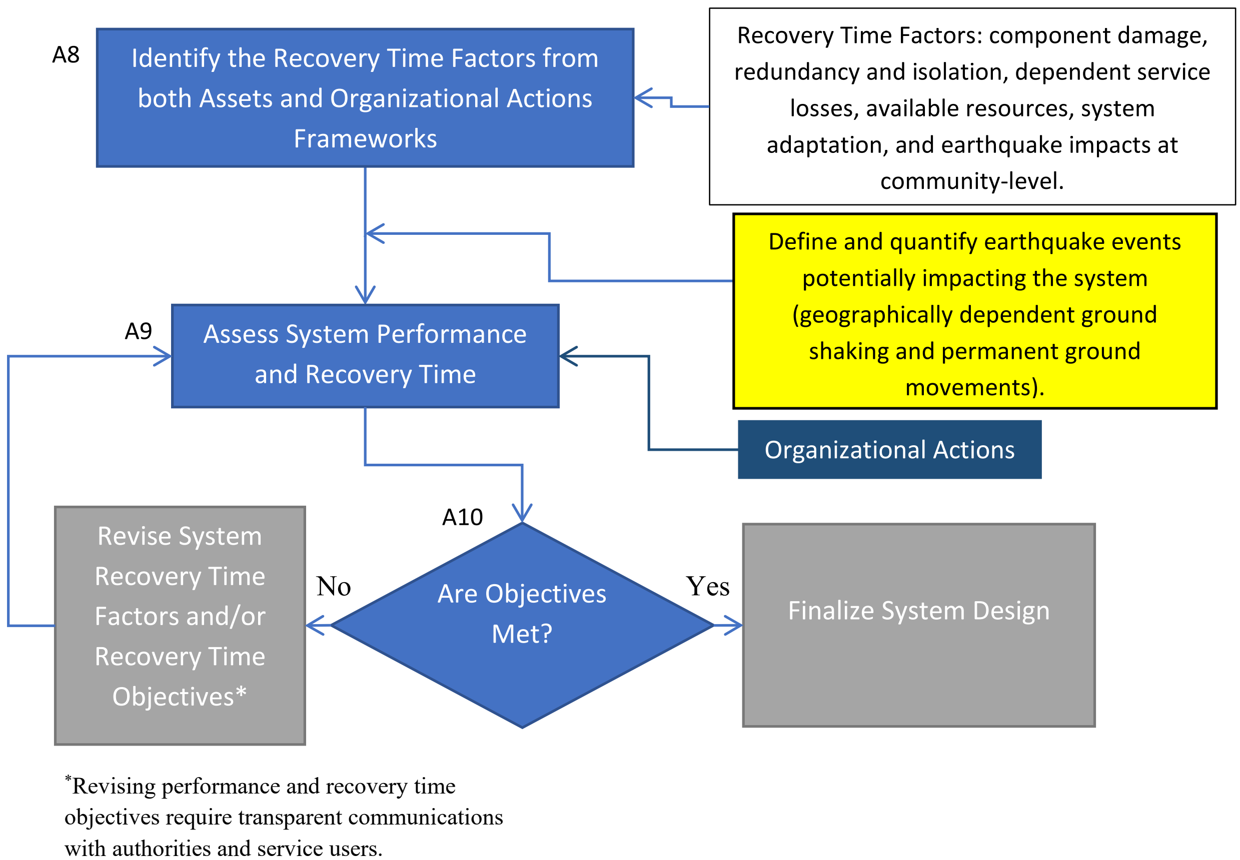

Figure 4-1b. Assets framework system-level assessment validation process flow. The steps are identified by the numbers A8 to A10.

The two yellow boxes in Fig. 4-1a deal with hazard intensity levels and how they affect lifeline infrastructure system components. This is a process performed in parallel to Steps A1 to A6. The results of a hazards assessment are used as input in the lower portion of Fig. 4-1a and to Fig. 4-1b. Figure 4-1a also shows the need to identify dependencies and interdependencies with other lifeline infrastructure. This is another parallel process associated with Step A5.

4.3. Step A1: Define System Layout and Operational Characteristics

The process in Fig. 4-1a starts with Step A1 by identifying the component location and its alignment (i.e., position and orientation within the network). The location is defined geographically and identifies the position of the component within the network topology. The location also allows the exposure to seismic hazards to be defined as identified in the yellow box to the right in Fig. 4-1a. Where feasible, instead or in combination with enhanced design, components may be relocated to reduce exposure to earthquake hazards, such as high intensity ground shaking and permanent ground deformation.

4.4. Step A2: Define Criticality Category and Earthquake Design Basis for System Components

The alignment within the system identifies the criticality of components to ensure system operation. The component's operational need is established in Step A2 in Fig. 4-1a based on the importance of the customer to the community during an earthquake disaster. Each component is assigned a Criticality Category using Table 4-1 based on the component's operational need for providing services to different customer types. The Criticality Category assignment is accomplished in this step without regard to any level of redundancy. Redundancy is considered in Step A3.

Table 4-1 provides summaries of Criticality Categories intended to apply to all lifeline infrastructure systems. The general descriptions given in Table 4-1 can be expanded for each lifeline infrastructure system to provide more specifics and greater detail, such as those presented in Volume 2 for water, wastewater, and electric power systems.

Critical Customer/User A, B, and C are defined as follows:

- Critical Customer/User A are those directly involved with activities related to life safety and public health, and essential to community response and livelihood.
- Critical Customer/User B are those needed in support of critical community resilience activities.
- Critical Customer/User C are those not categorized as A or B.

For example, Critical Customer/User A includes hospitals, emergency operation centers, evacuation centers, and other lifeline infrastructure facilities. Critical Customer/User B includes major social institutions such as schools, business, and industrial facilities needed to ensure that social and economic systems can function.

Table 4-1. Descriptions of Criticality Categories (adapted from Davis [2005; 2008] and ALA [2005])

Criticality Category	**Description**
I	Components, in the event of failure, present very low hazard to human life, no damage to property, and little to no effects on user ability to perform post-earthquake activities or functions. Not needed for post-earthquake system performance, response, or recovery.
II	Normal and ordinary components. Includes all components not in Criticality Categories I, III, and IV.
III	Components where failure represents a substantial hazard with significant risk, including significant levels of property damage. An extended operational disruption for these components may result in significant social or economic impacts and cause significant effects on users' ability to perform activities or functions. Operational disruption of these components causes long delays in post-earthquake system response or recovery. Provides services to **Critical Customer/User B.** Buildings and structures necessary for interacting with customers and users like customer service offices.
IV	Components needed to provide services to essential facilities for post-earthquake response, public health, and safety. These components are intended to remain functional and continue operating during and following an earthquake. Provides services to **Critical Customer/User A.** Buildings and structures necessary for performing essential and support functions by the lifeline infrastructure system organization, and facilities containing hazardous chemicals.

Water pipelines are used here to provide examples for identifying component criticality categories in a water system. Similar examples can be established for other lifeline infrastructure system components. Pipelines providing water services only for irrigation to recreational parks are examples of Criticality Category I components. Pipelines not part of a fire service backbone serving commercial businesses normally having relatively low water demands are examples of Criticality Category II components. Pipelines not needed for firefighting or to provide services for other public health and safety purposes and are supplying water to an elementary school that does not serve as an emergency evacuation center are examples of Criticality Category III components. Pipelines needed for firefighting service or supplying water to acute care hospitals are examples of Criticality Category IV components. Interaction among the pipelines with different critical functions is accounted for in the flow process of Figures 4-1a and 4-1b.

Many lifeline infrastructure facilities/components operate using services from other lifeline infrastructure systems. Each component using services therefore are customers of the other lifeline infrastructure systems. Commonly these components are identified as Criticality Category II, III, or IV within a given lifeline infrastructure system. However, this assets framework expresses these components in terms of Critical Customer/User types for the supporting infrastructure system. These Criticality Categories need to be communicated to the supporting lifeline infrastructure organization to which they are dependent upon using Critical Customer/User types. This communication should be accomplished using Step O3 in the organizational actions framework. To aid in communicating the criticality of lifeline infrastructure components the following correlation between Criticality Categories and Critical Customer/User types is provided:

- Criticality Category IV is equivalent to Critical Customer/User A.
- Criticality Category III is equivalent to Critical Customer/User B.
- Criticality Category II and I are equivalent to Critical Customer/User C.

As an example, a Criticality Category III pumping station within a water system, which uses electricity, is equivalent to a Critical Customer/User B to the supporting electric power system. The equivalencies outlined above are important tools for communication, especially for redundant components within a given lifeline infrastructure system. Step A3 in Sec. 4.5 describes how a component Criticality Category may be modified based on the level of redundancy. As a result of potential redundancy, the Criticality Categories and Critical Customer/User types may not be consistent across all lifeline infrastructure system sectors.

Step A2 in the process of Fig. 4-1a establishes the component design levels using the Criticality Category. Suggested design levels are presented in Table 4-2 in terms of an earthquake hazard design basis for each Criticality Category. Fig. 4-1a shows how the design basis interacts with the hazard analysis by using the suggested criteria in Table 4-2 to establish the intensity measure for each earthquake hazard. The design basis covers all earthquake hazards, such as ground motion, fault rupture, landslide, liquefaction, lateral spreading, differential settlement, and cyclic mobility.

For operational purposes, a component has a minimum required performance following an earthquake [NIST, 2015b], which can be described in terms of robustness [Bruneau et al., 2003]. The more robust, the higher likelihood for a component to continue functioning after an earthquake, which generally increases system resilience by reducing damage and decreasing recovery time. The level of robustness needed for any given component increases with increasing functional importance. The functional importance is represented by the Criticality Categories. Table 4-2 links the Criticality Category to the probability of a hazard exceeding P_e in 50 years, which is consistent with engineering practice. The probability of non-exceedance C is defined as $C = 1 - P_e$. C can be considered a confidence level and is the probability of the earthquake-induced demand parameters (e.g., acceleration, velocity, ground movement) not being exceeded. The return period, T, of a hazard exceedance level is the average time between occurrences of such events and is equal to one over the annual probability of exceeding the hazard level.

Table 4-2. Suggested Earthquake Hazard Design Basis for each Criticality Category (adapted from Davis [2005; 2008] and ALA [2005])

Criticality Category	**Hazard Probability of Exceedance P_e in 50 years**	**Probability of Non-Exceedance C**	**Return Period T (years)**
I	50 %	50 %	72
II	10 %	90 %	475
III	5 %	95 %	975
IV	2 %	98 %	2,475

Must meet minimums dictated by existing codes & regulations.

4.5. Step A3: Check Multiple Use, Continuity, and Redundancy

Step A3 in Fig. 4-1a is for checking component Multiple Use, Continuity, and Redundancy. The flow process for Multiple Use, Continuity, and Redundancy is presented with more detail in Fig. 4-2.

4.5.1. Multiple Use and Continuity

Components, based on their intended use, are classified using the highest applicable Criticality Category in Table 4-1. System connections to Critical A or Critical B customers, as described in Table 4-1, shall have a continuous reliable set of components, utilizing the same Criticality Category or higher for every component.

For water and electric power system continuity, components making up an entire supply chain from source to service connection shall be designed for the highest Criticality Category. Where line connections and branches come from a higher Criticality Category component to serve a lower Criticality Customer/User, the branch line shall be designed to the higher Criticality Category. These branch lines may be equipped with isolation capabilities, maintained to be operable when there is damage to that line. In such cases the branch line may be designed for the downstream Criticality Category associated with the Critical Customer/User being served. Sec. 4.5.2 provides a detailed outline for branch lines and isolation.

For wastewater system continuity, components making up an entire chain from collection to discharge shall be designed for the highest Criticality Category. Where lines having a lower Criticality Category branch into and connect with a higher Criticality Category component, the branch line shall be designed to the higher Criticality Category. These branch lines may be equipped with isolation capabilities, maintained to be operable when there is damage to that line, or in cases of unpressurized flow shown to not back up sewage. In such cases, the branch line may be designed for the Criticality Category associated with the upstream Critical Customer/User being served. Sec. 4.5.2 provides a detailed outline for branch lines and isolation.

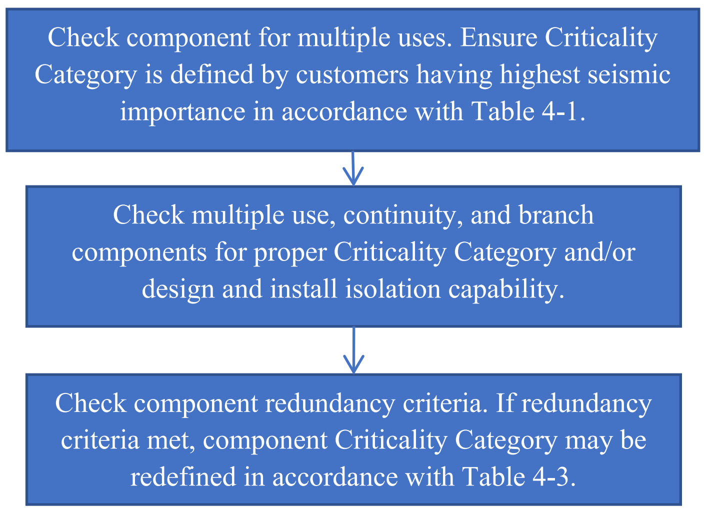

Figure 4-2. Flow diagram for Step A3 checking multiple use, continuity, and redundancy to establish performance objectives.

4.5.2. Branch Lines and Isolation

Post-earthquake reliability may be compromised in components along branch lines that are designed to a lower confidence level. To attain post-earthquake functional recovery, the following procedure is recommended for evaluating branch line component design requirements and isolation capability. This procedure is only applicable to components along lines of a lower Criticality Category branching from water and electric power or to wastewater components along lines branching to a higher Criticality Category.

- Determine the Criticality Category for the branch line components using Table 4-1.
- Determine the Criticality Category of the component it is branching from/to using Table 4-1.
- Design the branch line components for:
  - The lower Criticality Category if isolation is installed or an engineering analysis is performed to show the branch lines will not disrupt post-earthquake performance of

the higher component Criticality Category. This evaluation must account for the cumulative effect of potential damage on all branch lines.

- The higher Criticality Category if item above is not satisfied.

- Perform a check on isolated portions of the system to ensure that there are no significant life safety issues if a service disruption results due to component damage or isolation. If there is a concern, design the branch line components for the higher Criticality Category.

The practical application of the above criteria for newly installed seismic resilient lines requires isolation valves (for potable water systems), bulkheads (for wastewater systems), or disconnect switches and fuses (for electric power systems) to be placed on older non-resilient connecting lines. These isolation capabilities may already exist for design requirements other than seismic. The isolation valves, bulkheads, or disconnect switches and fuses may be actuated automatically or manually.

4.5.3. Component Redundancy

Redundancy is described in Sec. 2.3.4, is a desirable feature for functional recovery, and is encouraged to improve cost-effective reliability of service provision even during normal operating conditions.

Components are assigned a post-earthquake design capacity, N_e, (e.g., for quantity service) and a post-earthquake redundancy level, L_{Re}; an $N_e + L_{Re}$ criteria is defined for the seismic design of each component. The design may include:

- Designating a primary component(s), of all the redundant components, to have the capacity N_e to meet all post-earthquake operational needs, and to be designed for the highest required Criticality Category as defined in Table 4-1,
- Designating primary redundancy L_{Re} for post-earthquake operational needs to be designed for the highest required Criticality Category as defined in Table 4-1, and
- Reducing the seismic design criteria for all redundant components beyond the $N_e + L_{Re}$ requirements in accordance with Table 4-3.

Primary components are all those needed to fulfill the $N_e + L_{Re}$ design requirement. This process distinguishes between the design requirements for post-earthquake operations, N_e and L_{Re}, and for other normal operational needs, N and L_R. For example, the community may have a plan to operate under ration restrictions after an earthquake and have $N_e < N$ and $L_{Re} \leq L_R$. Unless otherwise designated as needing redundancy and different post-earthquake capacity, components will default to $N_e = N$ and $L_{Re} = 0$ (i.e., no redundancy to the normal capacity). Table 4-3 presents the suggested reclassification of component Criticality Category based on exceeding the seismic redundancy level $N_e + L_{Re}$, which is defined in the footnote to Table 4-3. This reclassification shall not be applied to a component that has the following features:

- Is a primary component as defined in the first two bullets above or otherwise required to have a higher Criticality Category based on public health, life safety, or other factors presented in Table 4-1.

- Is exposed to common cause failures, such as:
    - a leak or break in one component may result in damage on other redundant components,
    - two or more redundant components are exposed to the same earthquake hazards (e.g., redundant components crossing the same fault, landslide, liquefaction zone; equipment shaken in the same building/site; etc.). See description in Sec. 2.3.4.
- Is subject to foreseeable plans to remove the designated primary component from operation. In such a case, change the designated primary component or multiple redundant components shall be designated to the same highest-level Criticality Category.

Note that Criticality Categories can be reclassified as shown in Table 4-3 for earthquake design purposes only.

Table 4-3. Criticality Categories for Redundant Components (adapted from Davis [2005; 2008] and ALA [2005])

	X = Value Greater than $N_e + L_{Re}$		
Criticality Category as defined in Table 4-1	0 [P]	1 [P, S]	2 [P, S, A]
I	I	I, I	I, I, I
II	II	II, II	II, II, II
III	III	III, II	III, II, II
IV	IV	IV, III	IV, III, II

X is redundancy level exceeding the $N_e + L_{Re}$ designated seismic design requirement. [P] is primary components meeting $N_e + L_{Re}$ seismic design requirement, [S] is secondary redundant component(s), [A] is additional redundant component(s). X = 0 means no capacity or redundancy greater than $N_e + L_{Re}$, only [P] exists. X = 1 means up to one level of redundancy to [P] with [S]. X = 2 means [A] provides additional levels of redundancy to [P] + [S].

4.6. Step A4: Establish Component Objectives - Maximum Level of Damage and Return to Operation Time

Step A4 establishes the maximum earthquake damage to meet a certain pre-defined performance level. This step is in the lower portion of Fig. 4-1a, which provides more detail for the component-level design presented in Fig. 3-2. Table 4-4 identifies the four primary levels of component damage: minor, moderate, high, and severe. Some targeted maximum damage states fall between levels. They are designated with dual terms, such as moderate to high while others fall on an extreme side of one of the primary levels like very minor.

Table 4-4. Target Maximum Level of Component Damage based on Criticality Categories

		Adjusted Criticality Category[a]			
		I	II	III	IV
Hazard Return Period (yrs)	2,475	Severe	High to Severe	Moderate to High	Minor[b] to Moderate
	975	High	Moderate to High	Minor[b] to Moderate	Minor
	475	Moderate	Minor[b] to Moderate	Minor	Very Minor
	72	Minor[b] to Moderate	Minor	Very Minor	Very Minor

[a] Adjustments are made using Table 4-3
[b] Building structures requiring continuous use during and after an earthquake

The level of damage informs the potential of a component to continue to remain in operation, or not, after an earthquake. If the component must be removed from service for repair, there are associated repair times and costs to return it to operation.

Due to interaction between asset performance and organizational actions, it may be desirable to assign a range of performance levels for a component. In doing so, system owners can examine a range of organization action options to achieve system-level service recovery goals as part of Step A9.

4.6.1. Target Maximum Component Damage

Component performance objectives are established through definitions of maximum targeted damage. Table 4-4 is a matrix showing the targeted maximum level of damage for different Criticality Categories adjusted for redundancy and hazard return periods. Hazard return periods effectively represent event intensity. The top row in Table 4-4 is the component design level in terms of the redundancy adjusted Criticality Category. The left column is the hazard level experienced in terms of return period. Table 4-4 represents performance objectives for the design of new or the retrofit of existing components in a lifeline infrastructure system. The default performance objective occurs when the component experiences event intensities matching the design level. As a result, the default performance objectives lay along the diagonal of Table 4-4 from the upper right to the lower left. When the intensities experienced by a component is less than the design level, the anticipated damage level reduces, which is reflected in the portion of Table 4-4 to the lower right of the diagonal. When the intensities experienced by a component is greater than the design level, the anticipated damage level increases, which is reflected in the portion of Table 4-4 to the upper left of the diagonal. When a component is designed to meet the criteria defined in Table 4-2, it should not experience any more damage than the levels identified in Table 4-4. The damage levels are described in Table 4-5.

A Criticality Category IV component is designed for a hazard intensity having 2,475-year return period per Table 4-2. This component should be designed to accommodate associated seismic forces or earthquake-induced displacements and is expected to only have a “Minor to Moderate” level of damage when the 2,475-year hazard level is experienced. Because a Criticality Category IV component is expected to be repaired within a time increment of hours to days (see Table 4-6), “Minor to Moderate” level of damage is acceptable for a horizontal distributed component if it will be operational again within hours to days, with its recovery appropriately supported by organizational actions. However, for building structures to recover within such a short window, only “Minor” level of damage is acceptable so that the building structures can be safely re-occupied without structural repairs. A Criticality Category II component is designed for a hazard intensity return period of 475 years per Table 4-2. This component is expected to have a minor to moderate level of damage when the 475-year hazard level is experienced. However, when it is exposed to a higher hazard intensity, more damage is anticipated. In the case of a 975-year return period hazard, the component is expected to have a “Moderate to High” level of damage. In the case of a 2,475-year return period hazard, it will be expected to have a “High to Severe” level of damage.

Damage occurs to different types of components in different ways depending on their composition, method of construction, amount of deterioration, maintenance over time, exposure to different hazards (e.g., transient vs permanent ground deformations), and other factors. It may be difficult to identify the condition of existing components. However, damage levels for new or existing components should be defined following guidance descriptions in Table 4-5. The damage descriptions in Table 4-5 are general but can be applied to the specific components making up each lifeline infrastructure system like those provided in Volume 2, respectively for water, wastewater, and electric power systems.

Table 4-5. Damage Level Summary Descriptions

Damage Level	Summary Description
Minor	Minimal to no perceivable damage. Limited to no effects on operations; able to continue essential emergency operations and most normal operations. Injuries, if any, are minimal in number and minor in nature. Components and facilities remain operable and may require some minor repairs. There is little to no damage to mechanical and electrical equipment. Damage may warrant investigation due to safety precautions, but do not result in safety concerns or significant limitations to operations. Repairs, if any, are relatively simple and easy. Serviceability impacts, if any, are limited to a small number of customers. For facilities[1], this damage level is equivalent to the Immediate Occupancy Structural Performance Level and Operational Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023].
Moderate	Damage is repairable. There may be some delay in re-occupying buildings[1]. Essential emergency functions are fully operational. Emergency systems remain fully operational. Injuries may be locally significant but are generally moderate in number and in nature; the likelihood of life loss is low to very low. Some hazardous materials are released to the environment, but the risk to the community is minimal. Damages to major supply, generation, treatment and processing, transmission, and conveyance components may require temporary removal from operation for limited repairs, but not on an emergency basis (i.e., they can remain operable following the earthquake, but a temporary shutdown may be warranted within days to weeks after the event). Limited damage to mechanical and electrical equipment, but not to the extent system operations are seriously impacted (e.g., some equipment may require repairs but can be undertaken without serious disruption to operations). Components needing to function for life safety and property protection may have some damage and warrant immediate investigation due to safety precautions, and some repairs may be required but have limited to insignificant impacts on operations. Some distribution and collection network components may have damages with local impact on services. There may be some effect on system serviceability, but damage is localized and not widespread. For facilities[1], this damage level is equivalent to the Damage Control Structural Performance Level and Position Retention Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023].
High	Significant damage is expected. Structural damage to components may be repairable. Building[1] structural elements may have significant damage, but limited falling debris. Delays in building[1] re-occupancy can be expected. Nonstructural systems for normal building[1] use are significantly damaged and inoperable. Emergency systems may be significantly damaged but remain operational. Injuries may be locally significant with a high risk to life but are generally moderate in number and nature. The likelihood of life loss is moderate to low. Some hazardous materials are released to the environment and localized relocation is required. Damages to major supply, generation, treatment and processing, transmission, and conveyance components may be significantly damaged and require removing them from operation until repairs are completed. Mechanical and electrical equipment may require extensive repairs or replacement. Components needing to function for life safety and property protection may show observable and significant damage warranting immediate investigation and potential removal from use due to safety precautions, but do not pose a catastrophic threat. There may be much damage in distribution and collection network components, each potentially affecting services. If a collection or distribution network as a whole has this damage level, there will be significant repercussions to system serviceability, potentially affecting many customers. For facilities[1], this damaging level is equivalent to the Life-Safety Structural Performance Level and Position Retention Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023].

[1] Buildings and facilities that are part of the lifeline infrastructure system.

Table 4-5. Damage Level Summary Descriptions (continued)

Damage Level	Summary Description
Severe	Substantial damage is expected. Repair may not be technically feasible. Buildings[1] may be severely damaged making them unsafe for re-occupancy; partial or total collapse is possible [ASCE, 2023]. Systems for normal building[1] use may be inoperable, and emergency systems may be substantially damaged and inoperable. Injuries may be high in number and significant in nature. Life safety is threatened. The likelihood of life loss is high to moderate [ICC, 2022]. Significant amounts of hazardous materials may be released and relocation required beyond the immediate vicinity [ICC, 2022]. Damage may require immediate shutdown for repairs. Distribution and collection network components have much damage impacting service to many customers. If a collection or distribution network as a whole has this damage level, system serviceability is severely impacted to a large percentage of, or possibly all, customers. For facilities[1], this damaging level is equivalent to the Collapse Prevention Structural Performance Level and Hazard Reduced Nonstructural Performance Level as defined in ASCE 41 [ASCE, 2023].

4.6.2. Target Component Return to Operation Time

The component recovery time objective is described in terms of target return to operation time. The assets framework recognizes that damage to large complex systems cannot always be prevented when subjected to extreme earthquakes. As a result, target component return to operation times need to be identified. Component return to operation times are a function of many factors including component fragility, intensity and type of seismic hazard to which they are exposed, the extent of damage, materials and resources available to make post-earthquake repairs, crew experience, and site conditions at damage locations.

The return to operation time increment is the maximum amount of time after an earthquake that it takes to prepare a component so that it can be returned to operation. It is the sum of (a) the time it takes to initiate work plus (b) any lead time required for acquiring replacement units, repair parts and materials, and scheduling the repair plus (c) the duration to complete the work on a component so that it can be used in operation, which identifies the repair time increment. The repair time increment (c) may be accomplished through permanent repairs, temporary repairs, or system adaptations. Once the work is completed, the component may or may not be put into operation depending on the status of other components, which relates to system-level recovery. Since this step only addresses component-level objectives, it is limited to assessing in Step A7 the repair-time increment because the lead times and repair of other parts of the system are beyond the design scope of individual components. However, the increment of time to initiate work and lead times for items (a) and (b) above can be assumed as part of a design check. The time increments to initiate work and for lead times may increase with increasing earthquake event levels presented in Sec. 2.5 for reasons similar to those described in Sec. 5.6.2. The repair time increment, plus any assumed increment of time to initiate work and lead times, is estimated in Step A7 and compared to the target time increments for returning components to operation in Table 4-6.

Table 4-6 provides recommended target maximum time increments for a component to be returned to operation as a function of redundancy adjusted Criticality Category. Each cell in Table 4-6 has a corresponding cell describing damage level in Table 4-4. Like in Table 4-4, the top row in Table 4-6 is the component design level in terms of Criticality Category and the left column is the hazard level experienced in terms of return period. Similar to Table 4-4, Table 4-6 presents the default recovery time increment objective along the diagonal from upper right to lower left.

The repair time increment is independent of when the work is started as well as any parallel work undertaken at the same time. The combined effects of multiple repairs are covered in Steps A8 to A10. Assessing the likelihood of damage and potential repair time increment aids in establishing the preliminary design in Step A6. For example, if a repair time increment, along with any assumed time increment to initiate work plus lead times, is estimated to be longer than the target return to operation time increment in Table 4-6, then the design is recommended to be changed. Examples are provided in Volume 2 Sections 3.6.2, 4.6.2, and 5.6.2 having conditions requiring the need for increased design levels based on site conditions that do not allow the target return to service time to be met.

There is no guarantee that a component can remain undamaged and operational in all types of earthquake events. However, a component could be designed for a target of continuous operation during and after an earthquake. Criticality Category IV in Table 4-6 can include a lower limit of zero downtime, but a limited downtime of up to a few hours may be a practical approach.

Table 4-6. Recommended Target Time Increments for Returning Components to Operation

		Adjusted Criticality Category[a]			
		I	II	III	IV
Hazard Return Period (yrs)	2,475	Month or More	Weeks to a Month or more	Days to Weeks	Hours[b] to Days
	975	Weeks	Days to Weeks	Hours[b] to Days	Hours
	475	Days	Hours[b] to Days	Hours	Hours
	72	Hours[b] to Days	Hours	Hours	Hours

[a] Adjustments are made using Table 4-3

[b] Building structures requiring continuous use during and after an earthquake

4.7. Step A5: Identify Dependent Services

Dependencies and interdependencies are described in Sec. 2.3.2. Identifying component dependencies and interdependencies are indicated in Fig. 4-1a by the arrow from Step A1 to the right going to the Step A5 box. The flow process has a vertical line parallel to the component assessment from Step A1 to Step A6 preliminary design. The supporting services needed by the dependent component must have the same level of robustness as the supported component. Components providing the supporting services should also be designed for the same hazard intensity levels in Table 4-2. This is indicated by Step A2 being connected to the parallel vertical line in Fig. 4-1a. Figure 4-1a is intended for use by components in all lifeline infrastructure systems but is applied to only one system at a time.

When the process is applied to a dependent component in a system, it also defines the Criticality Category for the components providing the supporting service. For example, consider a hospital defined as a Critical Customer A. Criticality Category IV water or wastewater pumping stations for the hospital will depend on electrical power services either to provide water or collect wastewater. Therefore, the electric power supply chain, which energizes the pump stations will also have a Criticality Category IV. Following the line, one would also investigate multiple use, continuity, and redundancy (Step A3) and level of damage (Step A4) for the electric power supply chain as indicated by the dashed lines to the respective boxes in Fig. 4-1a. It is important for the designers to know the level of reliability of a critical supporting service (e.g., electric power) when developing the preliminary design and assessing the dependent component's (e.g., pumping station) performance capability. This may require that certain facilities, such as emergency generators, are available for water and wastewater pumping stations, which may introduce conditional dependencies described in Sec. 2.3.2. Similar examples can be made for other components and systems that depend on supporting services. It is also important for the supporting lifeline infrastructure organization to know the defined Criticality Category for the supported component and its equivalent Critical Customer/User type as defined in Sec. 4.4. This is best accomplished in Step O3 of the organizational actions framework for use in the supporting lifeline infrastructure system's application of the assets framework.

When evaluating dependencies and interdependencies, buffers should be identified to help mitigate negative effects on functional recovery. Buffers are described in Sec. 2.3.5. Primary service should be designed according to the component Criticality Category. Buffers should be used for backup to improve service restoration. Understanding services and buffers help to mitigate negative impacts as part of preliminary design in Step A6.

4.8. Step A6: Develop Preliminary Design

Step A6 develops the preliminary component design based on the performance level defined using Table 4-2. Step O1 in the organizational actions framework (Ch. 5) recommends using internal standards of practice for design (e.g., SFPUC, 2023) to complete this process, in the absence of other available peer-reviewed or nationally or internationally accepted standard of practice.

The preliminary design should include the employment of detailed seismic engineering procedures applicable to the different specialized components. There are many different engineering procedures that depend on the type of infrastructure system, the specific components being designed, and the earthquake hazards which need to be accommodated by the component or system. It is beyond the scope of this report to provide detailed seismic design guidance for the many infrastructure components. References for the natural hazard design of electric power, water, and wastewater systems are included in NIST [2014, 2016b, and 2020].

Functional recovery and resilience explicitly incorporate recovery time. As a result, restoration efforts are directly included in the process. This concept can be extended to design. All designs should consider the need for making post-earthquake repairs and possible system adaptations.

The design for Criticality Category I, II, and III components may additionally consider their designs to allow certain levels of damage, with guidance from Tables 4-4 and 4-5, and how to make repairs following an earthquake to achieve the service recovery time objectives. Table 4-4 intends to not allow much, if any, damage to Criticality Category IV components to limit impacts on customers and users. Additionally, the organization should have a robust emergency response plan as described in Ch. 5 with spare parts and equipment on hand to ensure components can be returned to operation quickly and within the repair time increment identified in Table 4-6. Applying this concept can aid in making seismic recovery-based designs more cost effective. When implemented effectively, it can reduce risks by improving components while at the same time avoiding over-designing.

In addition to the core component design process, this step includes the development of estimates for the following:

- The post-earthquake repair time to return a potentially damaged component to operation
- Direct and indirect costs for any new or modified components and expected post-event repairs and adaptations

The component-level restoration time and associated costs can be assessed using the tasks in Table 4-7, which, in turn, can be used in the process in Fig. 4-1b (Steps A8 to A10). The cost assessment determines the economic viability of potentially new or modified existing components.

In Table 4-7, Tasks 1 and 2 are mostly system-level assessment activities. A component-level recovery assessment requires Tasks 3 to 5 with addition of the inspection from Task 1 and potential need for engineering analysis and design from Task 2. In Tasks 3 and 4, dependencies for logistics include the supply chain for materials, equipment, and support crews (especially mutual aid and assistance) and event size affects the recovery rate through the broader extent of damage to the community, which influences the ability to communicate and access critical locations and have resources available for crews to make needed repairs, among other factors. In Task 5, post construction/repair activities may be undertaken before they can return the component to service. This may include safety and/or public health related tasks like disinfecting potable water pipelines or cordoning off the public from temporary installations such as open trenches or dangerous exposure to electrical and mechanical equipment. An inspection may be required for some components such as buildings but not necessarily needed for all system components.

4.8.1. Anticipating Potential Post-Earthquake Costs

The cost associated with emergency response and recovery involve the following primary factors for lifeline infrastructure systems: repair and recovery of utility facilities, impacts on the regional economy from property damages and lifeline service disruption, blockages of access to roads and buildings, hazardous materials releases, flood following earthquake and fire following earthquake. The ShakeOut Scenario [Jones, et al., 2008] is a cooperative emergency response and preparedness exercise involving millions of people to examine the implications of a major earthquake in Southern California. It provides information about potential costs. With respect to fire, it showed that the costs of building and facility damage as well as related content damage were $40 billion and $25 billion, respectively. Rose et al. [2011a] indicate that property damage from fire is 50 % greater in the ShakeOut Scenario relative to property damage from strong ground motion. Significant property inventories are at risk of burning, with a total of $4.7 trillion of insurance policies in force for California residential and commercial buildings, almost all of it exposed to fire following earthquake [Scawthorn, 2011]. The operability of lifeline infrastructure systems is closely tied to losses resulting from fire following earthquake [Scawthorn et al., 2005]. However, while calculating costs, it is important to reflect that exposure levels do not equate to likely losses. That is, even when in the previous example from [Scawthorn, 2011] almost all of the capital insured for $4.7 trillion is exposed to fire following an earthquake, the cost used in calculations should be a likely cost that is affected by the probability of having the considered assets affected if the scenario earthquake happens. As a result, the likely cost used for calculations may be lower than the cost of the total exposed assets when considering the probability of those assets being affected in an event. In the same way, planning cost for restoration or other equipment will also be affected by the probability of the scenario event happening.

With respect to the regional economy, an earthquake can incur substantial expenses. Rose et al. [2011b] show that water outages in Los Angeles County from an earthquake on the Verdugo fault could result in business interruption losses of several billion dollars without adaptation adjustments. Adaptations include rescheduling production, conservation, input substitution, and water storage. Such adjustments will reduce the regional economic consequences of an earthquake.

Costs related to fire and business interruption may be much higher than the expense associated with lifeline repairs and system recovery. Such costs are complex. Their evaluation is important for understanding the value of investing in component and system-level preventative improvements as well as service response and recovery improvements. A more detailed assessment of costs is beyond the scope of this framework. An optimal design should balance community needs, performance and service recovery time targets, probabilities of event, damage and impact, as well as cost of improvements.

4.9. Step A7: Assess the Component Performance and Repair Time, Compare with Target Objectives

Using the preliminary component design in Step A6 and the identified dependent services from Step A5, this step assesses the expected component performance and repair time when subjected to the earthquake hazards to which the components are exposed, using the levels designated in Table 4-2.

For this step the analyst should perform a series of simulations (analyses of the component response to seismic loading) to estimate the probable performance and restoration of the component under various scenario conditions. Using fragility relationships (damage functions defining the relationship between load and probability of damage) developed through post-earthquake observation, testing or calculation, the component responses are equated to damage states expressed as performance levels [FEMA, 2010]. This is part of a standard performance-based design procedure (e.g., ASCE 2017). Additionally, if the component being evaluated is expected to be damaged, then further effort is needed to determine if the damage state is at a level that may prevent it from operating; Table 4-5 can provide guidance. If the component is unable to operate, then an estimate is needed to identify the time to make repairs or adaptations to return it to operation using the criterion described in Sec. 4.6.2. FEMA [2022] provides some guidance on restoration times for lifeline infrastructure systems.

Table 4-7. Tasks to Accomplish System and Component Restoration

No.	Task	Activity Level	System Organizational needs	Dependencies
1	Identify damage	System and component	• Knowledge about earthquake impacts • Inspection • System data/construction documents • Available crew and equipment • Equipment (cameras, inspection tools, data collection and storage) • Community (volunteer) data collection – phone banks, internet	• Communication • Transportation • Dependent system services • Consultants and contractors
2	Planning and prioritizing	System and component	• Knowledge about service disruptions & community impacts • Service restoration strategy • Available crews, materials & equipment • Sufficient fuel for emergency power • Determine if engineering design is necessary to undertake repair • Ability to adapt (component or system) • Permitting requirements from jurisdictional authorities • Scheduling	• Mutual aid and assistance • Consultants
3	Mobilize	Component	• Crews • Materials • Equipment • Fuel/power	• Transportation • Logistics • Financing • Procurement • Event size
4	Construction/ repair	Component	• Crews • Materials • Equipment • Inspection • Fuel/power	• Contractors • Transportation • Logistics • Financing • Event size
5	Post-const./ repair activities	System and component	• System and component specific activities	• Dependent system services • Testing & support systems

FEMA [2022] provides fragility functions for some common lifeline infrastructure system components in terms of probability of a damage state at defined intensity measures (mostly peak ground acceleration, but some for peak ground velocity and permanent ground deformations). Fragility functions in terms of probability of damage do not exist for all specialized lifeline infrastructure system components and all the potential hazard intensity measures they may be exposed to. As a result, estimating the probable performance of some components under various design situations may be difficult. Further, the amount of effort required to assess various design conditions may be time or cost prohibitive for some components. For example, it may be unwarranted to undertake multiple advanced analyses for a 6-inch diameter buried pipeline subjected only to moderate levels of ground shaking, whereas multiple advanced analyses may be deemed necessary for a multi-story building.

Where fragilities are insufficient and/or the component does not warrant the multiple advanced analyses, this step may be reduced to a simple exercise to confirm if the component meets the performance and recovery time objectives. This approach may involve comparative analysis drawing from experience in past earthquakes or laboratory experiments, simple calculations using procedures independent of those used in the design to confirm expected performance, external expert review, and/or mental assessments to think through the problem to determine if the preliminary design is sufficient to meet the objectives. The analyzer may need to make some value judgements when making this assessment. Procedures suggested by FEMA [2022] may also be useful for some components.

Once the simulated performance is completed, the results are compared to the target objectives from Step A4. The expected level of damage from the simulations is compared to the target maximum damage levels in Tables 4-4 and 4-5. The estimated repair time increment plus any assumed time to initiate work and lead times, described in Sec. 4.6.2, is compared to the recommended return to operation time increment in Table 4-6. If the results do not meet or exceed the objectives, then path 'No' is followed in Fig. 4-1a and either the component design or the original objectives need to be modified, and the assessment repeated. There may be situations where meeting the stated objective may not be possible due to physical or cost constraints, in which case the team of designers, decisionmakers, and stakeholders may elect to modify the original objectives. Davis [2019a, page 28] describes some ways to accomplish this. If the results do meet or exceed the objectives, then path 'Yes' is followed in Fig. 4-1a, the component designs are finalized, and the system-level validation is undertaken using Fig. 4-1b.

When the analysis results do not meet the objectives, possible options include, but are not limited to, the following:

- Modifying the design to have increased capacity to accommodate earthquake-induced forces and displacements
- Incorporating the ability to adapt the system after an earthquake
- Incorporating the ability to respond and make repairs and other system-level changes identified as recovery-time factors in Step A8

The last two items may result in the lowering of the component-level performance objective. This is done by allowing a greater damage state while increasing the ability to respond and repair or adapt a component. The goal is to meet the system-level service recovery time objective.

4.10. Step A8: Identify Recovery Time Factors

The process shown in Fig. 4-1b is for system-level assessments to confirm or validate the component-level design(s) by checking to ensure the system-level recovery time objectives are met in relation to the many other factors influencing service disruptions and recovery. To undertake a proper system-level assessment, the factors influencing service recovery time need to be identified. The service recovery time is a function of the following items, herein referred to as recovery time factors:

- Potential component-level damage
- System-level redundancy and isolation capabilities, which are system-level design features
- Dependent service losses
- Resources available
- Ability to adapt the system temporarily
- Extent of earthquake impact at the community-level

These factors should be considered when assessing expected system-level performance and recovery. Each of the recovery time factors is described relative to assets in the subsections below. How these factors influence system-level performance, the total amount of service losses, and the time to restore services needs to be identified so they can be included in the Step A9 system-level assessment. The recovery time factors are also interrelated in that the improvement of one factor can reduce the need for or importance of other factors. This interaction is important to understand when optimizing the performance and recovery time objectives in Step A10.

Table 4-7 identifies the tasks to be taken for completing the repair and restoration throughout the system. In most systems, this is a nonlinear process that cannot be characterized by summing the individual component damage and resulting repair times because of: (1) earthquakes normally will not impose the seismic forces identified in Table 4-2 simultaneously to all components, (2) crews, equipment, and materials may not be available to make concurrent repairs, (3) the system-level performance depends on the ability to provide services through redundancy and isolation capabilities, (4) dependent services may delay service restorations independent of component repairs, (5) temporary system adaptations may be used in place of repairs to shorten service restoration times, (6) overall earthquake impact to the service area may reduce access to damage locations to make repairs. As a result, it is important to investigate the system-level performance based on different events (e.g., see Sec. 2.5). Expected service disruptions and recovery times can be based on the event-specific component damage, system redundancies, dependent service losses, number of available crews and repair materials, system adaptations, and expected community-level impacts. The investigation of system-level performance is undertaken as part of an overall assessment in Step A9. Incorporating results of the organizational actions framework will aid the assessment.

4.10.1. Potential Component-Level Damage

The potential component-level damage is related to the outcome of the process in Fig. 4-1a. Damage is a function of a component's exposure to hazard intensity and its ability to withstand or accommodate the seismic induced forces or displacements.

The hazard exposure is based on the component's geospatial location and alignment relative to seismic hazards. A location where larger intensity hazard levels are expected will require greater ability to accommodate seismically induced forces or displacements. For example, a buried pipeline or conduit passing through a landslide is exposed to and must be able to accommodate the landslide-induced ground displacements. Relocating the component outside of the landslide zone will change the hazard exposure to landslides and reduce or eliminate the need to design for the ground displacements.

The level of design or existing capacity of a component to withstand or accommodate the seismic-induced forces or displacements dictates the components fragility. The less fragile, the lower the potential damage level and number of damage locations. As the extent of damage at any single location and the number of damage locations decrease, the shorter is the time to make repairs and restore services. Conversely, the greater the fragility and extent of damage, the longer is the service recovery time. As a result, tradeoffs are made between improving the seismic design to reduce the possibility of seismic induced damages, along with related costs, and the option to allow greater likelihood for damages and potentially increase the post-earthquake recovery effort.

4.10.2. System-Level Redundancy and Isolation Capabilities

Redundancy is described in Sections 2.3.4 and 4.5. The system layout can incorporate built-in redundancies and isolation capabilities to help control potential service disruptions. This can aid in limiting potential service disruptions. System designs can also include the anticipation for the need to use post-earthquake redundancies by building in locations for post-event temporary hook ups. For example, building in valves and manifolds for portable pumping units, or interconnections to nearby systems.

4.10.3. Dependent Service Losses

Dependencies and interdependencies are described in Sections 2.3.2 and 4.7. The dependencies include all those identified for each component assessed using Fig. 4-1a and possibly additional dependencies affecting the system. The interdependencies should be previously included in the assessment in Fig. 4-1a through the definitions of Critical Customer/User A, B, and C. However, if not all components in the system were evaluated, then the remaining dependencies need to be identified. It is important to recognize the dependencies and interdependencies so they can be associated with impacts on service recovery time.

4.10.4. Resources Available

The available resources to identify damage, make repairs, and restore operations, while maintaining all essential functions (see Step O4 in the organizational actions framework) are strongly tied to the organizational actions framework. Resources include crews, consultants and contractors, materials, equipment, spare parts, and financing. The rate of recovery is a function of the number of available resources as compared to the need for resources. The fewer repairs, the fewer amounts of resources needed. As a result, the factors influencing needed resources are also strongly tied to the outcome of the process in Fig. 4-1a. The resources are also tied to the strategies used to prioritize repairs [FEMA P-2234, 2024, Appendix F]. Some repair strategies can restore services to customers more rapidly than others, the faster the service recovers, the less resources needed for those activities.

4.10.5. Ability to Adapt the System Temporarily

Adaptations are discussed in Sections 2.3.3 and 3.6.1. Making post-earthquake adaptations to the system can significantly increase the ability to provide services in advance of making repairs. For example, adding temporary lines to bypass severely damaged ones may restore operations faster than making the damage repairs. Adaptations may include the providing of services using alternate methods to the network such as providing potable water through manifolds connected to fire hydrants, adding large generators to energize a portion of an electric power system, or using temporary pumping units and lines to move wastewater from a basin where the network is not operable into another basin that is operating.

4.10.6. Extent of Earthquake Impact at the Community-Level

The size of an impacted area and the number of community-level damages influences the rate of repairs. This is a function of the overall vulnerability of the built infrastructure and includes the potential for cascading hazards like fire following earthquake and chemical releases. The less vulnerable the buildings and community systems, the fewer the damages and cascading effects, decreasing difficulty to access sites, identify damages, and make repairs. Conversely, the greater the community vulnerability, the slower repair rate is, lengthening service recovery duration. For example, access is blocked from collapsed buildings and bridges, fires and flooding, and permanent ground deformations.

4.11. Step A9: Assess System Performance and Recovery Time

NIST-FEMA [2021, Task 4.2] recommends that lifeline infrastructure systems be evaluated for their ability to meet recovery-based objectives. This step helps to fulfill this recommendation.

Lifeline infrastructure system evaluations need to consider the impacts from all anticipated earthquake hazards, across the entire system, from source to distribution or collection to discharge [NIST-FEMA, 2021]. A series of simulations, as described in Sec. 4.11.2, are undertaken to estimate the probable performance and recovery time of the entire system or a subsystem. The simulations use the system layout with all its components and subsystems, in combination with plausible earthquake event scenarios characterizing all likely seismic hazards to which the individual system components are exposed. The assessment should incorporate recovery time factors identified in Step A8 and address the organizational actions. Many aspects of the organizational actions flow into the systems assessment through defining the recovery time factors. The organizational actions input to Step A9 from the right side of Fig. 4-1b cover features such as operational capabilities.

The purpose of the assessment is to determine the amount of expected service disruptions to customers and users and how long it will take to recover the services so that the recovery times can be compared with the objectives. Therefore, the assessment must be able to analyze the same parameters and metrics as those used for defining the objectives. For example, if the recovery time objectives are defined in terms of basic service categories (e.g., FEMA P-2234), then the assessment should be able to estimate when the basic service categories may be restored.

4.11.1. Earthquake Event and Hazards

An earthquake event must also be defined and used as input into the assessment as shown in the yellow box to the right in Fig. 4-1b. Section 2.5 describes suggested earthquake events and recurrence intervals for use in this framework. An earthquake event is characterized by the source of a rupture scenario that is uniquely defined by the geospatial location, magnitude, a three-dimensional rupture plane in the Earth’s crust, and other source parameters that help to define the intensities and spatial extent of earthquake hazards. The earthquake hazards involve geologic conditions associated with an earthquake such as surface faulting, ground shaking, landslide, liquefaction, tectonic deformation, tsunamis, and seiches [USGS, 2020]. Multiple earthquake event scenarios may need to be evaluated for proper assessment of the systems’ exposure.

4.11.2. Subsystems with Different Owners and Operators

System assessments may cover individual subsystems, multiple interconnecting subsystems, or the complete set of subsystems making up the entire lifeline infrastructure system. Each subsystem provides services for customers and users. The customer or user may be another separately owned subsystem making up a portion of the entire lifeline infrastructure system. In the case of distribution or collection subsystems, customers and users are mostly external to the system. The key to the assessments is meeting objectives that fit the needs of the customer. All subsystem objectives must meet the needs of the upstream and/or downstream subsystem customers.

Owners and operators of individual primary subsystems or specific assets, as described in Sec. 2.3.6, need to perform evaluations of their infrastructure in a manner that links with the other subsystems and components making up the lifeline infrastructure system. This starts with identifying the target service recovery times in Fig. 3-1. If one subsystem fails to provide input to another subsystem, the overall system may fail. To evaluate the overall system, it is important for all the subsystem owners and operators to coordinate their evaluations and determine their dependencies and interdependencies. Scenario evaluations should involve all subsystem owners and operators.

The infrastructure evaluation for each owner and operator is undertaken using the boundary conditions constraining their subsystems and individual components. The simulations use input from upstream subsystems and components and provide outputs for the downstream subsystems and components.

4.12. Step A10: Compare System Assessment Results with Target Objectives

In this step, the results of the assessment in Step A9 are compared to the lifeline infrastructure system objectives selected in Ch. 3 to determine if the anticipated performance and recovery time meet or exceed the target criteria. If the assessment does not meet the target system-level objectives, then path 'No' is followed in Fig. 4-1b and either the recovery time factors must be modified, and/or the system-level performance and service recovery time objectives changed. The process is iterative and interactive with the organizational actions framework and other lifeline infrastructure systems. For example, if the assessment results do not meet the objectives, then an organization may choose to make post-earthquake repairs instead of increasing the design to prevent damage as described in Step A7. It is beyond the scope of this work to provide detailed guidance on how to modify the initial design to meet the performance objectives. A good place to obtain ideas for modifications is by reviewing the recovery time factors in Step A8 to determine which may be changed to help achieve the objectives. Sec. 3.6.2.2 provides more information and direction on methods and how to manage situations when the assessment results do not meet or exceed the system-level performance and recovery time objectives. The iteration may utilize multiple resilience options. If the system design or layout is modified through the exploration of recovery time factors then components may be modified, and the entire process reiterated back to Step A1 in Fig. 4-1a.

It is noted that even though the components may meet their individual targets in Step A7, the system performance and service recovery objectives may not be met in Step A10. If this situation arises, all attempts should be made to improve the system to meet or exceed the service recovery time objectives as described in Sec. 3.6.2.2.

If the assessment does meet the target objectives, then path 'Yes' is followed in Fig. 4-1b and the system seismic design may be finalized or other earthquake event scenarios evaluated.

4.13. Step A11: Report System Assessment Results

In this step, results from Step A10 combined with all the findings identified through the framework are documented and reported. An important aspect of reporting is to ensure all the appropriate findings can be put into practice. It is important to establish clear documentation. The assets framework involves procedures for complex systems that deal with both physical assets and organizational activities. It includes component, subsystem, and full network functional recovery. It involves both component design and time to recover essential services at all levels of the lifeline infrastructure.

Results of Steps A9 and A10, along with Steps O8 and O9 in the organizational actions framework will inherently identify areas where improvements to the infrastructure and organization can be made. These improvements need to be documented and implemented into the budget and capital improvement program, and all the processes identified in Step O1. Updates to the plans listed in Sec. 3.3.2 should also be made. An important part of documentation and reporting is to update the pre-earthquake mitigation plan to include seismic improvements to the infrastructure identified when implementing the assets and organizational actions frameworks. Any modifications to the service recovery times need to be transparent and reported to customers, users, and third-party organizations as described for Fig. 3-2.

5. ORGANIZATIONAL ACTIONS FRAMEWORK

5.1. Overview

The organizational actions framework comprises a set of processes that a lifeline infrastructure organization needs to have in place to achieve functional recovery. The primary focus of these processes is on the actions to be undertaken by groups within the organization and is based on the following features:

- Pre-disaster recovery policy development and associated plans and procedures.
- Identifying the groups within a lifeline infrastructure organization that provide essential and support functions and associated inter- and intra-agency interactions.
- Establishing policies and strategies for groups performing essential and support functions.
- Assessing the entire lifeline infrastructure organization for earthquake events and appropriately balancing the needs of customers, system performance and service recovery, and cost to ensure services can be provided to meet pre-established performance and service recovery time objectives.

These features include interaction with other dependent and interdependent systems and agencies. They are applicable to the development of new or improvement of existing organizational structures and apply to all lifeline infrastructure systems, of any size and location.

5.2. Framework for Organizational Actions

The goal of the organizational actions framework is to create lifeline infrastructure organizational processes and structures populated with groups of people who can perform a coordinated set of duties to meet the recovery-based objectives as described in Ch. 3. A group is defined as one or more people who must perform certain tasks necessary for the lifeline infrastructure system to operate.

The organizational actions framework provides a hierarchy for both system-level and group-level objectives. It is important to first focus on establishing system-level performance and recovery time objectives. Group-level objectives are developed in terms of responsibilities, resources, and capabilities to ensure the system-level objectives are met.

Therefore, before initiating work on the organizational actions framework, the system-level performance and recovery time objectives must be established consistent with the organizational governance and policy as described in Ch. 3 and shown in Fig. 3-1. The system-level objectives are common for both the assets and organizational frameworks.

The group-level objectives then also need to be established. The organizational actions framework presented in this chapter provides guidance on how to develop group-level objectives in the form of responsibilities, resources, and capabilities that are intended to meet the system-level objectives.

Similar to the assets framework defined in Ch. 4, the organizational actions framework addresses two types of objectives:

- **Performance Objective:** The planned transformed and/or impaired state of an organization at a specified earthquake event level, and
- **Recovery Time Objective:** The planned duration for restoring a group or an organization to a defined operational or functional level for a specified earthquake event so that the lifeline infrastructure components and system can be restored to a defined operational or functional level. Sec. 2.5 describes earthquake events. A system service recovery time objective for functional recovery is the duration when specified services are to be restored to specified users. A group recovery time objective is the duration at which the group can undertake activities necessary for reinstating and maintaining operations to provide the lifeline infrastructure system services.

To manage an earthquake event or other disaster, a lifeline infrastructure organization will commonly transform its normal operating managerial structure into an incident command system (ICS), or similar organizational crisis management structure, such as described by the National Incident Management System (NIMS) [FEMA, 2023]. Transforming the organizational structure is an action that follows pre-specified plans, procedures, and processes (e.g., FEMA, 2023). This transformation aids emergency management but modifies, and at times may inhibit, normal operations by pulling resources to manage the event response and ensure the organization can at least focus on its most essential functions. Temporary organizational transformations are typically maintained until the organizational response to the emergency is under control, at which time normal operational activities will resume with the resources that were diverted during the event response.

It is noted that the group recovery time objective is not intended to define a duration for which an organization will need to remain transformed in an ICS or similar organizational crisis management structure, in order to manage an emergency. Furthermore, the group recovery time can be fulfilled before the organization has returned to normal operational conditions and before any organizational impairments have been resolved.

An organization is considered impaired when an earthquake, or other disaster, reduces its ability to perform, for example, due to the loss of staff and supporting consultant capacity or the inability to function in a transformed state. The loss of employees or consultants occurs when staff, managers or their family are injured, their homes or office buildings are damaged, traffic or communications are disrupted, and other factors that inhibit normal work levels. Such effects on a single employee or consultant may not significantly impair a specific group or the entire organization, but the cumulative effects on many employees and consultants can impair the entire lifeline infrastructure organization. An impaired group may need to transform its organizational structure temporarily to perform its required duties, independent of ICS or similar organizational crisis management structures.

Physical and organizational repairs and service restorations cannot take place without leadership and coordinated organizational actions. Leadership capacity and knowledge gaps can affect single or multiple levels of organizational management which, in turn, can impair an organization's ability to function even in a transformed state using ICS or other crisis management structure.

Several types of organizational actions are needed to achieve functional recovery. These include the development and implementation of policies, plans and procedures, and an array of financial, regulatory, and educational activities [NIST-FEMA, 2021, Chapters 5 and 6], all of which are specified through processes. It is important to understand that functional recovery cannot be achieved across lifeline infrastructure systems until all these items are addressed and incorporated into the organizational actions portion of the overall framework. The portion of the overall framework that is presented in this chapter only addresses the organizational actions relevant to the assets portion of the framework and is limited in focus to the subset of groups that are necessary for functional recovery.

Figure 5-1a presents a flow diagram for the group-level activities in Steps O1 to O6 necessary to meet the performance and recovery time objectives of the organizational actions framework. Figure 5-1a is separated into upper and lower portions identified by dashed boxes. The upper portion of Fig. 5-1a presents a process to establish group-level performance and recovery time objectives. The lower portion of Fig. 5-1a duplicates a portion of the flow diagram in Fig. 3-2 and provides more detail on assessing and finalizing the group-level policies and strategies that meet the performance and recovery time objectives.

Figure 5-1b presents the validation process in Steps O7 to O9 so that group-level activities are properly coordinated to meet the system-level service recovery objectives. Step O10, which describes reporting the system assessment results is not shown in the flow diagram.

5.3. Step O1: Identify Groups within the Organization and their Functions

Lifeline infrastructure organizations are comprised of specialized groups that undertake actions to manage the assets and perform the operations needed to provide services to customers and users. The organizational actions framework process flow initiates with Step O1 to conduct an inventory of all the groups within an organization and their functions.

The groups will include employees and consultants and contractors hired by the organization. The groups making up the lifeline infrastructure organization perform tasks to accomplish functions. Groups performing similar and related types of functions may be organized into divisions, departments, sections, and teams. One aspect of planning is to identify all the groups, their functions, where they are positioned within the organization (i.e., an organizational chart), and how the groups interact within the organization or with key external agencies and other organizations.

An organizational business process analysis (BPA) is a systematic method of identifying and documenting the repeatable tasks or steps in a workflow that contribute to the organizational functions. The BPA is a method of examining, identifying, and mapping the functional processes, workflows, activities, personnel expertise, systems, data, partnerships, controls, dependencies and interdependencies, and facilities inherent in the execution of the functions [FEMA, 2018 Sec. 1.2]. A BPA can be performed to trace the tasks and workflows between groups across the entire organization. The BPA is first undertaken at a broad level organizationally to map out how groups and their functions interact with each other both internally and externally with other key organizations.

Recognizing all the groups and their organizational roles is an important step toward distinguishing the groups performing the essential functions necessary to provide services to customers during a disaster. Tasks for this step can draw from information normally contained in a continuity plan, such as a continuity of operations plan (COOP) or business continuity plan (BCP). The results of this step can also be used to develop or update these plans.

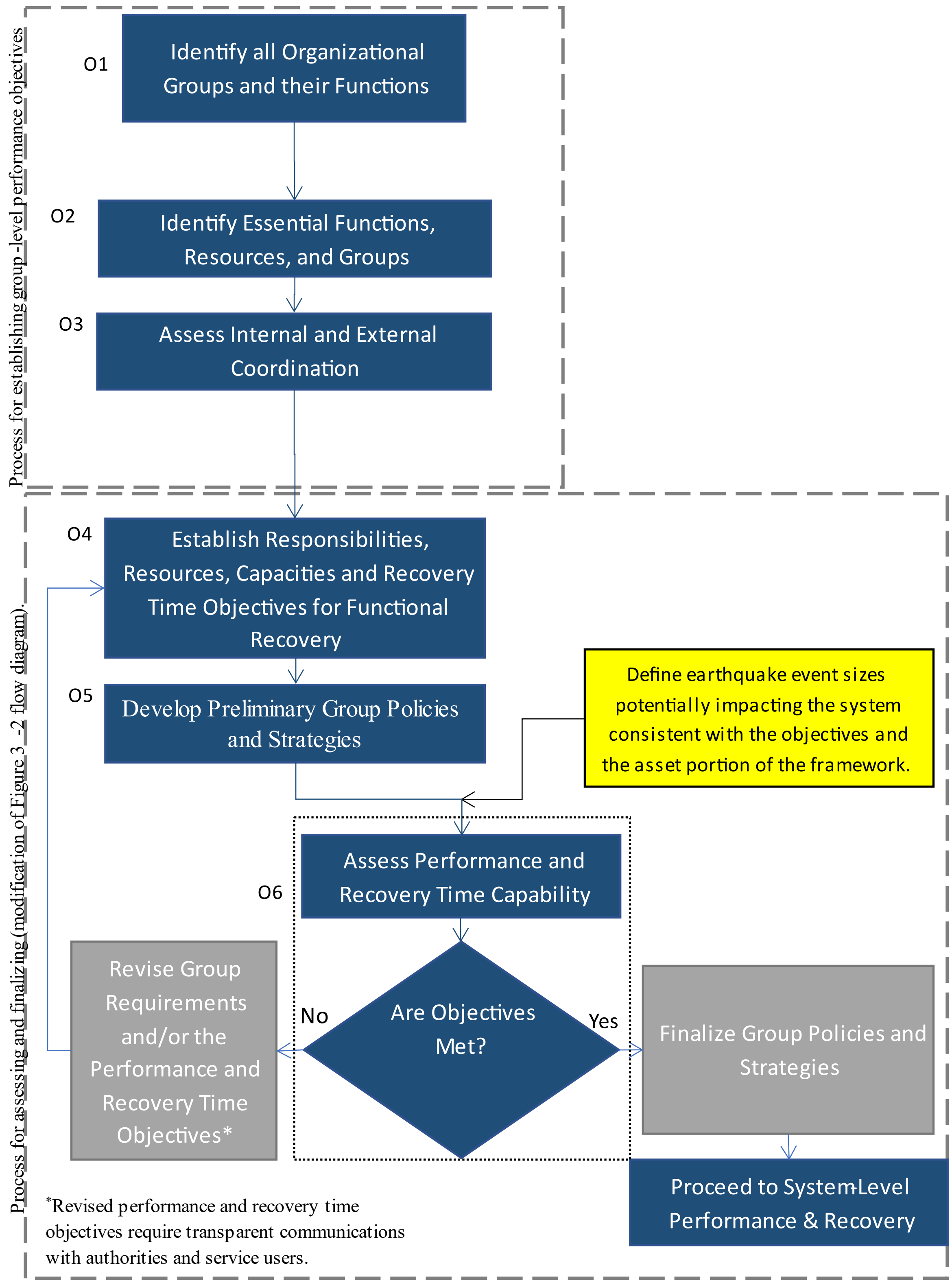

Figure 5-1a. Group-level process flow of organizational actions. The steps are identified by the numbers O1 to O6.

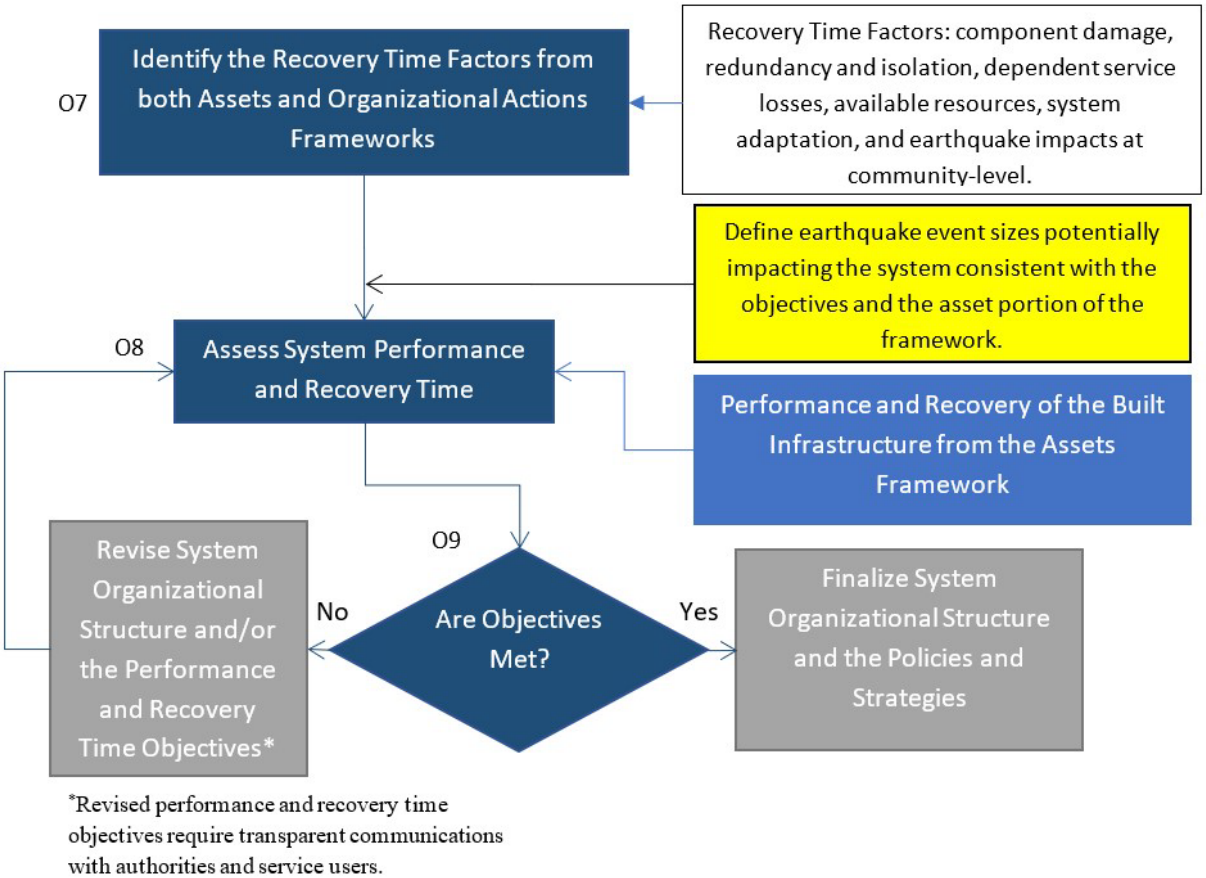

Figure 5-1b. System-level assessment validation process flow diagram for organizational actions. The steps are identified by the numbers O7 to O9.

The BPA also helps to identify the groups that perform the many pre-earthquake activities critical to functional recovery. These activities include:

- Development and use of institutional standards of practice for design, construction, and maintenance of the lifeline infrastructure system and its components and the activities to accomplish the assets portion of the framework. These standards of practice must be consistent with existing codes and standards. Existing codes and standards should be the minimum criteria.
- Preparation and use of emergency management plans and procedures and the ICS or other crisis management structure. ICS is a standardized approach for organizational command, control, and coordination of emergency response and is a component of NIMS used in all-hazards situations. When activated, organizational management temporarily transforms into a standard management hierarchy and procedures for managing personnel, facilities, equipment, funds, and communications during incidents of any size and complexity. It is designed to be used or applied from the time an incident occurs until emergency response management and operations are no longer needed. ICS allows personnel from a wide variety of agencies to meld rapidly into a common management structure with common terminology used in operations, communications, coordination, and other activities. It has

been effective in facilitating mutual assistance and mutual aid among lifeline infrastructure organizations to provide a surge in resources, labor, and materials to accelerate restoration and repairs.

- Asset management. Infrastructure asset management plans and programs are generally focused on the later stages of a physical asset life cycle, specifically maintenance, rehabilitation, and replacement. They identify the need for improving or replacing the assets/components, and when this should be put in the capital improvement program and budget. Improvement or replacement decisions are to incorporate the earthquake and other hazards the assets are exposed to, the probabilities of the hazards, component criticality and redundancy (see Ch. 4 Steps A2 and A3), and potentially other aspects. This is an important part of the program and should be leveraged for improving functional recovery. When an asset is identified as needing improvement or replacement in the asset management program, it is an incurred cost to the organization that cannot be recovered. This cost should be leveraged and used to make improvements for functional recovery (i.e., the total replacement cost is not attributed to functional recovery, only an incremental cost, if any, applied toward the improvement to achieve functional recovery). Asset management typically uses software tools to organize and implement an integrated, multidisciplinary set of strategies to preserve and extend the service life of infrastructure assets. Climate resilience has become an important part of infrastructure asset management competence.
- Financing and funding pre-and post-disaster needs. An organization must have activities for financing and funding to achieve functional recovery. The ongoing development and deployment of pre-disaster financial mechanisms are needed to provide the financial resources necessary to fulfill the necessary responsibilities, provide resources, and support capabilities before the earthquake (i.e., pre-earthquake planning and preparedness). Additional post-disaster financial mechanisms, such as disaster-related government programs, insurance, and private capital, also must be developed and deployed to provide the financial resources necessary to address potential revenue losses resulting from service disruptions, and to fund the labor and organizational expenses necessary to expedite post-earthquake recovery.

Not all organizations have groups with these specific names, but it is likely that the organization has groups that perform these activities. If not, it is important for functional recovery that the organization implements these activities ahead of disaster. Also, while each activity can be undertaken independently, it is the combination of activities that helps organizations to meet the performance and recovery goals and achieve functional recovery.

5.4. Step O2: Identify Organizational Essential Functions, Resources, and Groups

The post-earthquake operational need of each group is established in this step by identifying the subset of all the organizational functions that are defined as essential functions (EFs) and critical activities to restore basic services after an earthquake or other disaster [FEMA, 2018]. These functions must be performed during an emergency, and they must be performed continuously or resumed quickly following a disruption. The EFs are the organizational activities that must be carried out to accomplish the post-earthquake mission of the lifeline infrastructure organization to provide basic services to customers and users.

Lifeline infrastructure organizations can define their EFs through an organizational BPA followed by an organizational business impact analysis (BIA). The BPA and BIA processes are common and well established [FEMA, 2018; WRF, 2013; ISO, 2019; NFPA, 2019], and only an overview is presented here to demonstrate how they fit within the organizational actions framework.

The BIA is a method of identifying and evaluating the effects that an earthquake or other disaster may have on the ability of an organization to perform its functions and the resulting impacts and consequences [FEMA, 2018 Sec. 1.3]. The BIA can draw upon the earthquake assessments performed for the assets framework. Through the BIA, the consequences of failing to perform a function are identified. The consequences should be considered from multiple perspectives including (1) a single group failing to perform its functions, (2) multiple groups simultaneously failing to perform their functions (i.e., earthquakes can cause widespread impacts and simultaneously affect multiple groups), and (3) groups that may fail to perform their functions because of dependencies on other groups unable to perform their functions. Based on the consequences, EFs can then be identified.

EFs are activities necessary and directly related to providing post-earthquake services (e.g., operating valves and switchgear). Activities that do not directly accomplish the organization's mission are supporting activities (e.g., engineering design, human resources). They help ensure that the EFs can be accomplished. Functions that are not EFs or supporting activities are nonessential in the context of post-earthquake operational need. However, that does not mean that these functions are not important to the organization before an earthquake. Many of these functions may be important pre-earthquake activities necessary for functional recovery, especially for pre-earthquake mitigation activities, asset management, and the activities necessary for the assets framework.

Using Step O1, the BPA is first undertaken at a broad level organizationally to identify how all groups and their functions interact with each other internally and externally with other key organizations. Once this is accomplished, then the BIA is performed to separate the essential from nonessential functions.

After defining all the EFs and supporting activities, a more detailed BPA needs to be performed for each EF and supporting activity. It is through this detailed BPA that the necessary equipment, space, supplies, dependencies, services, staffing levels, work shifts, training, expertise, communications, information technologies, supporting activities, and other specifics are identified to accomplish each EF. The details for each EF are linked with the essential group performing the EFs and supporting activities.

The BPA and BIA methods expose the essential and supporting groups and essential and supporting resources. The essential groups are those undertaking the activities required to accomplish the EFs. The supporting groups are those undertaking the activities required to support the essential groups. The essential and supporting resources are those needed for the essential and supporting groups to perform their activities. The BPA and BIA methods identify how the essential and supporting groups interact across the organization to provide basic services to customers. These methods also help to ensure that the essential and supporting groups, equipment, capabilities, records, and supplies are identified and available during a post-earthquake or other emergency response.

The above descriptions are intended to show how EFs relate to the functional recovery of lifeline infrastructure assets and organizations. Essential groups are determined based on how the responsibilities of a group aligns within the organization and its ICS or other crisis management structure, and how they help the mission of the organization to deliver basic lifeline infrastructure system services.

5.5. Step O3: Assess Internal and External Coordination

Step O3 recognizes the intra-agency, interagency, and customer coordination needs related to organizational actions. An assessment of internal and external dependencies and interdependencies should be performed to ensure that the identification of essential and supporting functions, resources, and groups in Step O2 is complete. Essential groups within the organization need to be well coordinated before, during, and after a disaster and this creates internal dependencies and interdependencies. Further, there needs to be good coordination with other agencies and an understanding of the external dependencies and interdependencies. This includes the coordination of target service recovery times as explained in Sec. 3.4 and Critical Customer/User categories as explained in Sec. 4.4. Lastly, there needs to be good coordination with the customers and users of the lifeline infrastructure system services.

A high level of intra- and inter-organizational integration and coordination in planning for and responding to a disaster can help promote a collective vision of recovery and strengthen connections between groups within an organization, across organizations and organizational networks that provide external assistance, and with customers and users of the lifeline infrastructure system services, all of which can lead to better response and recovery outcomes [Berke et al.,1993; May and Williams, 1986; Smith and Birkland, 2012]. This includes education on the earthquake hazards and transparency about the expected ability to provide services for different earthquake levels and the coordination between different subsystem owners and operators described in Sec. 2.3.6.

5.6. Step O4: Establish Group Responsibilities, Resources, Capabilities, and Recovery Time Objectives for Functional Recovery

Step O4 establishes the responsibilities, resources, and capabilities of each essential and supporting group to perform their functions as defined in the BPA. This step provides for the prioritization of EFs that may be necessary because of resource and also defines the recovery time objectives for essential and supporting groups. It is in the lower portion of Fig. 5-1a, which provides more detail for the group-level activity process presented in Fig. 3-2.

Due to interaction between group capabilities and their recovery times and asset performance, it may be more desirable to assign a range of group resources, capabilities, and their associated recovery times. In doing so, system owners can examine a range of component performance levels in Step A4 to achieve system-level service recovery goals as part of Step O8.

5.6.1. Group Responsibilities, Resources, and Capabilities Objectives

The essential group functions are defined from the processes described in Step O2. The existing conditions under which the group performs are compared to the post-earthquake performance requirements to identify any needed modifications, such as staffing levels, communications capabilities, materials, or equipment.

Similarly, all groups that undertake pre-earthquake activities needed for functional recovery must identify their responsibilities, resources, and capabilities. However, groups undertaking pre-earthquake activities may or may not be defined as essential groups for post-earthquake activities.

The group capacities need sufficiently trained personnel. The essential and supporting groups are prioritized for post-earthquake staffing levels and response/recovery training. Backup personnel positions should be identified. The backup personnel can fill the essential and supporting group positions in the absence of a normally assigned personnel member, or add to the group size, after an earthquake. Personnel should be pre-identified to work during a post-earthquake disaster.

The financing and funding levels needed to fulfill the necessary responsibilities, provide resources, and support capabilities before the earthquake (pre-earthquake planning and preparedness) and during the post-earthquake disaster should be identified and budgeted.

The responsibilities, resources, and capabilities should be reviewed for the range of potential earthquake event sizes which may plausibly impact the lifeline infrastructure assets and organization. The size and extent of impact from an earthquake can change how the EFs can be achieved. For example, more materials may be needed for a larger earthquake affecting a broader area. Work shifts may need to be modified if longer recovery times are expected. The range of earthquake sizes should be the same as those used as part of the assets framework evaluations.

5.6.2. Group Recovery Time Objectives

To achieve functional recovery, target timetables for essential and supporting groups and resources to initiate their activities are as follows.

- Essential groups and resources: Immediately after the earthquake, or as soon as possible, if mobilization is required (e.g., during a time when personnel is off duty)
- Supporting groups and resources: Immediately, if possible, but can be delayed for a short duration of up to one or two days, depending on the responsibilities. Support group personnel may be used to supplement essential groups if there is inadequate staffing.

- Nonessential groups and resources: Not required immediately after an earthquake, but personnel filling nonessential positions can be used to supplement the essential and supporting groups.

Each EF needs to be assigned target recovery time objectives using the above outlined guidance for different earthquake sizes. The target recovery time objectives need to be consistent with the component return to operation time increments in Table 4-6 and the earthquake events evaluated for the assets framework as described in Sec. 2.5. These EF objectives are also based on the combination of what the group expects it can accomplish, and the service recovery times it believes can be achieved to meet the target system-level objectives.

Table 5-1 provides a template for identifying the target recovery time objectives for a group using three earthquake levels from Table 2-3. Earthquake event Level I in Table 2-3 is not shown in Table 5-1 because it represents a lower bound event for which limited to no response is necessary. The Level I event is more applicable to the assets framework. Specific target recovery times should be inserted for each group and for each event based on when the group is needed to perform its duties. The suggested target is the time when all groups are recommended to be recovered, assuming some groups will completely recover starting immediately after an earthquake and others up to the suggested target end recovery time.

Table 5-1. Target Group Recovery Times

Group Name:	**[**to be filled**]**	
Group Type (essential or support):	[to be filled]	
Earthquake Event	**Group Recovery Time**	**Suggested target**
Level II	[to be filled]	Immediately to a few hours
Level III	[to be filled]	A few hours to a day
Level IV	[to be filled]	A few days

A description of the post-earthquake conditions should accompany each earthquake event level identified in Table 5-1. Descriptions are provided below for earthquake event Levels II, III, and IV with the suggested target recovery times ranging from immediately post-earthquake to a few days following an earthquake. More or fewer earthquake levels can be used in the process in order to allow flexibility to accommodate local conditions, but they should attempt to cover the range of conditions expressed in the example descriptions for earthquake event Levels II to IV. The conditions should be consistent with the events used for the assets framework. For application in the framework, an assessment using all three earthquake event levels in Table 5-1 are recommended. However, if there are practical limitations to the number of assessments that can be made, then the framework is recommended to be applied using at least earthquake event Levels II and/or III. In the absence of specific detailed descriptions, the following are suggested for use.

- **Earthquake Event Level II:** Earthquake hazard intensities are sufficiently large and widespread enough to cause significant lifeline infrastructure system damage resulting in service disruptions. ICS, or other crisis management structure, is enacted. Communications and transportation are somewhat inhibited, but not completely disrupted. There is cosmetic damage and broken windows in buildings in the community, but no building collapses. There are a few fire ignitions that are easily extinguished and no dangerous chemical releases. Employees may have concerns because of damage in residential neighborhoods, but this does not prevent them from performing their duties.

- **Earthquake Event Level III:** Earthquake hazard intensities are sufficiently large and widespread enough to cause serious lifeline infrastructure component damage resulting in prevalent service disruptions. The ICS, or other crisis management structure, is enacted. Communications and transportation are seriously disrupted. There are some heavily damaged buildings, and a few collapsed buildings. Many buildings are not safe to enter. There are numerous fire ignitions, some of which take hours to extinguish. There are a few dangerous chemical releases. Fire, police, and public health agencies are overwhelmed but the event does not exceed their capacity. Some neighborhoods require temporary evacuation for safety precautions. Damage in residential neighborhoods prevent some employees from reporting to work.
- **Earthquake Event Level IV:** This is one of the largest expected earthquakes to occur in the service area. Earthquake hazard intensities are sufficiently large and widespread enough to significantly damage lifeline infrastructure resulting in extensive service disruptions. The ICS or other crisis management structure is enacted. Communications and transportation are completely disrupted, and such networks cannot be restored for many days. There are numerous seriously damaged buildings throughout the community, many of them have collapsed. Hundreds of buildings are not safe to enter, including several used by the lifeline infrastructure system. There are numerous fire ignitions and some grow into conflagrations that take days to extinguish. There are several dangerous chemical releases. The conditions exceed the capacities of fire, police, and public health agencies. Several neighborhoods require temporary evacuation for safety precautions. Damage in residential neighborhoods prevent many employees from reporting to work.

As identified in Table 5-1 and supported by the earthquake event level descriptions, when identifying the EF target recovery times, the analysis needs to recognize that the ability for personnel to report to duty and take on essential or supporting functions in any group, on average, will be longer for increasing earthquake sizes. There are many reasons for this as described by organizational impairments in Sec. 5.2. Personnel rely on the infrastructure dependencies like communications, transportation, and electric power to aid their ability to have situational awareness, to get to work locations, and perform their duties. Impacts to the dependent services generally are greater and extend longer with increasing earthquake size. As a result, not all the tasks and activities identified in Step O1 may be accomplishable in a resource-scarce environment. During an emergency, staffing and resources may be scarce and therefore prioritizing the EFs is important. Situations may arise that limit which EFs can be performed. Prioritization of those EFs that cannot be deferred will help the lifeline organization to meet its mission objectives in the shortest time possible.

Lifeline infrastructure includes many buildings and operating yards. Some facilities are nodes within the network, such as generating plants and pumping stations. Other structures are dispersed and are not interlinked within the network like office buildings, customer service buildings, and district/maintenance/construction yards. These facilities are needed for the groups to provide their essential or supporting functions. The organizational actions framework assumes the buildings and facilities (including back-ups to the main ones) are able to functionally recover in the timeframe that allows the groups to use them to meet their restoration time objectives. As a result, this process also defines the time for buildings and facilities to functionally recover.

This part of the framework extends continuity planning [FEMA, 2018] by including EF recovery time objectives to meet a system-level objective. This extension is necessary for functional recovery of lifeline infrastructure systems but may not in general apply to all the types of institutions in a community. Continuity planning establishes EF recovery time objectives but stops short of linking them to a system-level recovery time objective, similar to what is done in this step.

5.7. Step O5: Develop Group-Level Policies and Strategies

Based on the information from Steps O1 to O4, Step O5 develops preliminary policies and strategies for each group. These policies and strategies are analogous to the preliminary component designs prepared in the assets framework. The policies and strategies draw from the assessment of responsibilities, resources, and capabilities described in Step O4. Policies establish and define the roles and responsibilities for each group to meet their pre- and post-earthquake performance levels and their post-earthquake target recovery time. The group post-earthquake recovery time is targeted to allow restoration of basic services within the times established in Fig. 3-2. The strategies identify different schemes and procedures which may be used to achieve the group objectives. The policies and strategies should establish the roles, responsibilities, resources, and estimated funding for each group consistent with the assets framework, emergency response and assets management plans, and other key organizational policy and strategy documents. The group policies and strategies needed to support functional recovery, thereby ensuring service recovery times can be met for the range of plausible earthquakes the lifeline infrastructure system may experience.

The strategies for certain groups associated with making asset repairs and post-earthquake system adaptations must be coordinated with the component designs undertaken as part of Step A6. The designs are associated with the potential damage and post-earthquake level of effort required to return components to operation. It therefore influences strategies as well as the required group resources and capabilities described in Step O4. Strategies should also include knowledge about the criticality of different components and the services provided to different customers. The Criticality Category IV components serving Critical A Customers, defined in Step A2, should be given high priority in repair strategies.

5.8. Step O6: Assess Group Performance and Recovery Capability and Compare with Group's Target Objectives

In Step O6, the essential and supporting group performance and recovery times are assessed by performing a series of simulations to assess the group responses to potential earthquakes. The simulations may involve one or a combination of the following: comparative analysis, calculations on resources and scheduling, computer simulations, tabletop and field exercises, external expert review, and/or assessments to determine if the groups are sufficiently prepared to meet their objectives. The range of potential earthquakes should be informed by the evaluations performed in Step A9 of the assets framework. For example, post-earthquake conditions should be a descriptive part of the exercises. Example descriptions may draw from those provided for earthquake levels II to IV in Step O4.

Since organizations are dynamic and can change over short periods of time, these simulations are recommended to be repeated at least annually. A series of smaller simulations may be applied more often. Multiple assessments may be made over time. The assessments should be designed to probe for potential weaknesses so that group needs can be identified and improved.

The results of the assessments are compared to the responsibilities, resources, and capabilities and the group response times defined in Step O4 to confirm if these objectives for each essential and supporting group can be met at each earthquake event level. In the analyses for this step, some reasonable value judgements may need to be made when determining if the target objectives can be met or not. If the objectives cannot be met, then path 'No' is followed in Fig. 5-1a and either the group responsibilities, resources, and capabilities and/or response time need to be modified or the original objectives need to be modified, then another assessment performed. If the objectives are met, then path 'Yes' is followed in Fig. 5-1a, the policies and strategies are finalized, and the system-level validation is undertaken using Fig. 5-1b.

5.9. Step O7: Identify Recovery Time Factors

The process shown in Fig. 5-1b is for a system-level organizational assessment to confirm or validate the group-level policies by checking to ensure the system-level service recovery time objectives are met in relation to the following recovery time factors identified in Step A8 of the assets framework, and include:

- Potential component-level damage
- System-level redundancy and isolation capabilities, which are system-level design features
- Dependent service losses
- Resources available
- Ability to adapt the system temporarily
- Extent of earthquake impact at the community-level

In Step A8, each of the recovery time factors is described relative to assets. How these factors influence system-level performance, the total amount of service disruptions, and the time to restore services needs to be identified so they can be included in the Step O8 system-level assessment. For example, Sec. 4.10.2 describes system-level redundancy and isolation capabilities for infrastructure. Isolating portions of the infrastructure network requires effort from operating crews. This effort needs to be accounted for in the organizational actions framework. In addition to infrastructure redundancy, there is also redundancy of the groups and the efforts required of them. Non-essential groups can be used to back up the EFs. In addition, mutual aid and mutual assistance, normally addressed in emergency management, can also serve to provide redundant or back up personnel during an emergency.

Dependencies include all those identified for each group assessed using Fig. 5-1a and possibly additional dependencies affecting the system. The interdependencies should already be included in the assets and organizational actions frameworks, in Figures 4-1a and 5-1a respectively. However, if not all groups in the organization were evaluated, then the remaining dependencies need to be identified. It is important to recognize the dependencies and interdependencies so they can be associated with impacts to the group, organizational, and service recovery times.

Intra-dependencies are described in Sec. 2.3.2. Groups have many intra-dependencies because of their mutual reliance on services provided from within the system. These include building space, information collection along with processing and transfer, provision of materials and equipment by one group to transfer to another, provision of their own lifeline infrastructure system services within the organization (e.g., a water system providing potable water to their own staff), etc.

As described in Sections 4.10.6 and 5.6.2, the greater the impact of an earthquake to a community, the greater the impact to lifeline infrastructure organization personnel making up the groups performing the organizational actions and who also are likely to reside in communities impacted by the earthquake. As a result, it can take longer time to assemble the needed resources for EFs as earthquake magnitudes, shaking intensities, and corresponding impacts increase at the community level.

Earthquake events must also be defined and used as input into the assessment as shown in the yellow box to the right in Fig. 5-1b. Section 2.5 describes earthquake events. The same earthquake events used for the assets framework should be used for this organizational actions framework.

The recovery time factors are also interrelated in that the improvement of one factor can reduce the need for or importance of other factors. This interaction is important to understand when optimizing the performance and recovery time objectives in Step O9.

Table 4-7 identifies the tasks to be taken for completing the repair and restoration throughout the system. Incorporating results of the assets framework will aid the assessment in Step O8.

5.10. Step O8: Assess System Performance and Recovery Time

In Steps O1 and O2, using the system organizational structure with all its groups, in combination with the earthquake event scenarios (see descriptions in Sections 2.5, 4.11.1 and 5.6.2), BPA and BIA are performed at the organizational-level including how all the group-level impacts affect the ability of the whole organization to respond and recover. The organizational performance should be simulated for the range of earthquake events that may plausibly impact the system, including large, rare earthquakes, like those described in Table 2-5. Incorporate all the potential earthquake and cascading hazards, recovery time factors, and how they may impact the organizational response. Evaluations from the assets framework can be used as inputs to the systems organizational assessments. The assets evaluation provides the expected network damage and service disruptions to customers, with an analytical assessment of how long it will take to recover the services. The analytical modeling on expected recovery time, which makes gross assumptions on organizational actions, should be informative without superseding the independent assessment of the organization's capability to recover the essential and support groups.

The EF target recovery time objectives need to be aligned with other follow-on tasks necessary to restore basic services to customers. All activities to restore basic services should be scheduled to give a timeline for EF recovery consistent with the target service recovery time objective. The system-level analyses performed for the assets framework will give insight into the extent of damage and service disruptions that require recovery using repairs or component adaptations. The number of resources and activities required for making repairs and implementing the system adaptations can then be used to develop a work-flow process. The work-flow process can be scheduled to identify if the EF and supporting group recovery time objectives for the entire organization will achieve the target service recovery time objective.

The ability to recover the essential and supporting groups and the entire organization to accomplish EFs is critical to meet the target performance objectives. However, these recoveries unto themselves are insufficient to ensure the target service recovery times can be met because service recoveries are also a function of (1) the extent of required repairs and system adaptations, (2) available equipment, materials, and supplies, (3) logistical processes, (4) dependencies, (5) funding, and (6) organizational management. Logistical processes include the efficiency in moving goods and materials for groups to use. Organizational management includes the effectiveness in implementing the relevant organizational processes. In this analysis, reasonable value judgements of the assessment results may be needed to determine if the organizational actions are able to meet the target performance objectives or not, including self-assessment of the organizational structure and group capabilities.

This assessment will help to determine the amount of expected service disruptions to customers and users and how long it will take to recover the services so that the recovery times can be compared with the objectives. Therefore, the assessment must analyze the same parameters and metrics as those used for defining the objectives. For example, if the recovery time objectives are defined in terms of basic service categories (e.g., FEMA P-2234, 2024), then the assessment should be able to estimate when the basic service categories may be restored.

5.11. Step O9: Compare System Assessment Results with Target Objectives

In this step, the results of the assessment in Step O8 are compared to the lifeline infrastructure system objectives selected in Ch. 3 to determine if the anticipated performance and service recovery time meet or exceed the target criteria. If the assessment does not meet the target objectives, then path 'No' is followed in Fig. 5-1b and either the group-level policies and strategies must be modified in coordination with any organizational-level changes, or the system-level performance and service recovery time objectives must be changed.

The process is iterative and interactive with the assets framework and other lifeline infrastructure systems. For example, if the assessment results do not meet the objectives, then an organization may choose to modify infrastructure designs to prevent damage as described in Step A7 of the assets framework. Modifying the design to better accommodate earthquake-induced forces and displacements can reduce the personnel demand for undertaking post-earthquake response and making repairs.

It is beyond the scope of this work to provide detailed guidance on how to modify the initial group policies and strategies to meet the performance objectives. A good place to obtain ideas for modifications is by reviewing the recovery time factors in Steps O7 and A8 to determine which may be changed to help achieve the objectives. Sec. 3.6.2.2 provides more information and direction on methods and how to manage situations when the assessment results do not meet or exceed the system-level performance and recovery time objectives. The iteration may utilize multiple options to enhance ability to functionally recover. If the system organizational structure is modified through the exploration of recovery time factors, then organizational processes, policies, and strategies may be modified, and the entire process reiterated back to Step O1 in Fig. 5-1a.

The system performance and service recovery objectives may not be met in Step O9 even though the EFs and support groups may meet their individual targets in Step O6. If this situation arises, all attempts should be made to improve the system to meet or exceed the service recovery time objectives as described in Sec. 3.6.2.2.

If the assessment does meet the target objectives, then path 'Yes' is followed in Fig. 5-1b and the system seismic organizational processes, policies, and strategies may be finalized or other earthquake event scenarios evaluated.

5.12. Step O10: Report System Assessment Results

In this step, results from Step O9 combined with all the findings identified through work on the organizational actions framework are documented and reported. An important aspect of reporting is to ensure all the appropriate findings can be put into practice. It is important to establish clear documentation. The framework involves procedures for multifaceted organizations that deal with both specialized groups and complex infrastructure. It includes component, subsystem, and full network functional recovery related to the assets as well as group and organizational functional recovery. It involves the BPA and BIA and time to recover essential functions and their support services at all levels of the lifeline infrastructure organization.

Results of Steps O8 and O9, along with Steps A9 and A10 in the assets framework (Sections 4.11 and 4.12) will inherently identify areas where improvements to the infrastructure organization and system assets can be made.

These improvements need to be documented and implemented into the asset management, capital improvement, budget and program, and other key organizational activities described in Step O1, Sec. 5.3. Updates to the plans listed in Sec. 3.3.2 should also be made. An important part of documentation and reporting is to update the seismic mitigation plan to include seismic improvements to the infrastructure identified when implementing the assets and organizational actions frameworks. The defined criticality level, redundancies, and isolation capabilities from the assets framework as well as the exposures of components throughout the system to earthquake hazards also need to be integrated into the asset management program and plans when identifying the need and priorities for improvements and replacements. Any modifications to the service recovery times need to be transparent and reported to customers, users, and third-party organizations as described for Fig. 3-2.

6. APPLICATION OF THE FRAMEWORK AND NECESSARY FUTURE WORK

6.1. Application of the Framework

Volume 2, published as NIST SP 1311 [NIST, 2024], applies the framework to water, wastewater, and electric power infrastructure systems providing services to a fictitious city named Centerville.

6.1.1. Relevance to Other Lifeline Infrastructure Systems

The development of this framework was primarily based on water, wastewater, and electric power systems. However, the general framework presented in Chapters 3 to 5 is intended to apply to all lifeline infrastructure systems. It is important to pursue the development of this framework for communications, solid waste, gas and liquid fuels, and multimodal transportation systems.

6.1.2. Suitability for Other Hazards

Many aspects of this framework are applicable to other hazards. Additional efforts are recommended to develop similar frameworks for other hazards, such as hurricanes, flood, and severe storms. A multihazard framework covering many different hazards, or possibly goals for performance that can be hazard independent, is likely to be most helpful for lifeline infrastructure systems owners and operators and should be developed through future work.

6.1.3. Simplifying the Framework

The framework provides a comprehensive methodology and detailed process drawing upon a significant volume of work. It attempts to include all the items necessary to complete a comprehensive assessment for functional recovery to show what items are needed and where they fit within the process. As a result, this framework establishes a high bar to achieve and those organizations who reach this should be very prepared to support their communities when earthquakes strike. However, the all-inclusiveness has resulted in a very complicated process which is difficult for most lifeline infrastructure system organizations to implement. This level of complication may result in producing the opposite effect than what is intended, by turning lifeline infrastructure systems away from attempting to utilize this framework because it may be too difficult to implement in the whole for most organizations, especially the numerous smaller agencies that have limited resources and funding. To make this framework more practical to implement for any organization, regardless of their size, it is important to develop some simplifications to the frameworks that can be adopted by owners and operators that do not have the resources to develop a comprehensive framework. The simplifications should focus on the minimum things that need to be done in priority order over time for lifeline infrastructure systems to functionally recover and meet the objectives needed by their customers and users. The simplification process should encourage and show how the framework can be implemented over time through incremental stages until functional recovery goals to meet user and community needs can be met. The framework in this report provides the direction needed for functional recovery, but more work is needed to ensure modifications that meet user needs can be implemented at the capacity levels of each lifeline infrastructure system.

6.1.4. Costs and Savings Associated with Implementing the Framework

Implementing this framework results in some level of costs to the lifeline infrastructure systems due to investment of time and resources to implement the process, long-term overhead expenses for maintaining an organization at an improved performance level, and investments towards asset improvement. There are also savings associated with its implementation through improved assets and organizational groups which make the system more efficient for daily operations, increasing the lifecycle of assets, reduced damages after an earthquake strikes, reduce service outage times, and improved community recovery. These costs and savings should be investigated and documented to improve the interest in lifeline infrastructure systems to implement the framework.

6.1.5. Estimating Service Recovery Time Using the Recovery Time Factors

There is a tendency to believe the service recovery time may be estimated based on the summation of repair times for all assets. Unfortunately, for lifeline infrastructure systems this is not commonly the case. There are several recovery time factors described in Steps A8 and O7 which influence the time to make repairs and resulting service restoration times. Damage repair is only one of the many factors. Section 4.10 describes the nonlinear process. Nonetheless, there are great advantages for enhancing the framework by identifying processes that can use the recovery time factors for estimating the overall system service recovery times. The processes will be most helpful by:

- distinguishing between factors needed for recovering complete operability and full functionality, and
- Including impacts of potential loss-dependent services from other lifeline infrastructure systems and restoration time needed for the dependent systems.

6.1.6. Further Addressing of Lifeline Infrastructure Interdependencies

The framework includes the interdependent nature of lifeline infrastructure Systems. FEMA-NIST [2021] identifies the need to develop recovery-based objectives incorporating the dependence of each lifeline infrastructure upon the other systems. However, the development of the system-level recovery-based objectives is beyond the scope of this project; this framework uses these as input. FEMA P-2234 [2024] developed a framework for establishing service recovery time objectives and identifies lifeline infrastructure as customers and users of other system services. However, there remains a need to further address how to integrate the development of recovery-based objectives like that in FEMA P-2234 and the application in this framework using a multi-sector approach. Volume 2 of this report provides examples of how the framework is applied to water, wastewater, and electric power systems and identifies how dependencies and interdependencies play a role. However, the examples are applied one sector at a time and stop short of iterating the results to identify how to improve each system based on the interdependencies with all the other systems. Further, all the example system applications identify their strong dependencies on the transportation system which is not assessed. An interdependent iteration is a more complex process, and requires further research and development, and would enhance the use of this framework.

6.1.7. Additional Guidance Needed

The framework described is complex and the subject lifeline infrastructure systems also add more layers of complexity. Development of additional guidance and tools respectively, will be beneficial. In addition to the topics in the following subsections, the development of reporting templates for use in Steps A11 and O10 are recommended.

6.1.7.1. Guidance on Types of Assessments

Steps A9 and O8, respectively from the assets and organizational actions frameworks, recommend performing system-level assessments. Steps A7 and O6, respectively from the assets and organizational actions frameworks, recommend performing assessments of the constituent parts of the system. There are many different types and complexity of assessments that can be made from comparative analysis to field experience in past earthquakes or laboratory experiments, simple calculations, mental assessments to think through the problem to determine expected outcomes, intermediate level computer simulations which account for portions of the networks and/or organizations, to very complex computer simulations accounting for all assets and earthquake hazards and interdependencies with other lifeline infrastructure systems. Different lifeline infrastructure systems will have different needs for and capability of performing the possible range of assessments. It is therefore important to outline the different assessment options and how to perform the different assessments. Expanded guidance is necessary to allow for different levels of analysis, the levels of uncertainty associated with each, how to apply the results, and ensure consistency across lifeline infrastructure systems.

6.1.7.2. Guidance on System-Level Performance Objectives for Assets

This framework uses performance and recovery objectives at the component and system levels. There are many component-level performance objectives found in existing guidelines, codes, and standards for all the lifeline infrastructure system sectors. However, there are few, if any, system-level performance objectives for assets that can be used to aid the application of this framework. This is identified in Sec. 2.3.1 and in the water, wastewater, and electric power system examples presented in Volume 2 of this report. The framework can be enhanced with guidance on system-level performance objectives that owners, operators, and analysts can use to improve lifeline infrastructure systems for functional recovery.

6.1.7.3. Guidance for Service Recovery Time Objectives for Subsystem Owners and Operators

Sections 2.2.4 and 2.3.6 describe how the primary subsystems and assets making up the whole of any lifeline infrastructure system may be made up of multiple owners and operators. Each owner and operator must be able to evaluate the performance and service recovery times of their respective primary subsystem or asset which they own or operate. Lifeline infrastructure system service recovery time is commonly identified for the end user (e.g., FEMA P-2234) considering the system as a whole, but not each subsystem. As a result, each primary subsystem owner and operator must be able to figure out their individual target service recovery times by working together with all other owners and operators making up the entire lifeline infrastructure system. Methods to identify how the individual subsystem target service recovery times differ from the whole do not exist. Additional work is needed to provide guidance on how each subsystem owner and operator may be able to identify their respective target service recovery times so that the system as a whole can meet the target service recovery time to end users.

6.1.7.4. Guidance for Decisionmakers and Stakeholders

The framework described is to be implemented by a technical and administrative team, and resulting actions (e.g., seismic retrofit of components) are also to be undertaken by a design team. However, the decision to make the required investments or decide to revise target recovery objectives lies with decisionmakers and stakeholders who may lack the technical understanding of the complexity of lifeline infrastructure systems and their earthquake risk. Accordingly, development of guidance for translating the necessity for undertaking the framework application and vetting the recommendations to simpler terms, would benefit acceptance of such programs.

6.1.8. Combinations of Recovery Time Factors

The framework is an iterative process. If the system assessment results in Steps A9 and/or O8 do not meet or exceed the target performance and recovery objectives, then changes to the recovery time factors described in Steps A8 and O7 are needed. This can result in complicated sets of conditions for which an organization may need to iterate. There are numerous potential combinations of recovery time factors from which to select to optimize in the iteration process. The methodology may be simplified if the combinations were reviewed in detail and tabulated for lifeline infrastructure system organizations to select from. The tables can aid in determining the combination of recovery factors to use. This is accomplished by recognizing how the design assumptions are integrated with assumptions on organizational actions like stockpiled materials for repair, equipment and labor available for making repairs, finances available for covering costs to repair, etc. Tabulated sets of recovery time factors will allow for improved optimization of lifeline infrastructure systems for functional recovery.

Related to this topic is the need for guidance on how to make functional recovery design decisions which are influenced by organizational actions. A key decision is determining if it is better to make repairs after an event or improve the design to reduce the need for repairs in advance of an event. An associated decision is the level of design to prevent the possibility of repairs; a designer may attempt to allow for limited damage to reduce design and construction costs and require some post-earthquake response to make repairs. From some perspectives this approach allows for funding to be spent in advance of an event to make improvements to more assets as opposed to spending more money for creating greater robustness on fewer assets. Guidance is needed on this topic.

6.1.9. The Cost and Time of Asset Damage Repairs

The framework application can be improved if there are processes that can identify estimated costs associated with different lifeline infrastructure system asset repairs and the time associated with returning the assets to operation. This requires an understanding of the level of damage and is dependent on the local conditions. Guidance on how to rapidly estimate the cost and repair time for given assumptions will be of great importance for improving the framework.

6.1.10. Guidance for Modifying Component Design and Group Policy

The assets and organizational actions frameworks Figures 4-1b and 5-1b, respectively, include an iterative process. If the initial design and/or group policies and strategies do not meet the system-level recovery objective, then they need to be modified. There is little guidance on how the initial component design or group policies and strategies should be modified to meet the recovery objectives. Further work to provide guidance will help lifeline infrastructure system organizations implement the framework to its fullest extent.

6.2. Recommended Research

6.2.1. Translating Asset-Level Designs and Objectives to System-Level Performance

A basic concept behind this framework is that designing assets to defined performance levels is expected to result in the system meeting the performance and recovery objectives. The question remains as to how to associate the asset design levels to meet selected system-level performance and recovery-based criteria. The values in Table 4-2 are draft criteria commonly used in industry practice. However, this criterion needs further research to confirm if they will meet or exceed defined system-level objectives. This may be investigated with system flow modeling for earthquake event scenarios using fragilities defined for each component. Future research may be able to identify common correlations between asset design levels and system performance to meet specific service recovery times. Results of this research can be used to confirm the values used in Table 4-2, or modify those values. The return periods in Table 4-2 may also be refined in the framework flow process presented in Figures 4-1a and 4-1b, for example using some system configurations a shorter return period may be found as an efficient design basis that can meet the system-level service recovery objective validation process in Fig. 4-1b. Using other configurations and possibly longer return periods may be appropriate.

This is an extremely challenging issue for which there is an entire field of study using reliability/availability theory [Villemeur, 1992; Kwasinski and Krishnamurthy, 2024] with very specialized software and, thus, providing an answer to this challenge requires more significant research.

6.2.2. Lifeline Infrastructure System Fragilities

Lifeline infrastructure systems are made up of numerous interlinked specialized components and subsystems. The assessments in Steps A7 and A9 require simulations to estimate the probable performance and restoration of the asset(s) under various design scenario conditions using fragility relationships. The fragility relationships are to equate the earthquake loading levels (in terms of intensity measures) to the probability of component damage states. There are some shortcomings of this framework in that the fragilities as recommended to be used do not always exist for all the specialized components making up the lifeline infrastructure systems. Fragility functions also do not exist for all the types of seismic hazards to which the components may be exposed. For example, functions for ground shaking hazards may exist for some components, but functions for permanent ground deformations may not exist for the same components. If fragility functions do exist, some are not expressed in terms that allow engineers to estimate the probable performance of the asset under various design scenario conditions to identify a damage level. Therefore, there is a strong need for a significant amount of research to improve the development of lifeline infrastructure system fragility relationships for earthquake intensity measures.

It is important to understand how the state of practice for lifeline infrastructure systems differs significantly from buildings. The processes recommended for use in Steps A7 and A9 are similar to those used for building structures [ASCE 41, 2017; FEMA, 2010]. So the concepts are common for engineering practice, yet the functions needed for lifeline earthquake engineering are lacking, which ensures the practice for functional recovery of lifeline infrastructure systems will remain insufficient to meet societal needs until the appropriate and necessary fragility functions are developed.

Damage levels such as those described in Table 4-5 for new and existing components should form the basis for creating component fragilities and associated expected performance for different magnitudes of hazard intensities (e.g., increasing levels of peak ground acceleration, peak ground velocity, or permanent ground deformations). There is little guidance on how to identify fragilities of existing components currently in service. For new components, methods for developing fragility functions are widely available. For existing components, baseline fragility functions can potentially be developed if their age, design criteria, installation method, and environmental exposure are known. These baseline fragility functions can then be modified for aging, corrosion, and other deterioration factors. Additional research is needed first to develop a unified methodology for developing fragility functions for existing components using baseline conditions. Then guidelines for modifying baseline fragilities for aged components need to be formulated to account for deterioration and other time-related factors. Ideally, generalized fragility functions for key lifeline components should be developed for ready adoption by analysts.

6.2.3. Improved Computational Flow Models for Assets for Implementing into Practice

This framework encourages evaluation and assessments of the built infrastructure to earthquakes using all the potential hazards to which the assets may be exposed. The purpose for these evaluations is to identify if the service recovery time objectives can be met. The best way to confirm if the objectives can be met is by investigating the system flow. Flow analyses models exist for all lifeline infrastructure systems. However, they are complicated and difficult to use in practice. They require special expertise, take lots of time to use, and cost the organizations large sums of money. As a result, these types of models are mostly utilized in research. Very few organizations providing lifeline infrastructure system services have the capability to utilize advanced flow analysis on damaged systems to understand how the flow changes from the damages and during the repairs. This is a significant drawback to improving the resilience of lifeline infrastructure systems and their ability to functionally recover. Research is needed to develop models which can handle the flow analyses of damaged infrastructure systems and their repairs and be cost and time effectively used in practice.

This research can be enhanced if it also includes multiple systems and their interdependencies.

6.2.4. Social-Organizational Computational Models

This framework encourages evaluation and assessment of the organizational structure and their actions required to operate, repair, and restore services to meet the service recovery time objectives. There are not any existing practical computational models available to perform these tasks. This is a significant hinderance to improving the resilience of lifeline infrastructure systems and their ability to functionally recover. Research is needed to develop social-organizational models which can evaluate the organizational policies, strategies, and implement them into actions needed to prepare for, respond to, and recover from earthquakes.

6.2.5. Multidisciplinary Social-Technical Computational Models

This framework encourages the combined evaluations and assessments of the built infrastructures and interaction of the organizations that operate them. There are no practical computation models which can effectively integrate the built infrastructure and the organizational actions. Research along these topics is necessary and a combined extension of the recommended research for the computational flow models for assets and the social-organizational computational models.

6.2.6. Developing Earthquake Event Scenarios

There is a need to advance the research for developing earthquake event scenarios for use in the framework. Section 2.5 describes earthquake events. An event may be determined like what was done for Uniform California Earthquake Rupture Forecast, version 3, UCERF3 [Field et al., 2013]. However, the Field et. al. [2013] work is limited to portions of California and similar products are not available elsewhere. This requires the geotechnical practice to use various types of judgements to develop the scenarios for use in this framework. Further, all existing procedures are hazard-based, whereas this framework identifies the need for consequence-based methodologies.

There is limited research available on how the acceptance level of lifeline infrastructure system service disruption changes with increasing earthquake event size and associated hazard intensities. FEMA P-2234 [forthcoming] describes the need to perform multidisciplinary research to better identify the linkages between societal impacts from service outage and earthquake event size. This research recommendation differs from that in FEMA P-2234 by emphasizing the basic geohazard science in defining how to determine the most important earthquake event for developing scenarios, establishing a stronger basis for recommended event return periods like that shown in Table 2-3, and how to practically identify the associated seismic hazards in a region based on the event probability.

Guidelines are needed to identify for each event scenario the faults and hypocenter locations, the potential for surface fault rupture, radiation of seismic ground motion intensities, and the potential for landslides, liquefaction triggering, and resulting differential settlement and lateral spreading, along with other seismic hazards. The guidelines need to consider the practical nature of the earthquake event scenarios intended for use in this framework. It is difficult for most lifeline infrastructure organizations to perform assessments for multiple scenarios. This difficulty can be alleviated with improved modeling capabilities described in aforementioned recommended research. The development of guidelines and improved geoscience and geotechnical practice can also alleviate some of the difficulties currently existing within lifeline earthquake engineering practice. The basic research can improve current practice and then proceed with improving methodologies for fully probabilistic analyses using numerous multi-hazard maps across the entire infrastructure system service area. Results of this research can greatly enhance the improvement and application of recovery-based objectives.

6.2.7. Prioritizing Mitigations for Functional Recovery

The systems analysis process in Chapters 4 and 5, respectively, for the assets and organizational actions frameworks helps to identify deficiencies that prevent the system from meeting the target objectives. Volume 2 provides example applications of the framework and shows how the assessments can identify many different needed improvements. Methodologies to prioritize the identified improvements as part of the planning process will be useful for functional recovery. Objective functions for priority mitigations may include the restoration of basic services to the most customers and users over the shortest timeframes, meeting the user needs the quickest, or something else identified during the research.

REFERENCES

[1] ALA (2005) *Design Guidelines for Seismic Resistant Water Pipeline Installations* (American Lifelines Alliance).

[2] ASCE (2022) *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE/SEI 7-22 (American Society of Civil Engineers Structural Engineering Institute, Reston, Virginia).

[3] ASCE (2023) *Seismic Evaluation and Retrofit of Existing Buildings*, ASCE/SEI 41-23 (American Society of Civil Engineers Structural Engineering Institute, Reston, Virginia).

[4] Berke PR, Kartez JD, and Wenger DE (1993) Recovery after disaster: Achieving sustainable development, mitigation and equity. *Disasters*, Vol. 17, No. 2, pp. 93-109.

[5] Britannica (2021) *Public Utility*. Available at https://www.britannica.com/technology/public-utility, accessed October 24, 2021.

[6] Bruneau M, Chang SE, Eguchi RT, Lee GC, O'Rourke TD, Reinhorn AM, Shinozuka M, Tierney K, Wallace WA, and Winterfeldt D (2003) A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, Vol. 19, pp. 733-752.

[7] Cimellaro GP, Reinhorn AM, and Bruneau M (2010) Seismic resilience of a hospital system. *Struct. Infrastruct. Eng.*, Vol. 6 (1–2), 127–144 (Civil Contingencies Secretariat of the Cabinet Office, London).

[8] Collins Dictionary (2021) *Service*. Available at https://www.collinsdictionary.com/us/dictionary/english/service, accessed October 24, 2021.

[9] Davidson R, Kendra J, Starbird, K, Nozick L, Ewing B, and Leon-Corwin M (2023) Typology of household adaptations to infrastructure system service interruptions. *International Journal of Disaster Risk Reduction*.

[10] Davis CA (2005) Uniform confidence hazard approach for the seismic design of pipelines. *4th Japan-US Workshop on Seismic Measures for Water Supply* (JWWA and AWWARF, Kobe, Japan).

[11] Davis CA (2008) Assessing geotechnical earthquake hazards for water lifeline systems with uniform confidence. *ASCE Geotechnical Earthquake Engineering and Soil Dynamics IV* (May 18-22, 2008, Sacramento, CA) paper 4291.

[12] Davis CA (2014) Water service categories, post-earthquake interaction, and restoration strategies. *Earthquake Spectra*, Vol. 30, No.4, pp.1487-1509.

[13] Davis CA (2019a) *Performance Based Seismic Design for LADWP Water System,* (prepared for the Los Angeles Dept. of Water and Power), January 2, 2019, version 1, Report No. AX.747.

[14] Davis CA (2019b) A proposed performance based seismic design process for lifeline systems. *Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions: Proceedings of the 7th International Conference on Earthquake Geotechnical Engineering, (ICEGE 2019)* (CRC Press Balkema), pp 1986-1993.

[15] Davis CA (2021) Understanding functionality and operability for infrastructure system resilience. *Natural Hazards Review*, Vol. 22, No. 1.

[16] Davis CA (2023) *Infrastructure System Resilience An Engineering Framework for Assessment, Management, and Governance*, (Ed., Infrastructure Resilience Division of ASCE and Japan Society of Civil Engineers Infrastructure Resilience Research Group, ASCE Infrastructure Resilience Publication No. 8 (IRP8)).

[17] Davis CA, Kersting R, Nikolaou S, and Yu K (2022a) Recommendations toward functional recovery performance of lifeline infrastructure systems. *ASCE Infrastructure Resilience Publication No. 5* (San Fernando Earthquake Conference – 50-years of Lifeline Engineering, Lifelines 2021-22 Conference, UCLA, Jan 31 to Feb 11, 2022), pp 756-766.

[18] Davis C, Ayyub B, McNeil S, Kobayashi K, Tatano H, Onishi M, Takahashi Y, Honda, R, van de Lindt J, and Koike T (2022b) Overview of a framework to engineer infrastructure resilience through assessment, management and governance. *ASCE Infrastructure Resilience Publication No. 4* (San Fernando Earthquake Conference – 50-years of Lifeline Engineering, Lifelines 2021-22 Conference, UCLA, Jan 31 to Feb 11, 2022), pp 901-913

[19] Duke CM and Moran DF (1975) Guidelines for evolution of lifeline earthquake engineering. *Proceedings* (U.S. National Conf. on Earthquake Engineering, pp. 367–376, Oakland, California).

[20] FEMA (2010) *Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds*, FEMA P-424, Risk Management Series (Federal Emergency Management Agency).

[21] FEMA (1996) *Guide for All-Hazard Emergency Operations Planning*, (Federal Emergency Management Agency).

[22] FEMA (2016) *National Disaster Recovery Framework*, (Federal Emergency Management Agency).

[23] FEMA (2018) *Continuity Guidance Circular*, FEMA National Continuity Programs, (Federal Emergency Management Agency).

[24] FEMA (2021) *Hazard Mitigation Planning for Local Communities, FEMA Fact Sheet*, (Federal Emergency Management Agency).

[25] FEMA (2022) *HAZUS Earthquake Model Technical Manual*, HAZUS 5.1, July, (Federal Emergency Management Agency).

[26] FEMA (2023) *National Incident Management System*, (Federal Emergency Management Agency).

[27] FEMA (2024) *A Framework to Establish Lifeline Infrastructure System Service Recovery Objectives for Seismic Resilience*, FEMA P-2234 (prepared by Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.)

[28] Field EH et al.(2014) Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3) - The Time-independent model. *Bull. of the Seismo. Soc. of Am.*, Vol. 104, No. 3.

[29] IBM (2023) *What is FaaS (Function as a Service)?* Available at https://www.ibm.com/topics/faas, accessed November 29, 2023.

[30] ICC (2022) *2021 ICC Performance Code for Buildings and Facilities (ICC PC)* (International Code Council, Country Club Hills, Illinois).

[31] IPWEA (2015) *International Infrastructure Management Manual* (Institute of Public Works Engineering Australasia).

[32] ISO (2019) *Societal Security — Business Continuity Management Systems — Requirements,* ISO 22301 (International Standards Organization, Switzerland).
[33] Jones LM, Bernknoft R, Fox D, Goltz J, Hudnut K, Mileti D, Perry S, Ponti D, Porter K, Reichle M, Seligson H, Shoaf K, Treiman J, and Wein A (2008) *The ShakeOut Scenario*, USGS Open File Report 2008-1150, CGS Preliminary Report 25 Version 1.0 (US Geological Survey and California Geological Survey).
[34] Kwasinski A, Kwasinski A, and Krishnamurthy V (2024) *Resilience Engineering for Power and Communications Systems: Networked Infrastructure in Extreme Events* (Cambridge University Press).
[35] LGAM (2019) *Level of service* (The Local Government and Municipal Knowledge Base). Available at http://www.lgam.info/level-of-service, accessed December 13, 2019.
[36] Market Business News (2021) *What is a Public Utility? Definition and Meaning*. Available at https://marketbusinessnews.com/financial-glossary/public-utility-definition-meaning/, accessed October 24, 2021.
[37] May PJ and Williams W (1986) *Disaster Policy Implementation: Managing Programs under Shared Governance, Disaster Research in Practice* (New York: Plenum Press).
[38] Merriam-Webster (2021). Available at https://www.merriam-webster.com/ accessed October 24, 2021.
[39] NFPA (2019) *Standard on Continuity, Emergency, and Crisis Management*, NFPA 1600 (National Fire Protection Agency, Quincy, Massachusetts).
[40] NIST (2014) *Earthquake-Resilient Lifelines: NEHRP Research, Development and Implementation Roadmap*, NIST GCR 14-917-33 (prepared by the NEHRP Consultants Joint Venture, a partnership of the Applied Technology Council and Consortium of Universities for Research in Earthquake Engineering, for the National Institute of Standards and Technology, Gaithersburg, Maryland).
[41] NIST (2015a) *Community Resilience Planning Guide for Buildings and Infrastructure Systems*, Volume I, NIST Special Publication 1190 (National Institute of Standards and Technology, Gaithersburg, Maryland).
[42] NIST (2015b) *Community Resilience Planning Guide for Buildings and Infrastructure Systems*, Volume II, NIST Special Publication 1190 (National Institute of Standards and Technology, Gaithersburg, Maryland).
[43] NIST (2016a) *Conceptual Framework for Assessing Resilience at The Community Scale*, NIST GCR-16-001 (prepared by A Kwasinski, J Trainor, B Wolshon, FM Lavelle for National Institute of Standards and Technology, Gaithersburg, Maryland).
[44] NIST (2016b) *Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster Recovery*, NIST GCR 16-917-39 (prepared by Applied Technology Council for the National Institute of Standards and Technology, Gaithersburg, Maryland).
[45] NIST (2017) *Further Development of a Conceptual Framework for Assessing Resilience at the Community Scale*, NIST GCR 1-013 (prepared by A Kwasinski, J Trainor, R Francis, C Chen, FM Lavelle for National Institute of Standards and Technology, Gaithersburg, Maryland).
[46] NIST (2020) *Assessment of Resilience in Codes, Standards, Regulations, and Best Practices for Buildings and Infrastructure Systems*, NIST Technical Note 2209, T.P

McAllister, R. F. Walker, and A. Baker eds. (National Institute of Standards and Technology, Gaithersburg, Maryland).

[47] NIST (2024) *Initial Framework to Design Lifeline Infrastructure for Post-earthquake Functional Recovery*, *Volume 2,* NIST Special Publication 1311 (prepared by Applied Technology Council for the National Institute of Standards and Technology, Gaithersburg, Maryland).

[48] NIST-FEMA (2021) *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time*, FEMA P-2090/NIST SP-1254. Available at https://www.nist.gov/publications/recommended-options-improving-built-environment-post-earthquake-reoccupancy-and, accessed November 17, 2023.

[49] Oxford Languages, 2023, *Infrastructure.* Available at https://languages.oup.com accessed December 5, 2023.

[50] Peterson L, Fallou L, Reilly P, and Serafinelli E (2020) Public expectations of critical infrastructure operators in times of crisis. *Sustainable and Resilient Infrastructure*, Volume 5, No 1-2, pp. 62-77.

[51] Rinaldi SM, Peerenboom J, and Kelly T (2001) Complexities in identifying, understanding, and analyzing critical infrastructure dependencies. *Special issue IEEE Control Systems Magazine on Complex Interactive Networks*.

[52] Rose A, Wei D, and Wein A (2011a) Economic impacts of the ShakeOut scenario. *Earthquake Spectra*, Vol. 27, No. 2, pp. 539-557, May.

[53] Rose A, Liao S, Bonneau A (2011b) Regional economic impacts of Verdugo scenario earthquake disruption of Los Angeles water supplies: A computable general equilibrium analysis. *Earthquake Spectra*, Vol. 27, No. 3, pp. 881-906, August.

[54] Sattar S, Cook D, and Johnson K (2022) Preliminary Recovery Categories and Times for a Functional Recovery Framework. *12th National Conference on Earthquake Engineering* (Earthquake Engineering Research Institute, Salt Lake City, Utah, June 27-July 1, 2022).

[55] Scawthorn C (2011) *Water Supply in Regard to Fire Following Earthquake,* PEER Report 2011/08 (Pacific Earthquake Engineering Research Center, University of California, Berkeley, November).

[56] Scawthorn C, Eidinger JM, and Schiff AJ, Editors (2005) *Fire Following Earthquake* (TCLEE Monograph No. 26, ASCE).

[57] SFPUC (2023) *General Seismic Requirements for Design of New Facilities and Upgrade of Existing Facilities*, WSIP/CSP-001-R4 (San Francisco Public Utilities Commission).

[58] Sinha S, Davis C, Gardoni P, Sebens MB, Stuhr M, Huston D, Cauffman S, Williams W, Alanis LG, Anand H, and Vishwakarma A (2023) Water sector infrastructure systems resilience a social-ecological-technical system-of-systems and whole-life approach. *Cambridge Prisms: Water*.

[59] Smith G and Birkland T (2012) *Building a Theory of Recovery: Institutional Dimensions. International Journal of Mass Emergencies and Disasters,* 30, 147-170.

[60] Soleimani N, Davidson RA, Davis C, O'Rourke TD, Nozick LK (2021) Multihazard scenarios for regional seismic risk assessment of spatially distributed infrastructure. *ASCE Journal of Infrastructure Systems*, Vol. 27, Issue 1.

[61] Tierney K and Bruneau M (2007) Conceptualized and measuring resilience. *TR News* 250, 14-17. Available at http://onlinepubs.trb.org/onlinepubs/trnews/trnews250_p14-17.pdf, accessed November 17, 2023.
[62] USGS (2019) *Earthquake Hazards 101 - the Basics*. Available at https://www.usgs.gov/programs/earthquake-hazards/science/earthquake-hazards-101-basics, accessed November 17, 2023.
[63] USGS (2020) *Earthquake Hazards*. Available at https://www.usgs.gov/glossary /earthquake-hazards-program accessed January 31, 2024
[64] USGS (2022) *National Seismic Hazard Model*. Available at https://www.usgs.gov /programs/earthquake-hazards/science/national-seismic-hazard-maps, accessed November 17, 2023.
[65] Villemeur A (1992) *Reliability, Availability, Maintainability, and Safety Assessment. Volume 1, Methods and Techniques* (West Sussex, Great Britain: John Wiley and Sons).
[66] WRF (2013) *Business Continuity Planning for Water Utilities: Guidance Document*, Web Report #4319 (Water Research Foundation, Denver, Colorado). Available at https://www.waterrf.org/resource/business-continuity-planning-water-utilities-guidance-document-0, accessed January 15, 2023.
[67] Yao B, Xie L, and Huo E (2004) Study effect of lifeline interaction under seismic conditions. *Proceedings of the 13th World Conference on Earthquake Engineering* (Vancouver, B.C., Canada).

APPENDIX A. BASIC INTENDED FUNCTIONS

A.1 Function and Service

Lifeline infrastructure systems provide utility and mobility services [Britannica, 2021] using the physical or virtual infrastructure network [Market Business News, 2021] to fulfill public needs [Collins Dictionary, 2021]. To provide these services, the lifeline infrastructure systems must function. The definition and description of functional recovery in Sections 1.1 and 2.4 uses three forms of the word 'function' which need to be understood clearly for a usable and workable definition of basic intended functions. Section A.2 in this appendix defines basic intended functions based on the definitions from Merriam-Webster [2021] and other dictionaries. The definitions as applied to lifeline infrastructure systems are:

- Function, the action for which a lifeline infrastructure system is specially fitted or used.
- Functional, performing or able to perform a regular action for which a lifeline infrastructure system is specially fitted or used.
- Functionality, the quality or state of being able to perform a regular action for which the lifeline infrastructure system is specially fitted or used.

Merriam-Webster [2021] further identifies 'purpose' as a synonym to 'function'. The above definitions are intended to provide a clear, concise, and unambiguous understanding of what the phrases 'basic intended functions' and 'functional recovery' mean for lifeline infrastructure systems.

An important distinction is made here between functions and services – they are not the same and, in this context, they are not synonymous. The lifeline infrastructure system must be able to function to provide services. A function is what is done or used to provide a service. It involves system or component operation that results in a service. A service is what is provided to fulfill a public need or customer demand. For lifeline infrastructure systems a commodity or product may also accompany a service (e.g., water, gas). Further, services are only provided when the lifeline infrastructure system is functioning at a level sufficient to provide them.

The definition of service used herein is something that the public needs, which is provided in a planned and organized way, for example the supplying of water, electricity, gas, etc. or the collection of wastewaters, debris, solid waste are services.

There is a broader concept of 'function as a service' [IBM, 2023] that has merit when considering a service is what is provided to fulfill a public need, because a functioning lifeline infrastructure system does in fact fulfill a public need. This broad concept was used by Davis [2014] when defining functionality as a service. However, in this report function and functionality are only defined as described above by Merriam-Webster [2021]. It is too confusing to consider that function is both a broad concept of service and on the other hand a narrower concept of what is needed to provide the service; addressing both concepts simultaneously is somewhat of a circular description.

A.2 Basic Intended Functions

Lifeline infrastructure systems are designed to provide regular reliable services. Basic intended functions are the actions through which lifeline infrastructure systems provide basic services.

The definition can be expanded to include the knowledge that a lifeline infrastructure system does not work or operate without the human interaction (i.e., they are social-technical systems). Basic intended functions are the purpose for which the built infrastructure of a lifeline system is used by a social institution (i.e., lifeline system operator) to provide basic services.

The definition for basic intended functions makes a clear distinction between a function and a service. These are not the same. A service and/or commodity is provided is provided by a functioning lifeline infrastructure system.

GLOSSARY

The following definitions are provided to explain the terms used throughout this document.

Adaptations: Modifications implemented by taking action to address a specific set of needs due to a reduction in lifeline infrastructure system services.

Asset: The physical properties making up the lifeline infrastructure system and involves each component or subsystem and how they are interconnected to make up the overall system.

Basic intended functions (BIFs): The actions to provide basic services, or the purpose for which the built infrastructure of a lifeline infrastructure system is used by the lifeline system operators to provide basic services. The actions for which a built infrastructure system is used to provide basic services.

Basic service categories: Descriptive terms or phrases classifying basic services provided by a lifeline infrastructure system.

Basic services: The most fundamental services provided by the lifeline infrastructure systems on which users are dependent and reliant upon for personal or community-wide survival, safety, security, and well-being.

Business Impact Analysis (BIA): A method of identifying and evaluating the effects that an earthquake and associated hazards may have on the ability of an organization to perform any of its functions and the resulting impact of those effects (FEMA, 2018 section 1.3).

Business Process Analysis (BPA): A systematic method of identifying and documenting all the elements necessary to perform all the organizational functions. A method of examining, identifying, and mapping the functional processes, workflows, activities, personnel expertise, systems, data, partnerships, controls, interdependencies, and facilities inherent in the execution of the functions (FEMA, 2018 section 1.2).

Crew: A specialized group of people trained for constructing, repairing, and/or operating lifeline infrastructure system components. A crew may be made up of lifeline infrastructure organization staff, contracted staff, or staff obtained through mutual aid or mutual assistance.

Customer: Customers are those having a virtual or physical connection or access to a collection, distribution, or transport system. It is the customer who receives products and services from the lifeline infrastructure systems. Customers also serve as the point of contact between the lifeline system organization and the users; the customers pay the fees, where/when applicable, for service provision.

Cyber: Data and information, commonly managed through computer systems.

Dependency: The reliance of infrastructure on services or the influence provided by other infrastructure or social systems.

Earthquake event: An earthquake event is characterized by the source of a rupture scenario that is uniquely defined by the rupture's magnitude, a three-dimensional rupture plane in the Earth's crust, and other source parameters that help to define the intensities and spatial extent of earthquake hazards.

Essential functions: The lifeline infrastructure system organizational functions that need to be continued throughout, or resumed rapidly following, a post-earthquake disruption of normal operations.

Framework: A basic structure underlying a system, concept, or text.

Function: The action for which a lifeline infrastructure system is specially fitted or used.

Functional: Performing or able to perform a regular action for which a lifeline infrastructure system is specially fitted or used.

Functionality: The quality or state of being able to perform a regular action for which the lifeline infrastructure system is specially fitted or used.

Group: One or more people who must perform certain tasks necessary for the lifeline infrastructure system to operate.

Infrastructure: The physical and organizational structures and facilities needed for the operation of a society or enterprise [Oxford Languages, 2023].

Interdependency: Mutual dependencies between two systems.

Lifeline infrastructure system adaptations: Actions taken by the lifeline infrastructure system organizations to provide services in a manner other than normally used. This usually entails temporary modification to the infrastructure network and organizational response procedures and may include provision of alternative emergency services for users.

Lifeline infrastructure systems (lifelines): A subset of general infrastructure covering those critical to the functioning of modern society and include water, wastewater, drainage, communication, electric power, gas and liquid fuels, solid waste, and transportation systems [Duke and Moran, 1975].

Operability: The fitness, capacity, or ability to use a potentially impaired lifeline infrastructure system following an event to provide basic services allowing customers/users to receive normal, or near normal, amenities.

Organization: An organized body of people having a purpose and structure to manage and operate a lifeline infrastructure system. The organization includes human activities and their interaction with the built and cyber infrastructure, governing bodies, external agencies and organizations, and service users. The body of people may consist of employees of or consultants to the lifeline infrastructure system.

Organizational actions: The coordinated activities for functional recovery that need to be undertaken by the lifeline infrastructure organization.

Performance objective: The planned damage or impaired state of assets and the organization for a specified hazard level.

Recovery time objective: the time or duration for services to be restored to complete operability at a defined earthquake event level.

Service: Something that the public needs which is provided in a planned and organized way, for example the supplying of water, electricity, gas, etc. or the collection of wastewater, debris, solid waste, etc. What is provided to fulfill a public need or customer demand, and for lifeline systems a commodity or product may also accompany the service (e.g., water, gas).

Societal impacts: The effects on individuals or the whole community from the level of services provided by lifeline infrastructure systems. The levels of services may have positive or negative social impacts.

System adaptations: modifications to the physical system infrastructure and/or system operations because of earthquake damage. Usually, but not always, the adaptations are temporary and implemented to expedite the recovery of services.

Third party adaptations: Actions taken by third-party organizations to provide services to fulfill the needs of others by utilizing methods that are not common during their normal activities.

Third party organizations: An organization not directly a part of the lifeline infrastructure system organization that has a service reduction who provides adaptive services to the lifeline infrastructure system service users. The third part organization may or may not be a local lifeline infrastructure system customer and includes government and non-government organizations (for profit or nonprofit). Example third-party organizations include the Red Cross, FEMA, and large corporations.

User adaptations: Actions taken by the recipient of a lifeline infrastructure system service to fulfill their needs with methods other than those normally used when the service cannot be obtained through the lifeline infrastructure network.

User: The Individuals and institutions utilizing lifeline infrastructure system services provided through, by, or from the network. For some lifeline infrastructure systems users may also be known as consumers.