

FUNCTIONAL RECOVERY OF LIFELINE INFRASTRUCTURE SYSTEM SERVICES

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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. 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) establishing practical objectives to ensure societal needs can be met in a post-earthquake environment, and (2) efficient designed and operation of 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. Two Federal agencies in the United States, the Federal Emergency Management Agency (FEMA) and National Institute of Standards and Technology (NIST) are developing frameworks to design new or retrofit existing lifeline infrastructure systems to achieve recovery-based objectives. The 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; a design procedure can then be implemented to meet the objectives. The establishment of target lifeline infrastructure system basic service recovery times is dependent on the consequences of service interruptions. The consequences of service outages depend on the conditions present, services provided, and users and uses of the services. The earthquake event and its location determine circumstances surrounding an outage.*

1 Introduction

Lifeline infrastructure systems provide services to support communities, including managing public health, safety, and social-economic factors. For lifeline infrastructure systems to support community resilience they need to have limited service disruptions and recover to meet societal needs after an earthquake. Resilience thinking acknowledges that earthquake damage to and service disruption from lifeline infrastructure cannot be completely prevented but can be managed with the objective of providing services to customers when needed.

The NIST-FEMA (2021) report 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 to earthquakes. Two Federal agencies in the United States, the Federal Emergency Management Agency (FEMA) and National Institute of Standards and Technology (NIST) are developing frameworks to design new and retrofit existing lifeline infrastructure systems to achieve recovery-based objectives. This paper presents the results of two projects to accomplish Recommendation 1 for lifeline infrastructure by (1) identifying a procedure for establishing service recovery time objectives, led by FEMA, and (2) defining the initial steps necessary to design the systems, led by NIST.

To strengthen community resilience, service recovery time objectives are needed along with procedures to consistently design, construct, retrofit, and operate infrastructure across all lifeline sectors before an earthquake. Additionally, pre-event plans and procedures for the lifeline organizations are necessary to address their post-event responses and ability to repair and recover infrastructure service disruptions. These organizational actions must be aligned with the quality and expected infrastructure earthquake performance.

After this introduction, an overview of lifeline infrastructure is presented. This is followed by a review of the relationship between system services, operability, and function, providing the background for understanding how functional recovery can be applied to lifeline systems. Then, the framework to establish service recovery time objectives (FEMA, 2024) is presented followed by describing the framework to design lifeline infrastructure for post-earthquake functional recovery (NIST, 2024). Water systems are used to provide examples for application throughout the descriptions. Due to space limitations, details for each framework are not presented herein but are described in each of the aforementioned publications.

2 LIFELINE INFRASTRUCTURE SYSTEMS

Lifeline infrastructure systems are critical to the functioning of modern society. They include water, wastewater, drainage, communication, electric power, gas and liquid fuels, transportation, and solid waste systems. They are socio-technical systems made up of physical components and human agency. 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, 2016). As shown in Fig. 1, lifeline infrastructure embodies the social-technical system including the physical assets and organizational structure along with the information exchanged.

Fig. 1 identifies how 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. 1 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. Thus, Fig. 1 expresses how lifeline infrastructure systems are composed equally of the technical and human portions. Functional recovery cannot be achieved without incorporating both (NIST-FEMA, 2021).

2.1 Assets and Organizational Actions

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.

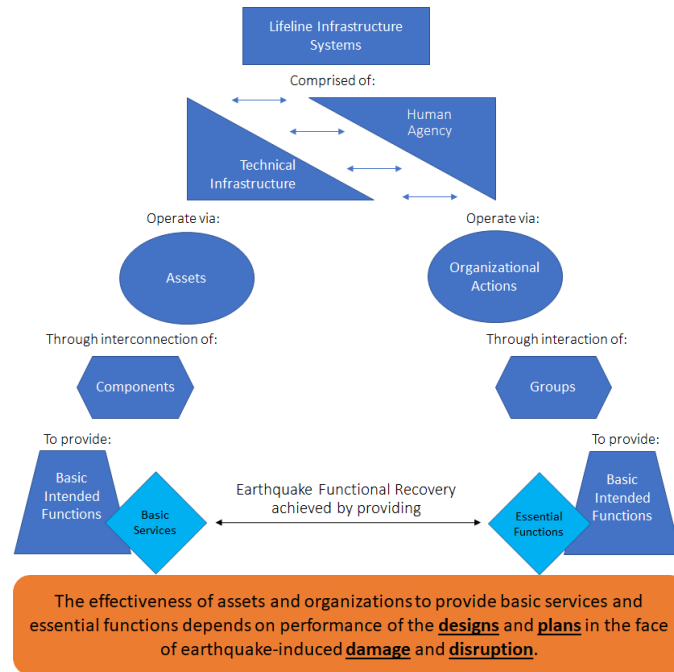


Figure 1. Lifeline systems consist of the technical infrastructure and human agency (NIST, 2024).

Organizations are comprised 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.

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 with 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 closely integrated with the 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 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.

3 RELATIONSHIP BETWEEN SYSTEM SERVICES, OPERABILITY, AND FUNCTION

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 frameworks in Sections 5 and 6. The NIST-FEMA (2021) definition of functional recovery is given in Section 1. In addition, 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 temporary provision of lifeline services. Further, functional recovery is defined as a state of the lifeline infrastructure system at some point in time after an earthquake.

3.1 Basic Services and Basic Intended Functions

The concept of basic services recognizes that lifeline infrastructure systems provide more than one single service. Basic services are used to define the fundamental services a lifeline infrastructure system provides to customers following an earthquake. Basic services may be measured (e.g., volume or flow rate) and used as objectives for system service recovery.

Basic services are fundamental to the normal levels of service provided by lifeline infrastructure systems. Before an earthquake event, customers receive a normal service. The normal service has multiple dimensions including all the basic services, a level of expected reliability, plus other enhanced levels of service (LGAM, 2019), such as treating water and wastewater to levels beyond that required by regulation. The basic services are necessities for any provision, while all other levels of service are niceties to enhance value.

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 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).

3.2 Functionality and Operability

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), thus providing all levels of service to customers.

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. 2a 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.

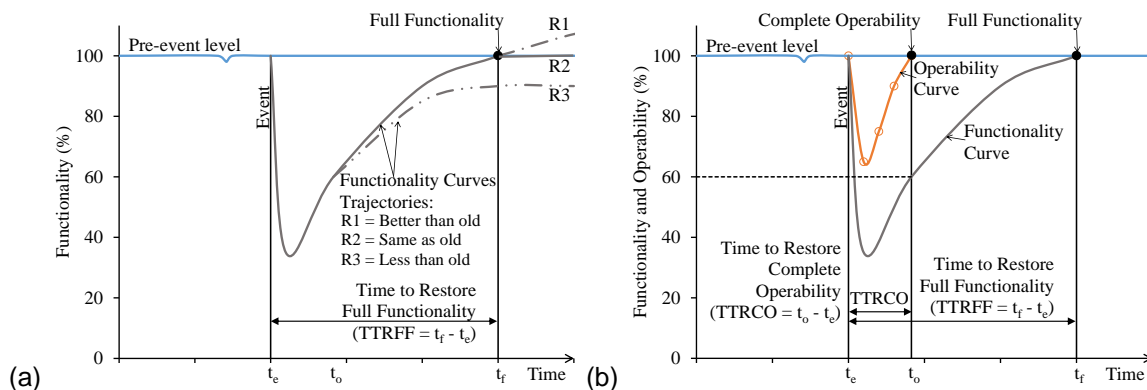


Figure 2. (a) Lifeline infrastructure functionality curve trajectories over time. (b) Conceptual representation of lifeline infrastructure system operability and functionality over time. Modified from Davis, (2021).

As shown in Fig. 2a, 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; 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 different trajectories exemplified as R1, R2, and R3 functionality curves in Fig. 2a. At time t_f or thereafter, the functionality curve may follow trajectory R1 and be rebuilt better than the original (better than old), 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).

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.

Fig. 2b presents the conceptual difference between operability and functionality. The functionality curve in Fig. 2b. is the same as R2 in Fig. 2a. Operability is achieved across the entire service area when the measure returns to 100% at time to restore complete operability (TTRCO). Due to system adaptability and/or pre-existing redundancies and isolation capabilities, 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. 2b 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. 2b, TTRCO is achieved sooner than TTRFF.

3.3 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 1 presents example BSCs for water, wastewater, and electric power systems (Davis, 2021). Table 2 describes each BSC presented in the top row of Table 1.

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

Lifeline Infrastructure	Delivery	Collection	Quality	Quantity	Disposal	Fire Protection
Water	X		X	X		X
Wastewater		X	X	X	X	
Electric Power	X		X	X		

Table 2. Lifeline Infrastructure System Basic Service Category Descriptions.

BSC	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), 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 suitable magnitude and duration to fight fires.

The operability curve in Fig. 2b involves the restoration of basic service categories (BSCs). As shown in Fig. 3a, operability is the fulfilment 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, then complete operability is accomplished throughout a service area, and user activities can essentially resume in a relatively normal manner. 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 Section 3.1.

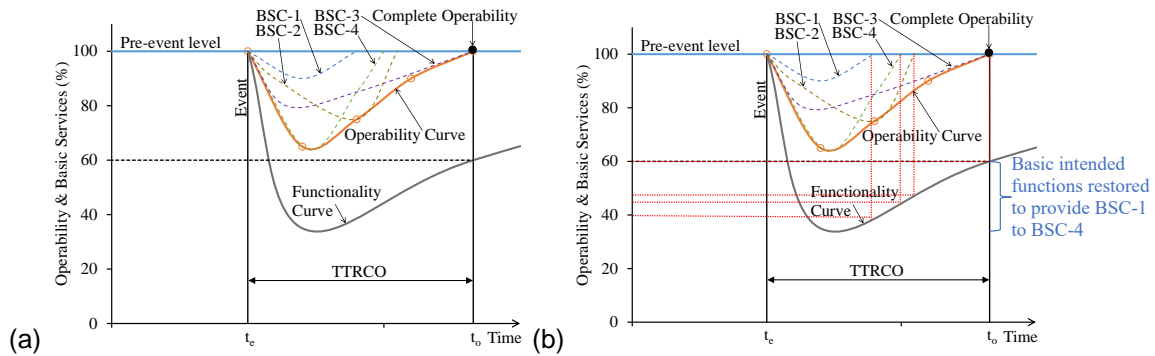


Figure 3. (a) Illustration of Basic Service Categories (BSC-1 to BSC-4) defining the operability curve. (b) Illustration of basic intended functions and relationship with BSCs.

3.4 Basic Intended Functions (BIFs) and Lifeline Infrastructure System Functional Recovery

BIFs are the actions to provide basic services. 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. Figs. 3a and 3b show how BIF restoration, which allow the BSCs to be restored, also increases the functionality measure of the system.

The main points in Section 3 applicable to the frameworks presented in the following sections are:

- Implementing the frameworks start 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 can be achieved before or when the system reaches complete operability

4 Overview of Functional Recovery Frameworks

Undertaking the framework development efforts described in Sections 5 and 6 first requires an organizational commitment to a functional recovery policy that integrates recovery-based objectives into lifeline infrastructure system programs, planning, design, and operations. Fig. 4 presents a governance and management schematic of the decision making, policy, programs, and planning process necessary to develop system-level service recovery time objectives and to design lifeline infrastructure systems for post-earthquake functional recovery. The governance and management levels for each part of the process are identified on the right side of Fig. 4. The lifeline infrastructure policy, programs, and planning are addressed elsewhere (e.g., NIST-FEMA, 2021; IRRG, 2023, Davis et al., 2018; NIST, 2015). This paper addresses the service recovery time objectives in Section 5 and how to design to meet them in Section 6. The assets and organizational actions frameworks together make up the framework to design lifeline infrastructure for post-earthquake functional recovery.

Governance is the role of leading an organization and management in its day-to-day running or operating. Making the decision to commit to design a system to meet functional recovery objectives is a policy choice influenced by governance (NIST, 2021). Governance includes activities and processes to achieve collaboration on behalf of the common interest to ensure societal needs are met (IRRG, 2023). It requires leadership and interaction among lifeline organizations and the communities they serve. Leadership from outside the lifeline system includes regulation and elected bodies on behalf of the lifeline infrastructure service 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. The pre- and post-event design, construction, operation, and modifications must meet all applicable codes and standards.

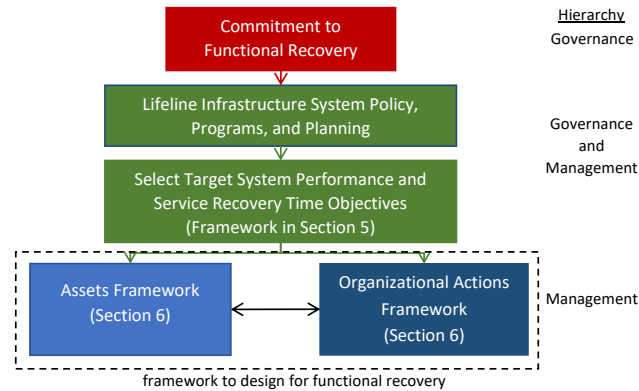


Figure 4. Hierarchy for decision making, policy, and planning for developing system-level objectives and implementing the framework to design for functional recovery (NIST 2024).

5 Framework to Establish Service Recovery Time Objectives (FEMA, 2024)

The aim of this framework is to set target recovery times that will limit negative societal impacts to specified parameters for given earthquake event levels. Fig. 5 illustrates the framework philosophy that consequences of a lifeline infrastructure system service outage are dependent on: (1) the conditions present; (2) the services provided (Fig. 5 left side), and (3) users and uses of the services (Fig. 5 right side).

The context of an event, known herein as conditions, including both the intensity of the earthquake hazards that precipitates the service disruption and the location, helps determine the consequences. To understand the consequences of outages, it is important to recognize that each lifeline infrastructure system may offer multiple basic services, that some may be interrupted while others are not, and that not all basic services are required to support all customer uses. The outage duration of each basic service helps determine the consequences of a service interruption. The consequences also depend on the user types and kinds of uses that rely on the lifeline infrastructure system service. The user types determine the uses, as well as the knowledge, experience, and resources for coping with outages through user adaptations. Interruptions of some uses lead to greater consequences than interruption of others. The consequences ultimately are a result of how service outages cause individual and societal needs to go unmet. The target service recovery times are a distillation of the anticipated consequences, users supported by each basic service, user type importance to the community during post-earthquake response and recovery, and uncertainty in the items illustrated in Fig. 5.

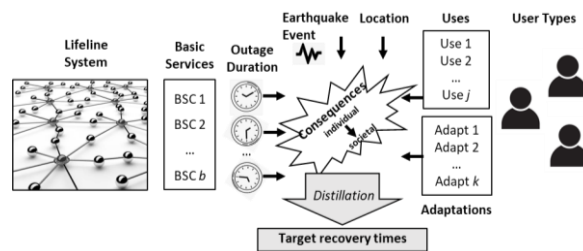


Figure 5. Service recovery time objectives framework philosophy schematic (FEMA, 2024).

The earthquake event determines the circumstances surrounding an outage, including the hazard intensities, geographic extent, and other types of simultaneous damage and disruption. It also may contribute to public expectations about what events an organization should be expected to plan for, and therefore, what recovery times are acceptable. The location may be important since it determines the climate, economic, social, cultural, and political context of an outage, and thus for example, the feasible adaptations and expected social and government support to mitigate and help recover from outages. All these possible determinants are distilled in a process to develop target recovery times (FEMA, 2024).

Application of the framework results in defining target recoveries times for each basic service category for groups of user types at specified societal impacts corresponding to earthquake event levels. Target recovery times depend on the outage consequences at the societal level, including dependencies of services by other lifeline infrastructure systems. It is typically easier to assess the consequences of service interruptions for individual

users, so the societal impact is assessed based on the aggregation of individual user impacts. Thus, the framework involves the following seven steps. An analyst can use the steps to establish post-earthquake target service recovery times for any lifeline infrastructure system.

- Step 1: Define Lifeline Infrastructure System and Basic Service Categories
- Step 2: Identify Kinds of Uses for User Types
- Step 3: Identify Adaptations
- Step 4: Identify Sets of Conditions and Target Societal Impact Levels
- Step 5: Determine User Consequences from Service Interruption
- Step 6: Determine Target Recovery Times for Basic Services
- Step 7: Summarize Recovery Time with the Societal Impact Levels

Steps 1 to 4 identify key elements and conditions that characterize the assessment. Using the conditions, Step 4 also defines the target societal impact levels linked to one or more earthquake events. Step 5 defines consequences of lifeline infrastructure service outage to individual users over a range of durations. Step 6 aggregates the individual user consequences to societal level consequences and distills the information from the earlier steps to identify the target recovery times. Step 7 links the target restoration times to societal impact levels and the earthquake events specified in Step 4. Due to space limitations details for each step are not presented herein but are described in FEMA (2024). Table 3 presents example outcomes for a potable water system water quality BSC for given different earthquake events and targeted societal impacts. Table 4 presents example recovery time objectives for all BSCs in a potable water system for the conditions in the second row of Table 3. Use of this framework provides consistency across lifeline infrastructure sectors.

6 Framework to Design Lifeline Infrastructure for Post-Earthquake Functional Recovery (NIST, 2024)

Lifeline infrastructure systems can be designed and operated to achieve post-earthquake service recovery times to meet societal needs. Recovery time objectives may differ for users of different criticality within a community. Lifeline infrastructure involves large, complex, geographically distributed systems built with specialized components made of many different materials over long periods of time. Moreover, most lifeline systems were not originally designed and built with resilience in mind. As a result, it is difficult, if not impossible, to prevent damage and potential service disruptions after an earthquake, but the loss and recovery of services can be managed to meet societal needs. This means that new lifeline infrastructure 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.

Table 3. Possible framework output for a potable water system – quality basic service.

Earthquake Event Description	Target Societal Impact Level	Recovery Time for Water Quality Service
Earthquake hazard intensities are sufficiently low to cause limited to no water system damages resulting in very few to no service outages.	<ul style="list-style-type: none"> • No user experiences high consequences from a water service outage • Few users have to implement adaptations. • Critical users implement few to no adaptations. 	1 day to critical users 3 days to all users
Earthquake hazard intensities are sufficiently large and widespread enough to cause significant water system damages resulting in service outages.	<ul style="list-style-type: none"> • No user experiences high consequences from a service outage when implementing adaptations. 	3 days to critical users 15 days to all users
Earthquake hazard intensities are sufficiently large and widespread enough to cause serious water system component damages resulting in prevalent service outages.	<ul style="list-style-type: none"> • Users may experience some high consequences but no user experiences serious risk of long-term impacts when implementing adaptations. • Use of adaptations remains manageable 	7 days to critical users 30 days to all users
Earthquake hazard intensities are sufficiently large and widespread enough to cause severe and a large number of component damages resulting in extensive service outages.	<ul style="list-style-type: none"> • No user experiences irrecoverable consequences from a water service outage when implementing adaptations. • Use of adaptations begin to reach an unmanageable stage 	14 days to critical users 60 days to all users

Table 4. Target water system BSC recovery times assuming user adaptations in Step 3 are applied.

BSC	Service Description	Target Recovery Time
Delivery	Restore to all customers	7 days
Quality	Restore to all customers	15 days
	Restore to all Critical A Users*	3 days
	Restore to all schools	7 days
Quantity	Restore to high-volume Commercial, Industrial, and Institutional Users	7 days
	Restore average winter day demand to all customers	20 days
	Restore to pre-event normal demand (rationing removed)	30 days
Fire Protection	Restore to all hydrants within ½ mile ¹ of Critical A Users* and multi-resident users; within 1 mile of any other area requiring fire protection.	3 days
	Restore to Critical A Users having fire service at main service connections	3 days
	Restore to 90% of hydrants	10 days
	Restore to all hydrants	20 days

*Critical A Users are necessary for safety and public health (e.g., hospital, police, emergency and evacuation shelters)

Fig. 6 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. Fig. 6 is used to describe the basis for and how the framework is formulated.

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. 6). The built infrastructure and cyber domains make up the technical systems and are the primary means through which services are delivered to customers (NIST, 2016). 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. 6. The services provided by lifeline infrastructure systems are essential for communities to function (upper right). During times of service disruption basic service restorations described in Section 5 are prioritized to the most critical users (lower right). Moreover, strategies are employed to reduce the societal consequences of the 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 ensuring public health, safety, and property protection objectives, satisfy the authorities having jurisdiction. 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).

The box containing assets and organizations in the lower left of Fig. 6 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 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 scenario earthquake events 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 of Fig. 6). These outcomes are applied to the lifeline infrastructure systems to support the communities they serve.

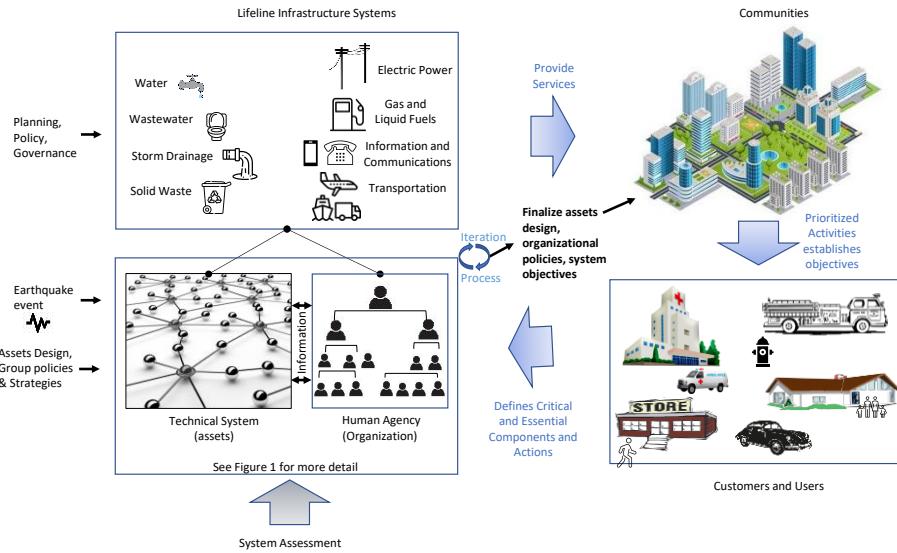


Figure 6. Framework philosophy schematic (NIST, 2024). (icons from www.flaticon.com, community from www.wallstreetmojo.com/public-infrastructure/).

It is important to recognize how an earthquake not only impacts the built infrastructure, but also the potential flow of information, and the groups of people making up the lifeline 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. As each user has their basic services restored from the lifeline infrastructure systems, they can begin resuming normal activities relative to those amenities.

6.1 Assets and Organizational Actions Frameworks

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 developed are the assets and organizational actions frameworks.

The processes and steps in the assets and organizational actions frameworks are interconnected. Figs. 1 and 6 show how the cyber domain is fundamental to this interconnection. 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. As shown in Fig. 4, the system-level performance and service recovery time objectives are used as inputs into the assets and organizational actions frameworks.

Assets Framework

The assets framework identifies, designs, and assesses the interlinking components and subsystems making up the built infrastructure so that lifeline infrastructure 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. It is presented in eleven steps. An analyst can use the steps to design the components in any lifeline infrastructure for post-earthquake functional recovery.

- Step A1: Define System Layout and Operational Characteristics
- Step A2: Define Criticality Category and Earthquake Design Basis for System Components
- Step A3: Check Multiple Use, Continuity, and Redundancy
- Step A4: Establish Component Objectives - Maximum Level of Damage and Repair Time
- Step A5: Identify Dependent Services
- Step A6: Develop Preliminary Design
- Step A7: Assess the Component Performance and Repair Time, Compare with Target Objectives
- Step A8: Identify Recovery Time Factors
- Step A9: Assess System Performance and Recovery Time
- Step A10: Compare System Assessment Results with Target Objectives

- Step A11: Report System Assessment Results

Step A1 identifies asset position within the network and exposure to seismic hazards. Step A2 defines the criticality of components within the network based on the importance of the customers they serve. Step A2 also establishes the seismic design basis for each component. Step A3 checks the continuity of the chain of components providing services to critical customers along with branch lines and isolation capabilities. It also allows component criticality to be reduced based on redundancy. Step A4 establishes component-level objectives using maximum level of damage for performance and repair time for recovery. Step A5 identifies the services from other systems a lifeline infrastructure system may be dependent upon. Step A6 develops a component preliminary design incorporating restoration time and cost into the process. Step A7 assesses the component performance and repair time using simulations and analytical procedures, then compares them with the target performance and recovery objectives. If the objectives are met the design is acceptable, if not then modifications are needed. Step A8 identifies recovery time factors for performing a system-level assessment in Step A9. Step A9 assesses the system-level performance to confirm the target service recovery time objectives can be met based on the component design(s). Step A10 compares the system assessment results with the target objectives. If the objectives are met the system layout and component design(s) are acceptable, if not then modifications are needed. Step A11 reports results of system-level assessments and establishes a basis for mitigation plans. Due to space limitations details for each step are not presented herein but are described in NIST (2024).

Organizational Actions Framework

The organizational actions framework creates a lifeline 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. It is presented in ten steps. An analyst can use the steps to develop policies and strategies in any lifeline organization for post-earthquake functional recovery.

- Step O1: Identify Groups within the Organization and their Functions
- Step O2: Identify Organizational Essential Functions, Resources, and Groups
- Step O3: Assess Internal and External Coordination
- Step O4: Establish Responsibilities, Resources, Capabilities, and Recovery Time Objectives
- Step O5: Develop Group-Level Policies and Strategies
- Step O6: Assess Group Performance and Recovery Capability and Compare with Group's Target Objectives
- Step O7: Identify Recovery Time Factors
- Step O8: Assess System Performance and Recovery Time
- Step O9: Compare System Assessment Results with Target Objectives
- Step O10: Report System Assessment Results

Step O1 uses an organizational business process analysis (BPA) to identify groups within the organization and their inter-related functions. Step O2 uses the BPA and a business impact analysis process to identify the organizational essential functions, resources, and groups. Step O3 assesses the internal and external coordination among groups. This is especially critical for coordinating dependencies on services from other lifeline infrastructure. Step O4 establishes group responsibilities, resources, capabilities, and recovery time objectives and provides for the prioritization of essential functions. Step O5 develops preliminary group-level policies and strategies needed for functional recovery. Step O6 assesses group performance and recovery capability and compares with the group's target objectives. If the objectives are met the group policies and strategies are acceptable, if not then modifications are needed. Step O7 identifies recovery time factors for performing a system-level assessment in Step O8. Step O8 assesses the system-level performance to confirm the target service recovery time objectives can be met based on the group capabilities. Step O9 compares the system assessment results with the target objectives. If the objectives are met the system layout and group policies and strategies are acceptable, if not then modifications are needed. Step O10 reports results of system-level assessments and establishes a basis for and modification of multiple plans and programs. Due to space limitations details for each step are not presented herein but are described in NIST (2024).

7 Conclusions

The efforts of FEMA and NIST have resulted in the development of frameworks to establish lifeline infrastructure system service recovery objectives for seismic resilience and to design lifeline infrastructure for post-earthquake functional recovery. These frameworks focus on delivering lifeline infrastructure basic services to meet user needs following earthquakes based on the importance of customers to the community during a disaster. They incorporate the practical utilization of adaptations by users to fill the gap when services cannot be provided through the network. Lifeline infrastructure functional recovery incorporates the design of assets and the organizational policies and strategies. The process involves components and groups meeting specified performance and recovery objectives and ensuring target service recovery time objectives can be met at the system-level. An iterative process is proposed to confirm the target service recovery time objectives are met, and if not changes should be made to the recovery time factors. Designing buildings and lifeline infrastructure systems for functional recovery reduces the time to resume community activities after earthquake events, and lessens the opportunity for catastrophic physical, social, and economic consequences.

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9 References

- Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., et al. (2003). *A framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities*, Earthquake Spectra 19, 733 –752.
- Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010). *Seismic Resilience of a Hospital System*, Struct. Infrastruct. Eng., 6(1–2), 127–144. Civil Contingencies Secretariat of the Cabinet Office, London. (2003).
- Davis, C.A. (2014). *Water service categories, post-earthquake interaction, and restoration strategies*, Earthquake Spectra, Vol. 30, No.4, pp.1487-1509.
- Davis, C.A. (2021). *Understanding functionality and operability for infrastructure system resilience*, Natural Hazards Review, Vol. 22, No. 1.
- FEMA (2024). *A Framework to Establish Lifeline Infrastructure System Service Recovery Objectives for Seismic Resilience*, FEMA P-2234, Prepared by ATC for FEMA, Wash. D.C, in review.
- Infrastructure Resilience Research Group (IRRG) (2023). *Infrastructure System Resilience An Engineering Framework for Assessment, Management, and Governance*, ASCE Infrastructure Resilience Division and Japan Society of Civil Engineers, C. Davis Ed., ASCE IRP8.
- LGAM (The Local Government and Municipal Knowledge Base) (2019). *Level of service*, Accessed December 13, 2019. <http://www.lgam.info/level-of-service>.
- NIST (2015). *Community Resilience Planning Guide for Buildings and Infrastructure Systems*, NIST Special Publication 1190, Volume II, National Institute of Standards and Technology, Gaithersburg, Maryland.
- NIST (2016). *Conceptual Framework for Assessing Resilience at The Community Scale*, NIST GCR 16-001, prepared by A. Kwasinski, J. Trainor, B. Wolshon, F. M. Lavelle.
- NIST (2021). *NIST-FEMA Post-Earthquake Functional Recovery Workshop Report*, NIST Special Publication 1269, National Institute of Standards and Technology, Gaithersburg, Maryland.
- NIST (2024) *Initial Framework to Design Lifeline Infrastructure for Post-Earthquake Functional Recovery*, Prepared by ATC for NIST, Gaithersburg, MD, in review.
- NIST-FEMA (2021). *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time*, FEMA P-2090/NIST SP-1254, Joint publication by FEMA and NIST. <https://doi.org/10.6028/NIST.SP.1254>.