Toward Resilient Communities: A Performance-Based Engineering Framework for Design and Evaluation of the Built Environment

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ABSTRACT

A community is a dynamic system of people, organizations, and patterned relationships and interactions. Most of these relationships and interactions are physically supported by a community's built environment, a complex and interdependent network of engineered subsystems and components, including buildings, bridges, pipelines, transmission towers, and other structures. As a result, the built environment plays a crucial role in enabling a community to function successfully, providing the foundations for much of the economic and social activities that characterize a modern society. Natural hazards such as earthquakes, hurricanes, and floods can damage a community's built environment, which in turn can disrupt the security, economy, safety, health, and welfare of the public. In response, many communities have developed and implemented regulatory frameworks to ensure that individual parts of the built environment attain minimum levels of performance.

This report proposes a performance-based engineering framework for design and evaluation of the built environment in order to improve the overall resilience of communities to natural hazards. It begins by examining the regulatory framework currently used in the United States to design and evaluate a community's built environment to withstand the effects of earthquakes and other natural hazards. Specifically, it analyzes building codes and other engineering standards that establish performance expectations for buildings and lifelines. To this end, the report first identifies attributes or characteristics of an ideal regulatory framework. Then, using these attributes as a guide, it discusses both the strengths and shortcomings of the current regulatory framework. The most significant shortcoming of the current framework is its lack of an integrated, coordinated, and comprehensive approach to establishing performance expectations for individual components of the built environment. Consequently, performance objectives for the individual components are not tied to broader performance targets for the community, primarily because these community-level performance objectives typically do not exist.

The growing interest in resilient and sustainable communities necessitates an updated regulatory framework, one that employs an integrated, coordinated, and comprehensive approach to account for the built environment's numerous subsystems, components, and interactions. The regulatory framework currently used in the United States to design, analyze, and regulate commercial nuclear power plants to assure their safety offers a promising template for communities to follow. Despite obvious differences in function and configuration, both communities and nuclear power plants are multi-faceted, dynamic systems comprising many interacting subsystems and components that cut across a diverse range of disciplines and professions. The current nuclear regulatory framework handles these numerous subsystems, components, and interactions in a consistent and logical manner, informed partly by an explicit set of system-level performance expectations for the nuclear power plant. Furthermore, the tools and procedures employed by the current nuclear regulatory framework have been implemented successfully and refined extensively over the past several decades, resulting in significant improvements in both the understanding of how these complex, dynamic systems behave and the efficacy of the regulatory framework itself.

This report studies the current regulatory framework for nuclear power plants and, using recent developments from the rapidly evolving fields of community resilience and lifeline interdependency, adapts it for use in a community setting. To this end, the report proposes and describes an integrated engineering framework for design and evaluation of a community's built environment. This new framework provides a transparent, performance-based, risk-informed methodology for establishing a consistent set of performance targets for the built environment and its various subsystems and components to enhance the overall resilience of the community. This report also presents several conceptual examples that illustrate implementation of the proposed framework, including a demonstration of how to develop seismic performance targets for a new residential building from a community-level performance goal.

Ultimately, the work presented herein has the potential to change the way engineers, planners, and other stakeholders design and evaluate a community's built environment. The engineering framework proposed in this report provides a comprehensive, integrated, and coordinated methodology for planners and policymakers to set community-level performance targets and, subsequently, for engineers to calibrate the designs of individual components to meet these community-level performance targets. Though additional work is required, the findings presented in this report establish the foundations for a much-needed transformation from engineering individual components of the built environment on a component-by-component basis to engineering community resilience using an integrated and coordinated approach that begins at the community level. Future iterations of the framework should aim to expand its scope beyond disaster resilience to address and incorporate broader sustainability considerations, for example, carbon footprint concerns, energy efficiency, resource consumption, and the environmental impact of a community and its built environment.

ACKNOWLEDGMENTS

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1   Introduction

A community is a dynamic system of people, organizations, and patterned relationships and interactions [Alesch 2005]. Most of these relationships and interactions are physically supported by a community's built environment, a complex and interdependent network of engineered subsystems and components, including buildings, bridges, pipelines, transmission towers, and other structures. As a result, the built environment plays a crucial role in enabling a community to successfully function, providing the physical foundations for much of the economic and social activities that characterize a modern society [O'Rourke 2007]. Natural hazards such as earthquakes, hurricanes, and floods can damage a community's built environment, which in turn may disrupt the security, economy, safety, health, and welfare of the public.

In response, many communities have developed and implemented regulatory frameworks to ensure minimum levels of performance for individual parts of the built environment. A regulatory framework provides the legal and technical basis for allowing a system to operate through all phases of its lifecycle. It comprises three basic elements: regulations, mechanisms for enforcing the regulations, and guidance for satisfying the regulations. Regulations, which usually carry the weight of law, include codes, standards, and other documents that specify the rules, requirements, and provisions for a system and its parts. Enforcement is accomplished by the agencies and organizations that are charged with promulgating and/or maintaining the regulations. Guidance, which is typically optional in nature, refers to anything that aids in satisfying the regulations, providing but one of many possible ways to satisfy the regulations.

This report examines the regulatory framework currently used in the United States to design and evaluate a community's built environment to withstand the effects of natural hazards. In particular, it examines building codes and other engineering standards that establish performance expectations, either implicit or explicit, for the built environment and its numerous components and subsystems. This examination reveals several significant shortcomings. Most crucially, the current regulatory framework approaches the design and evaluation of the built environment on a component-by-component basis, generally treating each subsystem or component as if it does not interact with or depend on other parts of the built environment. This component-by-component approach results in a community in which most individual subsystems and components of the built environment behave as intended; however, when aggregated, the performance of and interaction among individual components can result in unacceptable outcomes for the community.

The growing interest in sustainable and resilient communities necessitates an updated regulatory framework, one that employs an integrated, coordinated, and comprehensive approach to account for the built environment's numerous subsystems, components, and interactions. An approach like this derives an understanding of the behavior of individual components by first studying the behavior of the entire system, which stands in contrast to a component-by-component approach that arrives at an understanding of the behavior of the system by first studying the behavior of individual components [Bea 2007, 2008]. By focusing attention at the system level first, performance objectives for individual components within the built environment can be formulated in a way that is consistent with broad resilience goals for the community.

The regulatory framework currently used to design, analyze, and regulate commercial nuclear power plants in the United States offers a promising template for communities to follow. Similar to a community, a nuclear power plant is a complex, dynamic system comprising many interacting subsystems and components that cut across a diverse range of disciplines and professions. The current nuclear regulatory framework handles these numerous subsystems and components in a consistent and logical manner, informed partly by an explicit set of system-level performance expectations for the nuclear power plant. To this end, the current nuclear regulatory framework begins at the system level, identifying key functions that must be available in order for a nuclear power plant to operate successfully. It then establishes performance targets both for the overall nuclear power plant as a system and, subsequently, for its numerous subsystems and components. Finally, in order to ensure the plant satisfies these targets, the framework requires a detailed analysis of the system and its components in order to verify that the plant design satisfies the required system-level performance targets. The tools and procedures employed by the current nuclear regulatory framework have been implemented successfully and refined extensively over the past several decades, resulting in significant improvements in both the understanding of how these complex, dynamic systems behave and the efficacy of the regulatory framework itself.

This report explores the opportunities and challenges that arise when adapting pieces of the nuclear regulatory framework for use in a community setting. Throughout this process, the report draws from several major studies from the rapidly evolving fields of community resilience and lifeline interdependencies, including PCCIP [1997], Rinaldi et al. [2001], Bruneau et al. [2003], Miles and Chang [2003, 2006, 2007], Poland et al. [2009], Twigg [2009], SERRI and CARRI [2009], and Cutter et al. [2010]. Using the nuclear framework as a template, it leverages findings from these studies to create an engineering framework that addresses the built environment's numerous components, subsystems, and interactions using an integrated, coordinated, and comprehensive approach. In particular, the proposed framework uses findings from Poland et al. [2009], SERRI and CARRI [2009], Twigg [2009] and Cutter et al. [2010], to identify essential community functions that need to be maintained following a disaster. In addition, it uses PCCIP [1997], Rinaldi et al. [2001], ALA [2004], and Poland et al. [2009] to identify components and subsystems within the built environment (including their interdependencies) that have significant roles in supporting these essential community functions.

Ultimately, the framework described in this report can be used to ensure that individual components of the built environment perform in a manner that supports broad, community-level resilience goals. In this new framework, engineers will design individual structures and components in much the same way they have in the past. However, the performance targets specified by the framework for these individual components will be compatible with broader performance targets established for the entire community.

1.1   OVERVIEW AND BACKGROUND

1.1.1   Current Regulatory Framework for Communities

A community is a complex and dynamic system of people, organizations, infrastructure, and interactions. Equally complex, however, is the regulatory framework that governs how a community and its numerous components must operate. This report focuses on a small but important piece of this regulatory framework: the building codes and other engineering standards that establish performance expectations, either implicit or explicit, for a community's built environment. The following paragraphs describe these documents and briefly discuss their strengths and shortcomings.

At the heart of the current regulatory framework for buildings in the United States is the International Building Code (IBC), a document that specifies minimum requirements for buildings and other structures in order to safeguard the health, safety, and general welfare of the public [ICC 2006]. Historically, the focus of modern building codes like the IBC has been to "safeguard against major structural failures and loss of life, not to limit damage or maintain function" [ICBO 1997]. To this end, modern building codes, when properly enforced, have been effective at reducing casualties, as demonstrated in two recent earthquakes. On 12 January 2010 a magnitude 7.0 earthquake struck near Port-au-Prince, the heavily populated capital of Haiti. The city lacks both a modern building code and a means to enforce it [DesRoches et al. 2011]. As a result, nearly half the buildings in Port-au-Prince, many of which were constructed using materials and methods prohibited in the IBC, collapsed during the earthquake. While an exact estimate may never be possible, the resulting destruction claimed the lives of approximately 300,000 Haitians [DesRoches et al. 2011]. In contrast, the magnitude 6.3 earthquake that struck Christchurch, New Zealand, on 22 February 2011 claimed the lives of approximately 180 people [EERI 2011]. Despite both earthquakes having similar intensity, the casualties in New Zealand were a small fraction of those experienced in Haiti. The stark difference in the performance stems largely from the New Zealand building code, which closely resembles the IBC and is strictly enforced.

While the IBC has been effective at reducing the risk posed by earthquakes to life safety, it has been less effective at addressing other kinds of risk. For example, its provisions allow significant structural and nonstructural damage to occur in very rare, intense ground shaking as long as it does not lead to collapse [BSSC 2009]. While the resulting damage may pose minor risk to life safety, it can significantly impact the functionality of the building, which in turn can

impose substantial financial burden on its inhabitants and, ultimately, the community. For example, the magnitude 6.3 earthquake that struck Christchurch, New Zealand, on 22 February 2011 caused extensive damage to buildings in the city's Central Business District (CBD). Approximately 50% of all buildings in the CBD were rendered unusable because they either sustained significant structural damage or were located near hazardous buildings [EERI 2011]. Consequently, a significant portion of the CBD was closed for over a year [CERA 2012a], affecting over 50,000 workers (25% of the city's workforce) and approximately 6000 companies or institutions [EERI 2011]. The Canterbury Earthquake Recovery Authority [CERA 2012b] anticipates that it will take two–three years to demolish all heavily damaged buildings in the CBD, thereby slowing redevelopment prospects. In general, damage that forces a business to close for weeks or months may strain the finances of the owners, employees, and those who depend on the goods or services it produces, including other businesses. Closure of many such businesses, as happened in Christchurch, can result in a precipitous drop in tax revenues for local governments and even a significant outmigration of residents and businesses. Issues like these are beyond the consideration of the IBC.

As the 2011 earthquake in Christchurch highlights, the seismic performance levels specified for individual buildings by the IBC and other modern building codes are inconsistent and often inadequate when viewed from the perspective of the community. Typically, the performance levels established by modern building codes reflect choices that balance the desire to minimize initial construction costs with the need to ensure adequate levels of safety for the building's occupants [BSSC 2009]. Absent from this consideration, however, is the impact these choices have beyond the owners and occupants of the building. For example, if an earthquake damages a large apartment building and renders it unusable, it can impose significant financial burden on the local government agencies that provide emergency housing to displaced residents. It can also impact surrounding businesses, especially if emergency housing is located far from the damaged apartment building, causing their customer base to disappear overnight. Consequently, performance objectives that are appropriate for the safety of a building's occupants may not be appropriate for the general welfare and overall resilience of the community.

Buildings, which fall under the purview of the IBC, are but one piece of a community's built environment. Lifelines such as electric power, water, and telecommunications also play a crucial role in a community's ability to function successfully, both on a daily basis and in the aftermath of a major disaster. In spite of their importance, "seismic performance standards for lifelines vary widely and are not tied to generally applicable public policies for reducing risk or for ensuring community resilience in the face of a major earthquake" [Barkley 2009]. Figure 1.1 lists the various performance standards and guidelines that exist for each of the major lifelines. Note that for electric power, water, wastewater, and telecommunications, performance standards that address system reliability do not exist. The American Lifelines Alliance defines system reliability as "a component of design referring to practices that are specifically developed to provide reasonable assurance that consequences of a natural hazard on system service will meet the goals established by stakeholders (owners, operators, regulators, insurers, customers, and users)" [ALA 2004]. This lack of system-level performance standards for lifelines results in a

limited understanding of how these crucial systems are expected to perform in a major earthquake [Barkley 2009].

Furthermore, because lifelines are distributed systems, they often cross multiple legal and jurisdictional boundaries [ALA 2005], and can be controlled by either private or public entities. As a result, individual communities may have little control over how lifelines within their geographic boundaries are operated and maintained. In addition, lifelines are highly interdependent, meaning that the serviceability of an individual lifeline following a major earthquake depends not only its performance but also on the performance of other lifelines. Therefore coordination among the different lifeline operators and regulators is required in the development of system-level performance standards.

At the highest level, the current regulatory framework fails to establish an explicit set of seismic performance objectives for the entire community. This not only makes it difficult for engineers and planners to communicate the expected seismic performance of the community with stakeholders and members of the general public, it also makes it impossible to determine whether the performance levels specified for individual buildings and lifelines by building codes and other performance standards are appropriate for the surrounding community. This report addresses this important shortcoming by proposing an integrated, coordinated, and comprehensive engineering framework—one that establishes broad performance goals for the community before determining performance targets for individual components and subsystems within the built environment.

1.1.2 Community Resilience

In the past two decades, the field of resilience has gained traction and received considerable attention from both researchers and policymakers. Bruneau et al. [2003] define seismic resilience as "the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes." To date, most research in this rapidly evolving field has focused on defining resilience and establishing metrics to measure and quantify it [Miles and Chang 2003, 2006, 2007; Cutter et al. 2010; Twigg 2009]. These efforts have been instrumental in shifting the focus of designers and engineers (at least in part) from how individual components respond to how the entire community performs; however, much of this work has focused on the evaluation side of resilience. Less effort has gone into the design side. For example, if communities want to enhance or improve their resilience to disasters, exactly what level of performance is required from buildings and lifelines? Poland et al. [2009] establishes a comprehensive set of performance objectives that, if achieved, will make the city of San Francisco more resilient. Specifically, this set of objectives aims to have the city "back on its feet" four months after a magnitude 7.2 earthquake on the Peninsula segment of the San Andreas fault.

This report draws from and builds on these important studies, proposing a comprehensive, coordinated, and integrated engineering framework that any community can use to establish a consistent set of performance targets for individual subsystems and components

within the built environment in order to enhance overall resilience to natural disasters. In particular, the proposed framework uses findings from the resilience literature to identify essential community functions that need to be maintained following a disaster and, subsequently, to identify components and subsystems within the built environment (including their interdependencies) that support these essential functions.

OIL PRODUCTS SYSTEMS — NATURAL HAZARD PROVISIONS[8]

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Buried Pipelines	ASME/ANSI B31.4	none[2]	none	
	ASCE TCLEE 1984	earthquake	earthquake	•
Aboveground Piping	ASME/ANSI B31.4	none[2]	none	
	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	API 2510			
	API 2508			
	ASCE TCLEE 1984	earthquake	none	•
Pumping Station Piping	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	ASME/ANSI B31.4	none[2]	none	
	API 2510			
	ASCE TCLEE 1984	earthquake	none	•
Well Facilities	ASME/ANSI B31.4	none[2]	none	
	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	API RP 14E			
Refineries	API 2508			•
	ASCE Petrochem.	earthquake, wind	earthquake, wind	
	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	ASME BPV[3]	none[2]	earthquake, wind, ice	
Storage Tanks	API 620	earthquake, wind	earthquake, wind	•
	API 650	earthquake, wind	earthquake, wind	•
	NFPA 59			
	API 2508			
	ASCE TCLEE 1984	earthquake	earthquake	•

NATURAL GAS SYSTEMS — NATURAL HAZARD PROVISIONS[8]

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Buried Pipelines	ASME/ANSI B31.8	none[2]	none	
	PRCI (2000)	earthquake	earthquake	•
	ASCE TCLEE 1984	earthquake	earthquake	•
Aboveground Piping	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	ASME/ANSI B31.8	none[2]	none	
	ANSI Z223.1	none[2]		
	NFPA 54, SGC, IFGC	none[2]		
	ASCE TCLEE 1984	earthquake	none	•
Compressor Station Piping	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	ASME/ANSI B31.8	none[2]	none	
	ASCE TCLEE 1984	earthquake	none	•
Well Facilities	ASME/ANSI B31.8	none[2]	none	
	API RP 14E			
LNG Facilites				
System Reliability[6]	NFPA 59A	earthquake	earthquake	
Piping	NFPA 59A	earthquake	earthquake	
Storage Tanks	API 620	earthquake, wind	earthquake, wind	
	API 650	earthquake, wind	earthquake, wind	
	ASME BPV[3]	none[2]	earthquake, wind, ice	
	NFPA 59A	earthquake, ref. ANSI A58.1 for wind and snow	earthquake, ref. ANSI A58.1 for wind and snow	
	ASCE 1984	earthquake	earthquake	

WATER SYSTEMS (Potable & Raw) — NATURAL HAZARD PROVISIONS[8]

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Buried Pipelines	AWWA M11	none[2]	none	
	ASCE TCLEE 15	earthquake	earthquake	•
Aboveground Pipelines	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
Pumping Plants	ASME B31.3	none[2]	earthquake, wind, ice	
Storage Tanks	ACI 350	earthquake	earthquake	•
	AWWA D[5]	earthquake, wind, snow	earthquake, wind, snow	•
	ASCE 1984	earthquake	earthquake	•
Well Facilities				
Canals				

WASTE WATER SYSTEMS — NATURAL HAZARD PROVISIONS[8]

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Buried Pipelines	AWWA M11	none[2]	none	
	ASCE TCLEE 15	earthquake	earthquake	•
Aboveground Pipelines	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
Treatment Plants	ASME B31.3	none[2]	earthquake, wind, ice	•
	WEF	earthquake, flood		•
Storage Tanks	ACI 350	earthquake	earthquake	•
	AWWA D[5]	earthquake, wind, snow	earthquake, wind, snow	•
	ASCE 1984	earthquake	earthquake	•

ELECTRIC POWER SYSTEMS — NATURAL HAZARD PROVISIONS[8]

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Substations	IEEE-693	earthquake	earthquake	•
	RUS 1724e*	wind, ice, earthquake	wind, ice, earthquake	•
	ASCE Manual 96	earthquake	earthquake	•
Transmission Towers & Poles	ASCE-10*	wind, ice, earthquake	wind, ice, earthquake	•
	ASCE Manual 72*	wind, ice, earthquake	wind, ice	•
	ASCE Manual 74	wind, ice, earthquake[2]	wind, ice	•
	ASCE Manual 91*	wind, ice, earthquake	wind, ice, earthquake	•
	ASCE Concrete Poles*	wind, ice, earthquake	wind, ice, earthquake	•
	PCI Prest. Conc. Poles*	wind, ice, earthquake	wind, ice, earthquake	•
	RUS 1724e*	wind, ice, earthquake	wind, ice, earthquake	•
	IEEE 605*	wind, ice, earthquake	wind, ice, earthquake	•
	IEEE 691*	none	none	•
	IEEE 693	earthquake	earthquake	•
	NESC	wind, ice, earthquake	wind, ice	•
Distribution Poles	NESC	wind, ice, earthquake	wind, ice	•
	RUS 160-2*	wind, ice, earthquake	wind, ice, earthquake	•
Buried Conduits				

TELECOMMUNICATION SYSTEMS — NATURAL HAZARD PROVISIONS[8]

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Towers, Masts and Poles	TIA/EIA 222G (2003)	earthquake, wind, ice	earthquake, wind, ice	•
	TIA/EIA 222F	wind, ice	wind, ice	•
Buried Cables	Bell Core	earthquake, flood	earthquake, flood	
Underwater Cables				
Aboveground Cables	Bell Core	earthquake, wind, ice, snow	Earthquake, wind, ice, snow	
Switching Equipment	Bell Core	earthquake, fire	earthquake, fire	
Cable Trays	SMACNA	none	earthquake	
	BSP (Bell System Practice)	none	earthquake	
	ASCE 7	earthquake, wind, ice, snow	earthquake, wind, ice, snow	

PORTS AND INLAND WATERWAYS — NATURAL HAZARD PROVISIONS[8]

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]	ASCE TCLEE 12	earthquake		•
Piers/Wharves	NCEL R-939	earthquake	earthquake	
	NAVFAC DM-25.1			
	ASCE TCLEE 12	earthquake	earthquake	•
	NFESC TR-2069SHR	earthquake	earthquake	
Breakwaters/Jetties	NCEL R-939	earthquake	earthquake	
	ASCE TCLEE 12	earthquake	earthquake	•
Sea Walls	NCEL R-939	earthquake	earthquake	
	ASCE TCLEE 12	earthquake	earthquake	•
Container Handling	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	ASCE TCLEE 12	earthquake	earthquake	•
	AISC	none[2]	earthquake, wind, snow, ice	
Cargo Movement	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	ASCE-ASCE TCLEE 12	earthquake	earthquake	•
Marine Oil Terminals	CSLC	earthquake	earthquake	
	NFESC, TR-2103-SHR	earthquake	earthquake	
	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	NFPA[4]	earthquake	earthquake	

HIGHWAYS AND ROADS — NATURAL HAZARD PROVISIONS[8]

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]	FHWA 106	earthquake	earthquake	
Bridges	AASHTO	earthquake, wind, snow, Ice, flood	earthquake, wind, snow, Ice, flood	•
	CALTRANS	earthquake, wind, snow, Ice, flood	earthquake, wind, snow, Ice, flood	•
	FHWA-RD-94-052	earthquake	earthquake	•
	FHWA 106	earthquake	earthquake	•
Embankments	CALTRANS	earthquake	earthquake	•
Road Beds				
Culverts	AASHTO	none[2]	none	
	CALTRANS	none[2]	none	
Tunnels	AASHTO	none[2]	none	
	CALTRANS	none[2]	none	
Retaining Walls	FHWA 106	earthquake	earthquake	
Signs	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	

RAILROAD — NATURAL HAZARD PROVISIONS[8]

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]	AREMA Ch. 9			
Bridges	AREMA Ch. 7	wind	wind	
	AREMA Ch. 8	wind, ice	wind, ice	•
	AREMA Ch. 9	earthquake	earthquake	•
	AREMA Ch. 15	wind	wind	•
Embankments	AREMA Ch. 9	earthquake	earthquake	earthquake
Rails, Ties, and Ballast	AREMA Ch. 9	earthquake	earthquake	earthquake
Culverts	AREMA Ch. 9	earthquake	earthquake	earthquake
Tunnels	AREMA Ch. 9	earthquake	earthquake	earthquake
Signs	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	

ELECTRICAL, MECHANICAL, AND ARCHITECTURAL COMPONENTS — NATURAL HAZARD PROVISIONS

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
Elect./Mech. Equip	ASCE-7	earthquake, wind, ice	earthquake, wind, ice	
	ASCE TCLEE 1984	earthquake	earthquake	•
	ASME BPV[3]	none[2]	earthquake, wind	
	NFPA[4]	earthquake	earthquake	
	IBC, SBC, UBC	earthquake, wind	earthquake, wind	
	SMACNA	earthquake	earthquake	•
Suspended Ceilings	IBC, SBC, UBC	earthquake	earthquake	
Elevated Floors				

NOTES

1. Documents in **bold italics** indicate that the guidelines were not produced by a consensus process as defined for SDO's approved by the American National Standards Institute

2. "none" applies if a guideline or standard does not specifically identify how loads are to be obtained; if a group of standards is referenced, the natural hazard listed may be only covered in one document

3. ASME BPV refers to the ASME Boiler and Pressure Vessel Code that typically governs the design of all pressurized containers

4. NFPA refers to various NFPA standards governing fire protection systems

5. AWWA D refers to various AWWA standards governing water storage tanks

6. "System Reliability" is a component of design referring to practices that are specifically developed to provide reasonable assurance that consequences of a natural hazard on system service will meet the goals established by stakeholders (owners, operators, regulators, insurers, customers, and users). Consequences are defined by multiple performance requirements but typically include impact on public safety, duration of service interruption, and costs to repair damage.

7. **Existing** indicates that analysis or design procedures (NOT LOADS) could be applied for existing components

8. **Loading** refers to whether or not specific loads for various natural hazards are defined; "Design" refers to the existence of design and/or analysis procedures that account for loads arising from natural hazards

Figure 1.1   Matrix of performance standards and guidelines for lifelines [ALA 2004].

1.2 PROPOSED ENGINEERING FRAMEWORK

The engineering framework proposed in this report is an adaptation of the framework used to design and evaluate the safety of nuclear power plants in the United States. This report leverages findings from both the community resilience and lifeline interdependencies fields to create a transparent, performance-based, and risk-informed engineering framework that can be used to establish a consistent set of performance targets for the built environment and its many subsystems and components to enhance the overall resilience of the community. It addresses an important gap that exists in how the current regulatory framework establishes performance objectives for individual components within the built environment (e.g., buildings, bridges, pipelines, electrical grids, etc.). Currently, performance objectives for individual components are not tied to broader performance goals for the community, resulting in inconsistent and sometimes inappropriate performance targets for individual components within the built environment.

The proposed engineering framework provides a quantitative methodology for explicitly linking performance targets for individual components to broader goals for the entire community. This linkage is especially important in the context of improving community resilience for two reasons. First, a well-articulated set of performance goals provides communities tangible targets to strive toward. Second, an explicit set of community performance goals can serve as the basis for a more consistent set of performance objectives for individual components within the built environment, thus ensuring that individual components perform in a manner that is compatible with the best interests of the entire community.

1.2.1 Scope

A community is a dynamic and multi-faceted system of people, organizations, interactions, and infrastructure. This report, however, focuses primarily on the built environment because of the important role it plays in enabling a community to function successfully, providing the physical foundations for much of the economic and social activities that characterize a modern society [O'Rourke 2007]. At the same time, it is important to recognize that other aspects of a community (e.g., people, organizations, and political, social, and economic environments) can significantly influence how a community plans for, responds to, and recovers from a major disaster. This report acknowledges these other aspects to the extent that it is appropriate.

Much like a community itself, the regulatory framework that dictates how a community and its numerous components must operate is a complex system of regulations, enforcement mechanisms, and guidance. Again, this report focuses on a small but important piece of this regulatory framework: the building codes and other engineering standards that establish performance expectations, either implicit or explicit, for a community's built environment. Other parts of a community's regulatory framework, including planning, land use, and zoning regulations, can impact how the built environment develops and performs; however, this report does not explicitly address these items.

In addition, the proposed engineering framework seeks to improve community resilience primarily through mitigation, in particular through changes to building codes and other

engineering standards that improve how the built environment performs in earthquakes and other natural hazards. There are other actions that can enhance community resilience, including development of comprehensive emergency response and recovery plans, but again, these are not the focus of this report.

Lastly, while the intent of the proposed engineering framework is to remain broadly applicable to all types of hazards, it is developed with earthquakes in mind. As such, it may require modification if addressing other types of hazards.

1.2.2 Intellectual Contribution

To date, much of the research in the community resilience field has focused on defining and measuring resilience from a social sciences' perspective. This report brings a distinct engineering perspective to the field of community resilience. Using the nuclear framework as a template, this report demonstrates how these resilience measures, which are often qualitative in nature, can be translated into quantitative engineering performance targets for components and subsystems within the built environment.

The primary intellectual contributions of this report are as follows:

1. Identification and description of a comprehensive list of attributes of an ideal regulatory framework

2. Adaptation of a methodology originally developed for design and evaluation of nuclear power plants to be used in the design and evaluation of the built environment of communities

3. Demonstration of a procedure that enables derivation of consistent performance objectives for individual components from community-level performance targets

The work presented in this report has the potential to improve the way engineers, planners, and other stakeholders design and evaluate the built environment of a community. The framework and methodology proposed herein provide a transparent, structured blueprint both for planners and policymakers to set community-level performance targets and, subsequently, for engineers to calibrate the designs of individual components to meet these community-level performance targets. Together, the findings presented in this report establish the foundations for a much-needed transformation from engineering individual components of the built environment on a component-by-component basis to engineering community resilience using an integrated and coordinated approach that begins at the community level.

1.3 ORGANIZATION OF THE REPORT

The following report comprises two main parts. The first part, Chapters 2, 3, and 4, provides background information and demonstrates the need for the proposed engineering framework. The second part, Chapters 5, 6, and 7, describes the proposed engineering framework and

demonstrates several potential applications. The following paragraphs describe each chapter in more detail.

Chapter 2 reviews existing literature from the community resilience and lifeline interdependencies fields in order to demonstrate the need for the engineering framework described in the second part of this report. It also defines important terms and concepts used throughout the rest of this report, many of which can have different meanings depending on the context. Last, Chapter 2 introduces a list of attributes that characterize an ideal regulatory framework. These attributes will be used in Chapter 3 to give structure to a critical analysis of the current regulatory framework for the built environment.

Chapter 3 describes the current regulatory framework used in the United States to design and analyze the built environment of a typical community. It examines both the structure of the framework and the design philosophy it codifies, focusing in particular on the building codes and other engineering documents that establish seismic performance expectations for the built environment. Using the list of attributes of an ideal regulatory framework from the previous chapter, it discusses the strengths and shortcomings of the current regulatory framework, ultimately providing further justification for the engineering framework proposed in subsequent chapters of this report

Chapter 4 examines the regulatory framework currently used in the United States to design and analyze nuclear power plants. It identifies and defines important nuclear terminology and concepts that are used throughout the rest of the report, including undesired outcomes, vital functions, and frontline and support systems. The design philosophy codified in the current regulatory framework is described next. Lastly, it discusses several performance evaluation tools that nuclear engineers use to analyze the response of nuclear power plants, including probabilistic risk assessments, dependency matrices, and event and fault trees. These tools are then adapted for use in the engineering framework proposed in the second part of the report.

Chapter 5 begins the presentation of the proposed engineering framework for design and evaluation of the built environment. It extends and applies the general nuclear design philosophy described in Chapter 4 to communities. In particular, it discusses the range of potential undesired outcomes that can affect a community and the vital community functions that prevent these undesired outcomes from occurring. It also lists the frontline and support systems within the built environment that enable the vital community functions. Lastly, it describes how the performance evaluation tools presented in Chapter 4 are adapted for use in a community setting.

Chapter 6 presents and describes a set of community event trees that forms the backbone of the proposed engineering framework. Event trees provide a structured methodology for enumerating and, subsequently, evaluating the numerous combinations of events that can result in undesired outcomes for a community. Chapter 6 begins by outlining the conditions under which the event trees should be used before discussing their general structure and organization. Chapter 6 presents a set of four event trees corresponding to the vital functions in a community and details the rationale used to develop each one.

Chapter 7 presents two conceptual examples that demonstrate potential applications of the engineering framework described in Chapters 5 and 6. The first example demonstrates how the event trees from the previous chapter can be used to establish consistent performance objectives for individual components from a community-level performance target. More specifically, the example shows how to develop seismic performance targets for a new residential building from a community-level performance objective. Ultimately, this example outlines a procedure that can be used both to modify the implicit performance objectives contained in building codes and to lay the conceptual foundations of a "community performance code," a document that contains explicit performance targets for a community and the numerous components and subsystems of its built environment. The second example outlines a methodology that can be used to estimate the disruption to a community's services caused by an earthquake or other natural hazard.

Chapter 8 presents conclusions and discusses future work. Specifically, it outlines the work that remains in refining and expanding the framework presented in previous chapters. In addition, it discusses implications for the current regulatory framework, including the changes required before the proposed framework can be implemented in practice.

2 Background and Definitions

This chapter has three primary objectives. First, it reviews existing literature from the community resilience and lifeline interdependencies fields to demonstrate the need for the engineering framework described in later chapters of this report. This literature review reveals that, to date, most research has focused on defining and measuring community resilience and lifeline interdependencies (i.e., the evaluation side of resilience and lifeline performance). Less attention, however, has been given to the design side, including how to establish a consistent set of specific performance goals for a community and its built environment that, if achieved, will enhance overall community resilience. Second, to avoid any potential confusion, this chapter defines important terms and concepts used throughout this report, many of which can have different meanings depending on the context. Third, this chapter introduces a list of attributes that characterize an ideal regulatory framework. These attributes will be used in Chapter 3 to give structure to a critical analysis of the current regulatory framework for the built environment.

2.1 LITERATURE REVIEW

The following subsections discuss several important studies from the fields of community resilience and lifeline interdependencies. In particular, Section 2.1.1 summarizes the findings of Bruneau et al. [2003], Miles and Chang [2003, 2006, 2007], Poland et al. [2009], Twigg [2009], SERRI and CARRI [2009], and Cutter et al. [2010]; Section 2.1.2 summarizes Rinaldi et al. [2001], Barkley [2009], and others. Ultimately, these two subsections help demonstrate the need for the engineering framework described in later chapters of this report.

2.1.1 Community Resilience

The field of community resilience developed in response to the observation that, while the current regulatory framework for the built environment has been successful in reducing casualties in recent disasters in the United States, it does little to mitigate the damage and disruption caused by hazards. To date, most research in the field has focused on defining resilience and establishing metrics to quantify it. The conceptual resilience framework proposed by Bruneau et al. [2003] has been instrumental in both regards. The authors define resilience as "the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize

social disruption and mitigate the effects of future earthquakes." They describe four properties of resilience (robustness, redundancy, resourcefulness, and rapidity) and four dimensions of resilience (technical, organizational, social, and economic). Table 2.1 and Table 2.2 explain, respectively, the four properties and four dimensions in further detail.

Table 2.1   Four properties of resilience (adapted from Bruneau et al. [2003]).

Property	Description
Robustness	The ability of systems, components, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function
Redundancy	The extent to which systems, components, and other units of analysis exist that are substitutable
Resourcefulness	The capacity to identify problems, establish priorities, and mobilize resources when faced with conditions that threaten to disrupt some system, component, or other unit of analysis
Rapidity	The capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption

Table 2.2   Four dimensions of resilience (adapted from Bruneau et al. [2003]).

Dimension	Description
Technical	The ability of physical systems (including components, systems, and their interactions) to perform to acceptable/desired levels when subject to earthquake forces
Organizational	The capacity of organizations that manage critical facilities and have the responsibility for carrying out critical disaster-related functions to make decisions and take actions that contribute to achieving the four properties of resilience
Social	The capacity to lessen the extent to which earthquake-stricken communities and governmental jurisdictions suffer negative consequences due to the loss of critical services as a result of earthquakes
Economic	The capacity to reduce both direct and indirect economic losses resulting from earthquakes

Bruneau et al. [2003] proposed measuring resilience using three complementary metrics: probability of failure, consequences of failure, and recovery time. Figure 2.1 illustrates these metrics graphically, with the vertical axis measuring the consequences of failure and the horizontal axis measuring recovery time. It portrays three cases (A, B, and C). Each case has the same initial loss (i.e., consequences of failure) after the disaster; however, each has a different time to recovery. For simplicity, a community is assumed to have "fully recovered" when it restores 100% of its pre-disaster functionality. As shown in Figure 2.1 [Miles and Chang 2006], the community depicted in Case C never fully recovers, whereas the community in Case B recovers in the shortest amount of time and actually achieves a higher level of functionality than existed before the disaster (i.e., Case B is more resilient). In general, resilient communities are those that have reduced probabilities of failure, reduced consequences of failure, and reduced time to recovery.

The work done by Bruneau et al. [2003], though conceptual in nature, was an important step in attempting to quantify community resilience. Other important studies include Miles and Chang [2003, 2006, 2007], Cutter et al. [2010], Twigg [2009], and SERRI and CARRI [2009]. The following paragraphs summarize the principal contributions of each study to the resilience literature.

Building upon concepts introduced in Bruneau et al. [2003], Miles and Chang [2003, 2006, 2007] developed ResilUS, a computer program based on a comprehensive conceptual model of community recovery. This conceptual model "enumerates important relationships between a community's households, businesses, lifelines, and neighborhoods" [Miles and Chang 2006]. Figure 2.2 shows schematically the relationships among these four groups. The ultimate goal of the conceptual model is to "facilitate better understanding of the community recovery process in hopes that decision makers and citizens can increase their community's resilience against disaster" [Miles and Chang 2006]. To this end, ResilUS can be used to track community recovery at varying levels of detail, ranging from individual households and businesses to entire lifeline networks and neighborhoods. However, Miles and Chang [2003, 2006, 2007] stop short of recommending specific recovery targets that will enhance community resilience.

Cutter et al. [2010] established a set of baseline resilience indicators for communities. These indicators can be used to measure both the resilience of a particular community and the effectiveness of programs and policies that aim to improve disaster resilience. Cutter et al. [2010] identify 36 indicators, which are grouped into five main categories: social resilience, economic resilience, institutional resilience, infrastructural resilience, and community capital. Table 2.3 lists all 36 indicators. The resilience score for a community is an aggregation of each indicator, and can range between zero and five, with zero being the least resilient and five being the most. Using this information, specific programs and policies can be developed to target those resilience indicators that are deficient. However, Cutter et al. [2010] stop short of recommending specific resilience scores for which communities should aim.
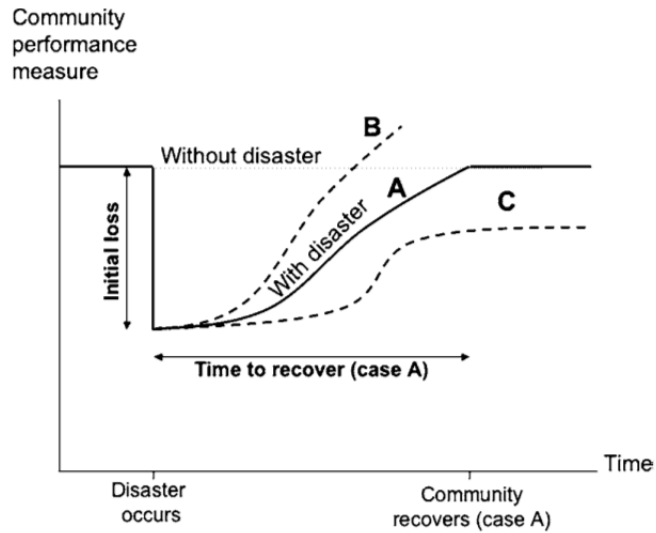
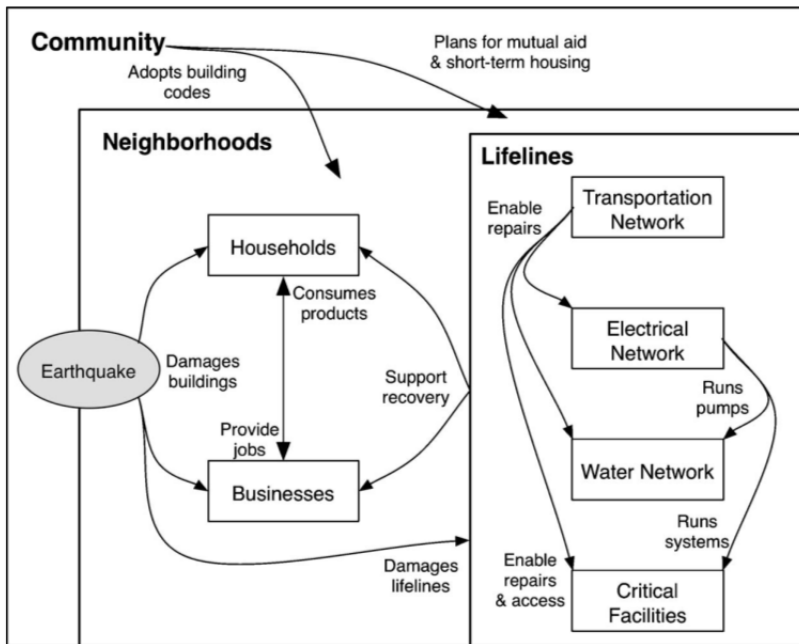**Figure 2.1   Schematic of disaster recovery [Miles and Chang 2006].**

Figure 2.2   Overview of conceptual model of community recovery from earthquakes [Miles and Chang 2006].

Table 2.3   **Baseline resilience indicators for U.S. communities (adapted from Cutter et al. [2010]).**

Category	Indicator
Social resilience	Educational equity: ratio of percent population with college education to percent population with no high school diploma Age: percent non-elderly population Transportation access: percent population with a vehicle Community capacity: percent population with a telephone Language competency: percent population not speaking English as second language Special needs: percent population without a sensory, physical, or mental disability Health coverage: percent population with health insurance coverage
Economic resilience	Housing capital: percent homeownership Employment: percent employed Income and equality: GINI coefficient Single sector employment dependence: percent population not employed in farming, fishing, forestry, and extractive industries Employment: percent female labor force participation Business size: ratio of large to small business Health access: number of physicians per 10,000 population
Institutional resilience	Mitigation: percent population covered by recent hazard mitigation plan Flood coverage: percent housing units covered by NFIP policies Municipal services: percent municipal expenditures for fire, police, EMS Mitigation: percent population participating in Community Rating System for flood Political fragmentation: number of governments and special districts Previous disaster experience: number of paid disaster declarations Mitigation and social connectivity: percent population covered by Citizen Corps programs Mitigation: percent population in Storm Ready communities
Infrastructural resilience	Housing type: percent housing units that are not mobile homes Shelter capacity: percent vacant rental units Medical capacity: number of hospital beds per 10,000 population Access/evacuation potential: principle arterial miles per square mile Housing age: percent housing units not built before 1970 and after 1994 Sheltering needs: number of hotels/motels per square mile Recovery: number of public schools per square mile
Community capital	Place attachment: net international migration Place attachment: percent population born in state that still resides in state Political engagement: percent voter participation in 2004 election Social capital (religion): number of religious adherents per 10,000 population Social capital (civic involvement): number of civic organizations per 10,000 population Social capital (advocacy): number of social advocacy organizations per 10,000 population Innovation: percent population employed in creative class occupations

Twigg [2009] identified 28 components of resilience, which are organized into five thematic areas: governance, risk assessment, knowledge and education, risk management and vulnerability reduction, and preparedness and response. Table 2.4 lists each of these 28 components. For each component of resilience, Twigg [2009] enumerates a more specific and detailed set of characteristics of disaster-resilient communities that "brings users closer to reality on the ground." Table 2.5 lists the characteristics of a disaster-resilient community corresponding to the "Hazards/risk data and assessment" component of resilience within the "Risk assessment" thematic area (see Table 2.4). In total, Twigg [2009] lists 167 characteristics of disaster-resilient communities. The resilience of a particular characteristic or thematic area is evaluated on a scale from one to five, with one being the least resilient and five being the most. However, Twigg [2009] stops short of recommending specific targets for which communities to aim.

Table 2.4   Components of resilience [Twigg 2009].

Thematic area	Components of resilience
Governance	- Policy, planning, priorities and political commitment - Legal and regulatory systems - Integration with development policies and planning - Integration with emergency response and recovery - Institutional mechanisms, capacities and structures; allocation of responsibilities - Partnerships - Accountability and community participation
Risk assessment	- Hazards/risk data and assessment - Vulnerability/capacity and impact data and assessment - Scientific and technical capacities and innovation
Knowledge and education	- Public awareness, knowledge and skills - Information management and sharing - Education and training - Cultures, attitudes, and motivation - Learning and research
Risk management and vulnerability reduction	- Environmental and natural resource management - Health and well being - Sustainable livelihoods - Social protection - Financial instruments - Physical protection; structural and technical measures - Planning regimes
Disaster preparedness and response	- Organizational capacities and coordination - Early warning systems - Preparedness and contingency planning - Emergency resources and infrastructure - Emergency response and recovery - Participation, voluntarism, accountability

Table 2.5   **Characteristics of a disaster-resilient community corresponding to a specific component of resilience [Twigg 2009].**

Thematic Area 2: Risk Assessment	Characteristics of a disaster-resilient community
Component of resilience 1: Hazards/risk data and assessment	• Community hazard/risk assessments carried out which provide comprehensive picture of all major hazards and risks facing community (and potential risks) • Hazard/risk assessment is participatory process including representatives of all sections of community and sources of expertise • Assessment findings shared, discussed, understood and agreed among all stakeholders, and feed into community disaster planning • Findings made available to all interested parties (within and outside community, locally and at higher levels) and feed into their disaster planning • Ongoing monitoring of hazards and risks and updating of assessments • Skills and capacity to carry out community hazard and risk assessments maintained through support and training

The Southeast Region Research Initiative (SERRI) and Community and Regional Risk Institute (CARRI) defined three broad groups of community functions that healthy and vibrant communities provide to their residents [SERRI and CARRI 2009]. The first group includes infrastructure-based functions like energy, water, and transportation. The second group involves economic functions like employment opportunities, adequate wages, and affordable housing options. And the third group includes social functions like community ownership and participation, education and training opportunities, and a sense of community and place. Figure 2.3 shows these three groups of functions and their interactions. The innermost ring represents the infrastructure-based functions, which must be restored first following a disaster. The middle ring represents the economic functions of a community, which cannot be restored until infrastructure-based functions are recovered. The outermost ring represents the social functions of a community, which cannot be restored until both infrastructure and economic functions are recovered.

As mentioned previously, much of the research in the community resilience field has, thus far, focused on defining and measuring community resilience (i.e., the evaluation side of resilience). Less effort has gone into the design side: in particular, if communities want to enhance or improve their resilience to disasters, exactly what level of performance is required from buildings and lifelines? The San Francisco Planning and Urban Research Association (SPUR) established a comprehensive set of performance objectives that, if achieved, will enhance the City of San Francisco's resilience to earthquakes. Specifically, this set of objectives aims to have the city "back on its feet" four months after a magnitude 7.2 earthquake on the Peninsula segment of the San Andreas fault [Poland et al. 2009]. Figure 2.4 displays the set of

performance objectives for the entire city as a function of time, while Figure 2.5 displays more specific performance objectives for important classes of buildings and lifelines. Figure 2.5 also shows the current level of performance expected from each piece of infrastructure (the "X" mark) relative to its specified target (the shaded box).
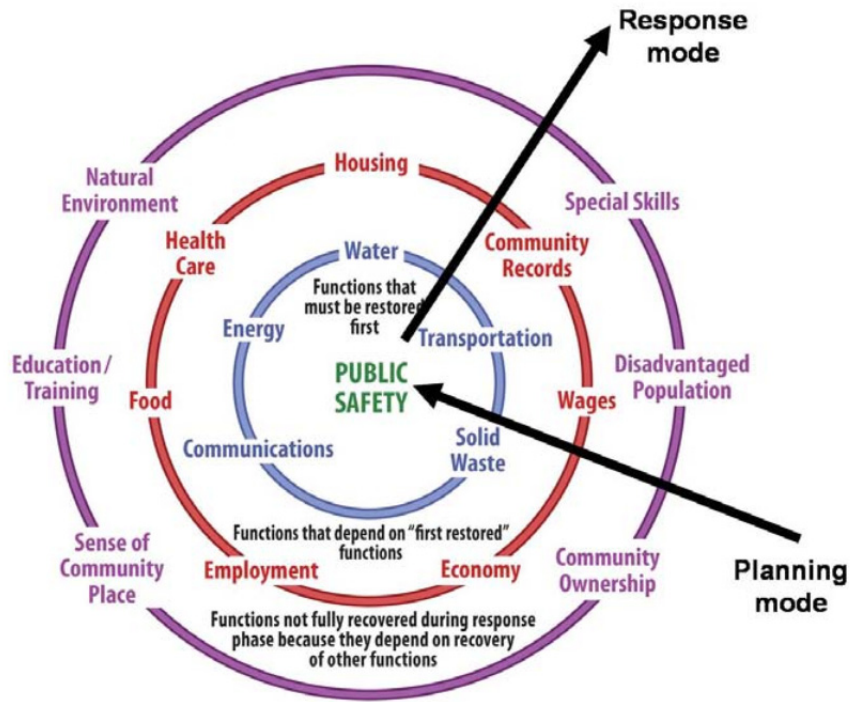

Figure 2.3   Important community functions [SERRI and CARRI 2009].

DEFINING STAGES OF DISASTER RECOVERY

PHASE	TIMEFRAME	CONDITION OF THE BUILT ENVIRONMENT
1	1 to 7 days	Initial response and staging for reconstruction
	Immediate	Mayor proclaims a local emergency and the City activates its Emergency Operations Center. Hospitals, police stations, fire stations, and City department operations centers are operational.
	Within 4 hours	People who leave or return to the city in order to get home are able to do so. Lifeline systems that support critical response facilities are operational.
	Within 24 hours	Emergency response workers are able to activate and their operations are fully mobilized. Hotels designated to house emergency response workers are safe and usable. Shelters are open. All occupied households are inspected by their occupants, and less than 5 percent of all dwelling units are found unsafe to be occupied. Residents can shelter in place[1] in superficially damaged buildings even if utility services are not functioning.
	Within 72 hours	Ninety percent of the utility systems (power, water, wastewater, natural gas and communication systems) are operational and serving the facilities supporting emergency operations and neighborhoods. Ninety percent of the major transportation system routes, including Bay crossings and airports, are open at least for emergency response. The initial recovery and reconstruction efforts will be focused on repairing residences and schools to a usable condition, and providing the utilities they need to function. Essential City services are fully restored.
2	30 to 60 days	Housing restored — ongoing social needs met
	Within 30 days	All utility systems and transportation routes serving neighborhoods are restored to 95 percent of pre-event service levels, public transportation is running at 90 percent capacity, public schools are open and in session. Ninety percent of the neighborhood businesses are open and serving the workforce. Reconstruction efforts will be focused on repairing residences, schools and medical provider offices to a usable condition, and providing the utilities they need to function. Essential City services are fully restored and medical provider offices are usable..
	Within 60 days	Airports are open for general use, public transportation is running at 95 percent capacity, minor transportation routes are repaired and reopened.
3	Several years	Long-term reconstruction
	Within 4 months	Temporary shelters are closed, with all displaced households returned home or permanently relocated. Ninety-five percent of the community retail services are reopened. Fifty percent of the non-workforce support businesses are reopened.
	Within 3 years	All business operations, including all City services not related to emergency response or reconstruction, are restored to pre-earthquake levels.

Source: SPUR analysis

Figure 2.4   General performance objectives for San Francisco as a function of time [Poland et al. 2009].

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

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

Source: SPUR analysis

TARGET STATES OF RECOVERY

Perfor-mance measure — Description of usability after expected event

BUILDINGS — LIFELINES

Category A: Safe and operational

Category B: Safe and usable during repairs — 100% restored in 4 hours

Category C: Safe and usable after moderate repairs — 100% restored in 4 months

× Expected current status

Figure 2.5 **Specific performance objectives for San Francisco's buildings and infrastructure as a function of time [Poland et al. 2009].**

The work of SPUR and Poland et al. [2009] is unique because it establishes explicit performance objectives for the city to improve its disaster resilience. To date, most resilience studies, including Miles and Chang [2003, 2006, 2007], Cutter et al. [2010], Twigg [2009], and SERRI and CARRI [2009], focus on defining and measuring resilience, but stop short of establishing concrete targets to aim at, thereby leaving the following question unanswered: when is a community resilient enough? Poland et al. [2009] provides a clear answer for the city of San Francisco.

This report builds on these efforts, proposing an engineering framework that can be used by communities to establish a consistent set of performance targets for individual subsystems and components within the built environment (e.g., buildings and lifelines) in order to enhance overall community resilience. In the end, this set of performance targets may resemble those described by Poland et al. [2009] (see Figure 2.4 and Figure 2.5); however, they will be developed using a more robust, transparent, and technically grounded engineering framework. As such, the proposed framework provides the technical justification for the performance objectives described by Poland et al. [2009].

2.1.2 Lifeline Interdependencies

Lifelines are a critical piece of a community's infrastructure, providing sustenance to both residents (water networks deliver drinking water to homes; transportation networks deliver food to grocery stores; energy lifelines deliver the fuel needed to heat residences) and businesses (roads and highways enable the flow of goods and services; energy networks deliver power to factories and office buildings). In spite of their importance, both in day-to-day operations and in recovering after a major disaster, lifelines have received considerably less attention than buildings. Barkley [2009] described some of the unique challenges associated with lifelines:

> *In general, a lifeline system incorporates a wide range of elements necessary for system operation, including linear components; mechanical, electrical, and electronic equipment; buildings containing system components; operating centers; and other supporting elements. The circumstances under which individual elements may fail vary widely, as do applicable design guidelines and standards. The performance of the entire system is as critical as the performance of individual elements; however, damage to individual elements may be sufficient to shut down part or all of the system.*
>
> *Lifeline systems are also distinguished by their interdependency. The continued operation of a lifeline system, such as the communications network, may be dependent on the operation of another system, such as the power system. Similarly, the ability for system owners to restore their respective systems following an earthquake may be dependent on the condition of highways and other transportation elements.*

To date, most research in this field has focused on defining, identifying, monitoring, and measuring lifelines and their interdependencies. Many studies, including PCCIP [1997], Rinaldi

et al. [2001], Barkley [2009], and ALA [2004], identify and enumerate lists of critical lifelines within a community. This report adapts and combines these lists into the following set of lifelines: communication, energy (electric power, natural gas, oil, and solid fuels), transportation (roads and highways, mass transit, ports and waterways, railways, and airports), water, and waste disposal (waste water and solid waste).

Rinaldi et al. [2001] serves as an excellent primer on lifeline interdependencies. The authors define four principal classes of interdependencies (physical, cyber, geographic, and logical) and three types of failures (cascading, escalating, and common cause). Table 2.6 and Table 2.7 describe, respectively, the four classes of interdependencies and three types of failures in more detail and provide simple examples to help illustrate the concepts. The authors also identify the challenges associated with modeling lifelines and their interdependencies; however, they stop short of developing such a model.

Subsequent studies, including Haimes and Jiang [2001], Zhang et al. [2005], Dueñas-Osorio et al. [2007], Lee et al. [2007], Svendsen and Wolthusen [2007], Rosato et al. [2008], Ouyang et al. [2009], and Hernandez-Fajardo and Dueñas-Osorio [2011], have developed and implemented comprehensive models of lifeline networks and their interdependencies to measure and monitor their response to earthquakes and other hazards. While this work has been instrumental in improving the understanding of how these complex systems respond and interact with each other in the face of natural hazards, much of it has, thus far, focused on the evaluation side of the equation (i.e., real-time monitoring of network performance). Similar to the field of community resilience, less attention has been paid to the design side, including establishing appropriate performance targets for lifelines and their numerous components that support broader community resilience goals. One notable exception is Poland et al. [2009], which was described in the previous subsection (see Figure 2.4 and Figure 2.5).

This report leverages the knowledge of lifelines and their interdependencies gained from recent studies in order to inform the development of an engineering framework that can be used to establish appropriate performance objectives for lifelines.

Table 2.6   Four principal classes of lifeline interdependencies (adapted from Rinaldi et al. [2001]).

Class	Description	Example
Physical	Arises from a physical linkage between the inputs and outputs of two lifelines: a commodity produced or modified by one lifeline (an output) is required by another lifeline for it to operate (an input)	A railway delivers coal to a power generating station; the station supplies electricity to the railway's signals, switches, and control centers
Cyber	Arises when the functionality of a lifeline depends on information transmitted through the communications lifeline	The electric power lifeline relies on supervisory control and data acquisition (SCADA) systems to control the grid
Geographic	Occurs when elements of multiple lifelines are in close spatial proximity	An electrical line and a fiber-optic communications cable slung under a bridge
Logical	Arises when the functionality of each lifeline depends on the state of the other via a mechanism that is not a physical, cyber, or geographic connection	Low gas prices motivate more people to drive, resulting in increased congestion on roads and highways

Table 2.7   Three types of lifeline failures (adapted from Rinaldi et al. [2001]).

Type	Description	Example
Cascading	Occurs when a disruption in one lifeline causes the failure of a component in a second lifeline, which subsequently causes a disruption in the second lifeline	Disruption of a distribution network within the natural gas lifeline can result in a failure of an electricity generating unit located in the service territory of the gas system, which can cause power disruptions
Escalating	Occurs when an existing disruption in one lifeline exacerbates an independent disruption of a second lifeline, generally in the form of increasing the severity or the time for recovery or restoration of the second failure	A disruption to the communications network may escalate because of a simultaneous or subsequent disruption in a transportation network, which in turn could delay the arrival of repair crews and/or replacement equipment
Common cause	Occurs when two or more lifelines are disrupted at the same time: components within each network fail because of some common cause	A train derailment that damages railroad tracks could also disrupt communications cables and power lines that are located within the same corridor

2.2 DEFINITIONS

The following subsections provide concrete definitions and other background information for several important terms used extensively in this report, including system, hazard, performance, and regulatory framework. Each of these terms can have somewhat ambiguous meaning depending on the context; therefore, the objective of each of the following subsections is to clarify what these terms mean when used herein.

2.2.1 System

In general, a system is a dynamic entity comprising a collection of interacting, potentially correlated components assembled to perform an intended function or functions (adapted from Vesely et al. [1981], Buede [2000], ISO and IEC [2008], and Kossiakoff et al. [2011]). This report focuses on a particular subset of systems: those that are engineered for a specific purpose (e.g., buildings and lifelines). Throughout this report, these engineered systems will be referred to simply as systems. Note that components within a system can themselves be systems [Buede 2000]. For example, a building system comprises, among other things, a structural system, heating, ventilation, and air conditioning systems, and mechanical, electrical, and plumbing systems. Each of these systems, in turn, comprises various subsystems and components. For example, a structural system comprises beams, columns, braces, walls, and floors, to name only a few.

The following subsections discuss and expand upon the definition given above. This discussion, which is purposely generic, provides the foundation for a more detailed examination of communities, which themselves can be considered complex, dynamic, and adaptive systems.

2.2.1.1 Types of components

As defined above, a system is a collection of components (note that the interactions among these components are discussed in the next subsection). These components can be classified into seven general types: structures, hardware, people, organizations, procedures, environments, and interfaces (adapted from Buede [2000], Bea [2007, 2008], and NASA [2007]). Table 2.8 provides brief descriptions of each, listing specific examples from the built environment to further illustrate each type of component with the caveat that it might not always be possible to draw clear, unambiguous boundaries for each component. Figure 2.6 graphically portrays the relationships among the seven types of components. While engineers tend to focus on the physical elements in a system (i.e., structures and hardware), the other types of components can have strong influence over how the system behaves and responds.

Table 2.8   Description of the seven types of components in a system (adapted from Bea [2007, 2008]).

| Type	Description	Examples
Structures	The physical elements that support or protect the system and its functions	Buildings, bridges, dams
Hardware	The physical equipment that enables or facilitates the system and its functions	Electrical transformers, pumps, computers
People	Those who design, analyze, construct, operate, use, maintain, rehabilitate, and decommission the system (i.e., anyone who is involved in or impacted by the system during its lifecycle)	Engineers, architects, electricians, bus drivers, passengers
Organizations	The companies, institutions, or agencies involved with the system during its lifecycle	Design firms, government agencies, professional societies
Procedures	The rules and guidelines (formal and informal) that operators and organizations use to perform their activities	Laws, regulations, codes, ordinances
Environments	The conditions (external, internal, social, political, economic) in which people and organizations perform their activities	Weather conditions, company culture
Interfaces	The links that connect different components in the system together	Supply chains, Internet, physical proximity
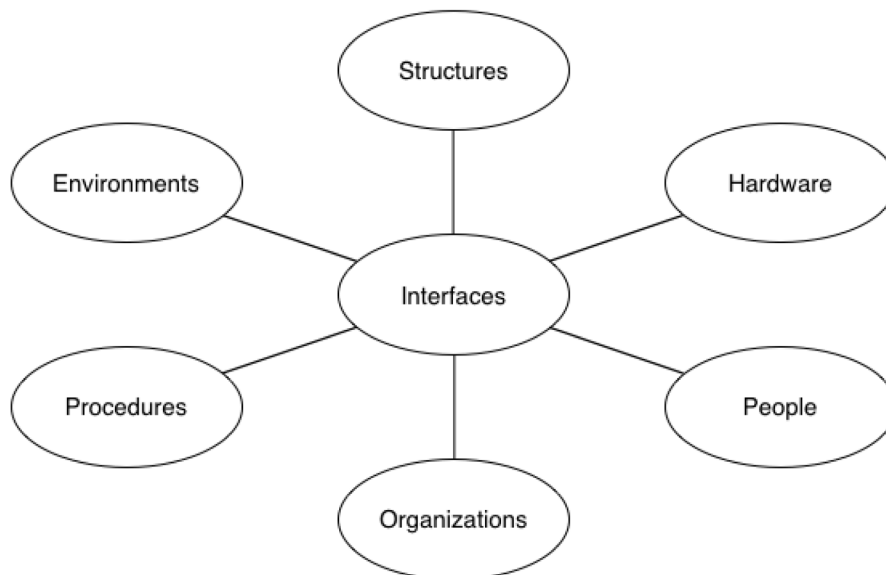
Figure 2.6   Relationships among the seven types of components in a system [Bea 2007 and 2008].

2.2.1.2 Interactions

A system is much more than a collection of components or simple sum of parts. It is the interactions among its components that enable a system to successfully perform its intended function or functions. These interactions can be very complex, especially if the system comprises many components, or very simple, as is the case for systems with configurations that are exclusively parallel or series [Billinton and Allan 1983]. In this report, these interactions will be referred to as dependencies and interdependencies. Dependency describes a unidirectional relationship between two components, meaning that one component depends on the other, but not vice versa [Rinaldi et al. 2001]. For example, a water pump depends on electricity delivered by the power grid; however, if the pump were to stop functioning it would not affect the functionality of the power grid. Interdependency, on the other hand, indicates a bidirectional relationship between two components, meaning both components depend on each other to function successfully [Rinaldi et al. 2001]. For example, an electrical generating station relies on natural gas to run its generators and produce electricity; conversely, electricity is required in the delivery of natural gas to the generating station.

Interactions are dynamic in nature. If the configuration of the system changes, the interactions among its components can also change. For example, as more and more businesses migrate from local to web-based computing, the dependence on Internet service providers also grows. As a result, a service disruption (caused by an earthquake, for example) will have greater impact on the local economy because of this increased dependency on the Internet.

2.2.1.3 Correlation

In addition to interacting with each other, components in a system may also be correlated. Correlation measures the relationship between the responses of two distinct objects. It typically arises from similarities in the design and/or location of the components [Dezfuli and Modarres 1985]. For example, the responses during an earthquake of two identical, adjacent houses will be highly correlated: if one fails during the earthquake, the other will also likely fail. Correlation differs from interaction in that there is no functional dependency or interdependency between the two components. For example, the functionality of one house does not, in general, directly affect the functionality of another, even if it is identical and located in close proximity. Therefore, the response of two identical, adjacent houses would be considered highly correlated but not functionally dependent or interdependent.

Systems with a large number of identical, co-located components are vulnerable to correlated failures, an event in which a large number of components fail simultaneously during an earthquake or other hazard, resulting in a potentially significant degradation in performance [Lin et al. 2012]. One way to address these correlated failures is to build sufficient diversity into the components of a system. For example, instead of installing two identical diesel generators, one can procure each from a different vendor to ensure they have varying designs. Alternatively, instead of placing the generators next to each other, one can locate them far enough apart that they do not experience similar effects from nearby hazards. Diversity and correlation are inversely related: as the diversity of components increases, correlation decreases.

2.2.1.4   Phases in the lifecycle of a system

A system is a dynamic entity: if the nature of any part of the system changes, the system itself changes [Vesely et al. 1981]. Its lifecycle comprises many phases, including conception, design, analysis, construction, operation, maintenance, rehabilitation, and decommission (adapted from Buede [2000], Wasson [2006], Blanchard and Fabrycky [2006], and Bea [2007, 2008]). This report focuses primarily on the design phase, examining the design frameworks that establish performance targets for complex systems, including nuclear power plants and communities. It is important to note, however, that subsequent phases, especially analysis and operation, need to be considered when establishing design targets for these systems.

2.2.1.5   System definition and analysis

Perhaps the most crucial characteristic of a system is that it is determinable. Determinable means that the system is identifiable and, more importantly, can be defined and subsequently analyzed.

System definition begins by establishing appropriate external boundaries for the system [Vesely et al. 1981]. These boundaries, which need not be purely geographic in nature, depend in part on the aspects of performance that are of interest. For example, if we want to compute the probability of a building collapsing in a particular earthquake scenario, the external boundary for the system will likely coincide with the geographical boundary of the building. If, on the other hand, we were interested in the probability that a building loses power following a specific earthquake scenario, the external boundary would need to be expanded to include the electrical grid that services the building. Consequently, external boundaries determine the comprehensiveness of the analysis.

It is important to note, however, that a system can be impacted by events and systems beyond its external boundaries [Buede 2000]. For example, businesses in a community can be impacted by an earthquake that strikes a distant city or region, especially if it disrupts the production of goods and services that local business rely on, as happened to carmakers in the United States following the 2011 Tohoku earthquake and tsunami that struck northern Japan. To the extent possible, these external events and system should be included in the system analysis.

Another important aspect of system definition involves establishing a limit of resolution for the system. Limits of resolution serve to define the discrete elements of the system and to establish the basic interactions within the system [Vesely et al. 1981]. They also limit the detail of the analysis. For example, if we want to compute the probability that a building collapses in an earthquake, the system would likely need to include key structural subsystems (e.g., gravity and lateral force-resisting subsystems) and components (e.g., beams, columns, braces, walls, floors, etc.), with the resulting fragility curve being quite specific. However, if we want to evaluate the vulnerability of a large group of buildings (for example, the housing stock of a community), it will not be practical to resolve the system down to the level of individual structural members for each building. Instead, it might be satisfactory to specify basic information about the gravity and lateral force-resisting systems for each building in the system, or even group the buildings into several broad categories based on key structural properties, and use generic fragility data.

Note that the external boundaries and/or limits of resolution may need to be updated as a better understanding of the system or issue under consideration emerges. For example, a previously unknown interaction with an external system will require the boundaries of the analysis to expand to include this system. Similarly, the limits of resolution for a system may need to be refined as its design moves beyond the conceptual stage.

Only after a system has been properly defined can it be analyzed. The type of analysis performed depends on the aspects of performance that are of interest. In general, two analytical approaches exist: reductive and expansive [Bea 2007, 2008]. Reductionism involves the following steps:

- Identify the components in a system

- Study the behavior of individual components

- Derive an understanding of the behavior of the system from the behavior of individual components

Expansionism is the complement of the reductive process and involves the following steps [Bea 2007, 2008]:

- Identify the system

- Study the behavior of the entire system

- Derive an understanding of the behavior of individual components from the behavior of the system

This report proposes and develops an engineering framework that employs an expansionist (i.e., comprehensive, integrated, and coordinated) approach in order to enhance community resilience. Specifically, it begins at the system level by establishing explicit performance goals for the entire community. Then, using these community-level targets, it studies the system to identify key community functions that need to be available in order for a community to satisfy its specified targets. Lastly, after identifying these key functions, the framework identifies components and subsystems within the built environment that support these functions, and establishes appropriate performance objectives for individual components that are consistent with previously established community-level goals.

2.2.1.6 Attributes of an ideal system

In the context of this report, the word "ideal" refers to an abstract or hypothetical optimum; therefore, an ideal system may not be realistic. It does, however, represent a desirable end point that, to the extent practical, should be aspired to. In general, ideal systems have the following attributes: they are safe, serviceable, compatible, durable, and analyzable (adapted from Minai et al. [2006] and Bea [2007, 2008]). The following paragraphs discuss each in further detail.

First, an ideal system is safe, meaning it does not pose undue threat to the health and safety of the operators, general public, and surrounding environment. This attribute is of fundamental importance and is often the focus of most regulations for a system. Another aspect

of safety is security. Security involves an absence of vulnerability to malevolent events (e.g., terrorism, sabotage, etc.).

Second, an ideal system is serviceable, meaning it is highly suited for its intended purpose. It should not be used for purposes other than those for which it was originally intended. For example, a building originally designed for lightweight office space should not be used for heavy manufacturing, at least not without substantial retrofit. In addition, the system should not operate under conditions that exceed those for which it was initially designed. For example, a crane with 20-ton capacity should not be used to lift a 25-ton section of a bridge.

Third, an ideal system is compatible, meaning it does not have excessive negative impact on society and the surrounding environment. Its performance aligns with societal expectations. It uses resources in an efficient and sustainable manner—one that minimizes operating costs and consequences while protecting the ability of future generations to operate similar systems [WCED 1987].

Fourth, an ideal system is durable, meaning it maintains its safety, serviceability, and compatibility throughout its lifecycle. Consequently, it is reliable, robust, resilient, and redundant. A reliable system has high likelihood of remaining functional over time. A robust system can tolerate significant amounts of damage or a large number of defects and errors without losing functionality and, therefore, is insensitive to small perturbations. A resilient system can recover functionality quickly following a disruption or disturbance. A redundant system comprises several independent, diverse paths for ensuring functionality.

Finally, an ideal system is analyzable, meaning it features a design or configuration that enables reliable and accurate analysis of its response to a wide range of hazard scenarios. Similarly, the design of a system should also be sufficiently constructible, operable, maintainable, and repairable.

2.2.2 Hazard

In the most general sense, a hazard is a potential source of danger. Typically, it refers to a threat that is unrealized but has potential to occur in the future. More specifically, the Federal Emergency Management Agency (FEMA) defines a hazard as "any event or condition with the potential to cause fatalities, injuries, property damage, infrastructure damage, agricultural loss, environmental damage, business interruption, or other loss" [FEMA 1997]. Hazards can be either natural or human-made. Regarding this distinction, the Organization of American States writes [OAS 1991]:

> *A widely accepted definition characterizes natural hazards as "those elements of the physical environment, harmful to man and caused by forces extraneous to him" [Burton et al. 1978]. More specifically… the term "natural hazard" refers to all atmospheric, hydrologic, geologic (especially seismic and volcanic), and wildfire phenomena that, because of their location, severity, and frequency, have the potential to affect humans, their structures, or their activities adversely. The qualifier "natural" eliminates such exclusively manmade phenomena as war, pollution, and chemical contamination.*

Hazards to human beings not necessarily related to the physical environment, such as infectious disease, are also excluded from consideration here.

Notwithstanding the term "natural," a natural hazard has an element of human involvement. A physical event, such as a volcanic eruption, that does not affect human beings is a natural phenomenon but not a natural hazard. A natural phenomenon that occurs in a populated area is a hazardous event… In areas where there are no human interests, natural phenomena do not constitute hazards… This definition is thus at odds with the perception of natural hazards as unavoidable havoc wreaked by the unrestrained forces of nature. It shifts the burden of cause from purely natural processes to the concurrent presence of human activities and natural events.

The terminology contained in the above excerpt is adopted in this report. Furthermore, the scope of this report is similar to that outlined above. However, even if a hazardous event does not immediately or directly affect any human interests, it can still have profound impact. For example, a volcanic eruption on a remote island may not directly harm any human activities, but it could destroy important natural habitats and alter global weather patterns, producing crop failures and food shortages. These effects are important but difficult to address or plan for. Therefore, this report focuses mainly on the more direct, immediate effects of hazards on a system. Specifically, this report focuses on the effects arising from natural hazards like earthquakes.

2.2.2.1 Multiple effects of hazards

In some instances, a natural hazard can produce multiple effects. For example, a hurricane can produce a combination of violent wind (including tornados), torrential rain, and damaging storm surge. Similarly, an earthquake can produce ground shaking, surface rupture, lateral spreading, liquefaction, tsunamis, and landslides. A natural hazard can also induce human-made hazards. For example, an earthquake can trigger large fires if gas lines rupture throughout a community [Scawthorn 2003b]. It can also produce extensive flooding if nearby dams or levees fail as a result of an earthquake. These induced hazards can have as much impact as the primary hazard and, therefore, should be accounted for when performing a hazard analysis for a system. Furthermore, the effects of a hazard can vary from location to location. For a spatially distributed system subject to earthquakes (e.g., the electrical grid in Los Angeles), areas closest to nearby faults will likely experience stronger shaking than those farther away. Also, portions of the system founded on soft soil may experience amplified shaking relative to locations founded on rock.

2.2.2.2 Hazard analysis

Each system faces a unique set of hazards that depends on the surrounding natural and human-made environment. System designers and operators must carefully analyze the system's surroundings in order to properly identify and characterize potential hazards. Only after thoroughly evaluating these hazards can operators plan and prepare accordingly. A hazard analysis for a system identifies potential sources of hazard, as well as the range and frequency of hazard scenarios that each source may produce.

A hazard analysis can be either deterministic or probabilistic. In a deterministic hazard analysis, one particular hazard scenario is evaluated. This scenario might, for example, postulate the occurrence of a hazard with a specific size and location (e.g., a magnitude 7.6 earthquake on a particular fault segment). Such an analysis would be appropriate if attempting to establish a worst-case scenario for a particular hazard source. A deterministic hazard analysis, however, neglects to include uncertainties in the hazard such as its size, location, and frequency of occurrence. A probabilistic hazard analysis, on the other hand, provides a framework that identifies, quantifies, and combines these uncertainties to obtain a more complete picture of the hazard [Kramer 1996]. A probabilistic hazard analysis includes all possible hazard scenarios and combines them using the frequency of occurrence of each scenario. For this reason, a deterministic hazard analysis corresponds to a particular scenario in a probabilistic hazard analysis [Thenhaus and Campbell 2003].

2.2.3 Performance Measures

In the context of this report, performance refers to the ability of a system or component to achieve objectives and targets pertaining to its functionality, safety, or costs. Typical performance measures for buildings include casualties, lifecycle costs, and time to restore functionality (i.e., downtime). In contrast, response refers to the physical behavior of a system when subjected to a stress or stimulus (e.g., earthquake ground shaking or liquefaction). Traditional response measures for buildings include forces, accelerations, displacements, and drifts.

As the definition above indicates, system performance is typically evaluated relative to specified targets or objectives. These performance targets or objectives can take many different forms, depending on the system or component being considered and the desired outcomes. For example, if a building owner is only concerned with protecting the safety of occupants during an earthquake, performance objectives for the building will seek to minimize casualties. These performance objectives can be achieved, for example, by assuring that the response of the building during an earthquake remains within certain thresholds (e.g., peak interstory drift ratios less than 2%). On the other hand, if a building owner is also concerned with maintaining functionality after an earthquake, performance objectives for the building will seek to minimize downtime in addition to casualties.

While this report focuses primarily on the process of establishing performance objectives for a system and its components, an essential corollary to establishing performance objectives is evaluating whether or not they have been satisfied. Many techniques and methodologies exist for evaluating system performance; however, this report does not explicitly address them. That said, it is important to note that performance objectives influence the scope of the evaluation required for a particular system. For example, if the performance objectives for a building specify that it minimize casualties during an earthquake, then only its structural system needs to be analyzed, as most earthquake-related casualties are caused by structural collapse [BSSC 2009]. On the other hand, if performance objectives for the building specify that it remain functional following an

earthquake, then both the building (including its structural and nonstructural systems) and any supporting lifelines need to be evaluated.

2.2.4 Regulatory Framework

A regulatory framework provides the legal and technical basis for allowing a system to operate through all phases of its lifecycle. It comprises three basic elements: regulations, mechanisms for enforcing the regulations, and guidance for satisfying the regulations. The following paragraphs discuss each element in further detail.

Regulations include codes, standards, and other documents that specify the rules, requirements, and provisions for a system. Regulations typically exist in the public domain and carry the weight of law. If a system does not comply with regulations, it can potentially face a variety of penalties, ranging from fines and lawsuits to temporary or permanent shutdown of the system. Regulations typically arise in response to societal problems. For example, in the United States, building codes were developed to protect the public from unsafe living and working conditions brought about by poorly designed, constructed, and maintained buildings.

Enforcement mechanisms include the agencies and organizations charged with interpreting and enforcing the regulations. These agencies and organizations are commonly referred to as regulators. Enforcement is a crucial component in any framework. Without it, system operators and designers might ignore certain regulations if they impose significant cost or burden.

Guidance includes anything that aids in satisfying the regulations. It can range from written documents developed by technical societies (and later adopted by regulators) to electronic communications with regulators. Guidance is typically optional, providing one of many possible ways to satisfy the regulations. Often, however, guidance becomes the *de facto* means to satisfying the regulations and thus plays a crucial role in a regulatory framework.

2.3 ATTRIBUTES OF AN "IDEAL" REGULATORY FRAMEWORK

A regulatory framework is ideal when it produces systems that are also ideal (see Section 2.2.1 for a discussion of attributes of an ideal system). Again, the word "ideal" refers to an abstract or hypothetical optimum. Therefore, although an ideal regulatory may not be realistic, it represents a desirable end point that, to the extent practical, should be aspired to. In general, an ideal regulatory framework is expansionist, risk-informed, comprehensive, performance-based, probabilistic, technology-neutral, transparent, acceptable, feasible, consistent, and enforceable (adapted from the USNRC [1998] and ONRR [2007]). The following subsections describe a subset of these attributes, focusing on those that are most pertinent in the context of this report. This subset includes five attributes: expansionist, risk-informed, comprehensive, performance-based, and acceptable.

2.3.1 Expansionist Framework

An ideal regulatory framework employs an expansionist or top-down approach. In other words, it begins by establishing basic requirements for the entire system first [ONRR 2007]. This stands in contrast to a reductionist, bottom-up, or component-by-component approach in which requirements are first established for individual components without consideration of the performance of the system as a whole. A top-down approach is important because it sets the stage for the entire regulatory framework. It ensures that provisions for individual components are consistent with system-level requirements. Furthermore, it facilitates understanding of the intended performance of the system, unlike a bottom-up approach in which it may be difficult to determine the performance of the system, especially if the system comprises a large number of interactive and correlated components.

2.3.2 Risk-Informed Framework

An ideal regulatory framework contains requirements that are risk-informed, where risk is defined as the product of two quantities: (1) the likelihood or probability that an undesired event occurs; and (2) the consequences once it occurs. A risk-informed approach considers risk insights, together with other factors, to establish provisions and requirements for a component that are commensurate with its importance in protecting the health and safety of the public and environment [USNRC 1998]. In other words, the regulations for a particular component are proportional to its overall risk to safety or functionality. For example, if the failure of a particular component has limited impact on the safety or functionality of the system, a risk-informed regulatory framework would specify only limited provisions for the component. If, on the other hand, failure of a particular component has significant impact, a risk-informed regulatory framework would establish stringent performance requirements for the component. In contrast, a framework that is not risk-informed would specify the same performance requirements for both components regardless of their impact on system safety or functionality. In summary, a risk-informed regulatory framework focuses attention on those components within the system that are most important to overall safety and functionality.

2.3.3 Comprehensive Framework

An ideal regulatory framework is comprehensive in three respects. First, it establishes provisions that require consideration of all hazards, both natural and human-made, that can potentially affect the system. For practical purposes, however, many of these hazards can be "screened out" because either they do not significantly impact the performance of the system (e.g., earthquakes of small magnitude) or they have an extremely small chance of occurring (e.g., earthquakes of extremely large magnitude). Justification for screening out particular hazard scenarios should be provided. Those that cannot be screened out can be organized into groups with similar attributes (e.g., earthquakes within a certain magnitude range). An enveloping or worst-case scenario can then be selected from each group, resulting in a thorough but manageable set of scenarios that forms the basis for design and evaluation of the system.

Second, a comprehensive regulatory framework establishes provisions and requirements for all subsystems and components important to the system in the selected scenarios. As discussed in Section 2.3.1, provisions should begin at the level of the system and eventually work down to the level of individual components. Provisions for a particular subsystem or component should be based on its risk contribution to the system (see Section 2.3.2). In addition to including important components and subsystems, provisions should also identify and address potential interactions between subsystems and components.

Third, a comprehensive regulatory framework accounts for uncertainty, both in identifying and analyzing potential hazards and in characterizing the system and its numerous components. Uncertainty stems from two primary sources. The first source, commonly referred to as aleatory uncertainty, arises from inherent randomness in behavior of the entity under consideration, while the second, referred to as epistemic uncertainty, arises from limitations in knowledge [Parry and Winter 1981; Helton 1994; Parry 1996; Ang and Tang 2007]. Over time, epistemic uncertainty can be reduced as knowledge improves; aleatory uncertainty, however, always remains [Der Kiureghian and Ditlevsen 2009]. Provisions and requirements for a system and its components should address both types of uncertainty.

2.3.4 Performance-Based Framework

An ideal regulatory framework is performance-based in character. In general, a performance-based regulatory approach "specifies the outcome required but leaves the concrete measures to achieve that outcome up to the discretion of the regulated entity" [Coglianese et al. 2002]. In contrast, a prescriptive regulatory approach specifies exactly how to achieve compliance. In other words, performance-based regulations are defined "with respect to desired outcomes rather than prescribed means or technologies" [May and Koski 2004]. A hallmark of performance-based regulation is "the explicit statement of goals and objectives that reflect societal expectations and desires, along with functional statements, operative requirements, and in some cases performance criteria, which are to be used for demonstrating that goals and objectives have been met" [Meacham et al. 2005].

May and Koski [2004] summarize the potential advantages and disadvantages of performance-based regulations. In general, performance-based regulations can increase the incentive for innovation, increase the flexibility in how regulations can be satisfied, and decrease the costs of compliance for regulated entities (e.g., designers, architects, utility providers, etc.). At the same time, however, performance-based regulations can also increase the costs to government regulators and reduce the predictability in regulatory expectations.

A performance-based framework establishes explicit performance objectives or outcomes for a system and all necessary subsystems and components. In turn, these objectives can form the basis for a more detailed set of provisions and requirements. In a truly performance-based framework, however, only performance objectives would be specified; the designer would be given complete flexibility in deciding how to satisfy the specified objective. Often, though, a typical designer will require further, more detailed guidance. In addition, the agency charged

with enforcing truly performance-based regulations might struggle to verify compliance without a more detailed set of performance criteria and requirements.

For these reasons, a truly performance-based regulatory framework is usually not practical. However, the framework should still use explicit performance objectives as the foundation for all resulting regulation (i.e., the framework should be performance-informed). For example, consider the following performance objective: a hospital must remain operational after an earthquake. This performance objective could be supported by a more detailed set of performance criteria, including specific limits on peak interstory drift ratios, floor accelerations, and residual displacements, and provisions requiring onsite backups of all critical utilities. However, this more detailed set of performance criteria would stop short of prescribing specific means for satisfying the requirements (e.g., requiring use of a particular structural system or specifying a particular approach for providing backup electricity).

2.3.5 Acceptable Provisions and Requirements

An ideal regulatory framework contains provisions and requirements that are acceptable. In particular, regulations represent a level of risk that is consistent with what society expects from the system and, perhaps more importantly, what costs society is willing to incur. For example, while it would be ideal for a system to be able to withstand the effects of an extremely large, rare earthquake without suffering any damage, the costs of doing so might exceed what the public is willing to pay. It is crucial that these costs be weighed carefully against benefits associated with preventing the potentially adverse consequences if something goes wrong. For example, in the case of nuclear power plants, not only could an accident at one facility affect the communities and environment surrounding the plant, but it could also force other facilities to close or cause a national or global shift away from nuclear power altogether.

Only after careful consideration of all potential consequences can risk targets for a system be established. However, no matter what the final target or targets are, residual risk will always remain. For example, an earthquake exceeding the design basis could occur, even if the design basis earthquake is extremely rare. An ideal regulatory framework takes necessary steps to ensure that this risk is acceptable to society. It contains mechanisms and processes to inform the public about risks and to gather input and feedback. These mechanisms help ensure the framework achieves an acceptable level of risk that appropriately balances costs and benefits.

3   Communities

A community is a dynamic system of people, organizations, and patterned relationships and interactions [Alesch 2005]. Most of these relationships and interactions are physically supported by a community's built environment, which is a complex and interdependent network of engineered subsystems and components, including buildings, bridges, pipelines, transmission towers, and other structures. Subsequently, the built environment plays a crucial role in enabling a community to successfully function, providing the physical foundations for much of the economic and social activities that characterize a modern society. Natural hazards such as earthquakes, hurricanes, and floods can damage a community's built environment, which in turn can disrupt the security, economy, safety, health, and welfare of the public. In response, many communities have developed and implemented regulatory frameworks to ensure minimum levels of performance for individual parts of the built environment.

This chapter addresses these issues in greater detail. Specifically, Section 3.1 describes the configuration of a typical community, including general characterizations of its components, interactions, and correlations. Section 3.2 summarizes the potential impact earthquakes can have on a community and its built environment. Finally, Section 3.3 describes the regulatory framework currently used in the United States to design and evaluate a community's built environment to withstand the effects of earthquakes, focusing in particular on building codes and other engineering standards that establish performance expectations for the built environment. Using the list of attributes presented in the previous chapter as a guide, Section 3.3 analyzes the current regulatory framework's strengths and shortcomings. Ultimately, this analysis will provide further justification for the engineering framework proposed in subsequent chapters of this report.

3.1   SYSTEM DESCRIPTION

As detailed in Section 2.2.1, a system is a dynamic entity comprising a collection of interacting, potentially correlated components assembled to perform an intended function (adapted from Vesely et al. [1981], Buede [2000], ISO and IEC [2008], and Kossiakoff et al. [2011]). As such, a community can be considered a system, albeit an incredibly large and multi-faceted one. Unlike other types of systems (such as nuclear power plants or commercial aircraft), no two communities are identical. However, many share similar characteristics and configurations. The

following subsections describe the basic composition of a typical community, including its key components, interactions, and potential sources of correlation.

3.1.1 Components

Bea [2007, 2008] defined seven general types of components in a system: structures, hardware, people, organizations, procedures, environments, and interfaces (see Section 2.2.1 and Table 2.8 for additional discussion). These seven categories will be used to guide the discussion of the numerous components that comprise a typical community. This discussion, by no means exhaustive, aims to provide a general sense of the many different components within a community, focusing in particular on the built environment.

3.1.1.1 *Structures*

Structures refer to those components that physically support a community and its vital functions. There are two primary categories of structures: buildings and lifelines. Buildings support a wide range of functions, including residential, commercial, industrial, and governmental. Lifelines refer to the systems and facilities that provide services necessary to the function of an industrialized society and important to emergency response and recovery activities after a disaster. Lifelines can be grouped into the following five categories (adapted from PCCIP [1997], Rinaldi et al. [2001], ALA [2004], O'Rourke [2007], and Barkley [2009]): water; telecommunications; energy (electric power, natural gas, oil, and solid fuels); transportation (roads and highways, mass transit, ports and waterways, railways, and airports); and waste disposal (wastewater and solid waste).

3.1.1.2 *Hardware*

Hardware refers to those components that physically enable the vital functions of a community to be performed. Typically, hardware works in conjunction with structures to perform these functions. For example, by themselves, structures like electric transmission towers and lines do not make a community's electric power network functional; equipment like generators and transformers are required in order for the power grid to operate successfully. In general, hardware has moving parts whereas structures do not. Taken together, structures and hardware form the built environment.

3.1.1.3 *People*

In general, people refer to the residents of a community. Residents can serve many different roles simultaneously, including that of operator, user, and/or member of the general public. Operators are those residents who actively participate in or enable the vital functions of a community. They include service and industry workers like truck drivers, firefighters, electricians, custodians, bankers, city planners, and doctors, to name only a few. Operators typically rely on a specific subset of structures and hardware to perform their duties successfully. In addition, their behavior can be strongly influenced by the organizations, procedures, and environments in a community. For example, firefighters not only require functional communication, transportation, and water

infrastructure in order to extinguish fires successfully, but also extensive training and rigorous command structures.

In addition to operators, residents can also serve as users or customers. In general, users do not directly participate in the operation of a particular system or service; however, because they use or consume the service or product, they can be affected if the system or service is disrupted. For example, an ophthalmologist who relies on public transportation may be unable to commute to and from work if bus service is disrupted. An especially important group of users within a community is students, as they have little control over how their community's education system is run.

Lastly, residents can serve as members of the general public. Members of the general public neither operate nor use the service or system under consideration; however, they can still be affected by its operation. For example, a chemical factory may emit pollutants into the surrounding environment that affects nearby residents who do not use the chemicals produced by the factory. In this example, the nearby residents are neither operators nor users, but they are still affected by operation of the factory.

3.1.1.4 Organizations

Organizations refer to the groups or teams of people that actively participate in the vital functions of a community. There are two main types of organizations: businesses and institutions. Businesses provide goods and services to customers for a profit. They include grocery stores, banks, restaurants, engineering firms, and private utility providers. Institutions provide vital public services to the residents of a community. They include public and other non-profit entities like schools, universities, churches, and government agencies (e.g., police and fire departments, post offices, transit authorities, and public utility providers).

Certain types of organizations specify and enforce the procedures that dictate how people and other organizations behave. For example, the building department specifies and enforces the procedures (i.e., building codes) that engineering firms must follow when designing and constructing buildings. In addition, engineering firms typically specify additional procedures their engineers must follow; for example, a particular process for analyzing the response of a building to an earthquake.

3.1.1.5 Procedures

Procedures refer to the formal and informal laws, regulations, guidelines, and customs that govern a community and its vital functions. They include, for example, legally adopted statutes, bills, and ordinances, codes and standards, operating manuals, and emergency response plans. Procedures, which are typically developed, implemented, and enforced by organizations, dictate the way people and organizations behave. They can also influence how structures and hardware perform. For example, fuel economy standards affect the types of cars that manufacturers produce. In light of this discussion, a regulatory framework includes both procedures (i.e., regulations and guidance) and the organizations that develop and enforce them.

3.1.1.6 Environments

Environments refer to the conditions under which a community and its vital functions are performed. There are many different types of environments, including natural, economic, social, and political. Environments can strongly influence the behavior of structures, hardware, operators, and organizations. For example, the natural environment that surrounds a community determines the hazards for which its buildings and other structures must be designed. In addition, the economic environment influences the actions of investment firms, developers, and other businesses, which in turn can impact the size and condition of a community's building stock.

3.1.1.7 Interfaces

Interfaces refer to those components in a community that link or connect other components together. Interfaces enable control in the sense of feedback control, making it possible for components to interact in a rational manner. An increasingly ubiquitous interface is the Internet, which can be used, for example, to connect a traffic engineer (i.e., operator) to sensors, cameras, and other instruments (i.e., hardware) that monitor traffic conditions and loads a bridge (i.e., structure). Another example of an interface is the dashboard in a car, which links the driver (i.e., operator) to the car's controls and instrumentation (i.e., hardware).

3.1.2 Interactions

The interactions among its many different components enable a community to perform its vital functions successfully. These interactions can be extraordinarily complex, especially given the large number of components in a community. As discussed in Section 2.2.1, these interactions take the form of dependencies and interdependencies. Figure 3.1 portrays some basic interdependencies among the lifelines in a community. Note that SCADA stands for supervisory control and data acquisition. As the figure makes evident, electric power plays a central role in a community, supplying power to the essential functions of most other lifelines. However, as the figure also demonstrates, electric power in turn relies on a large number of other lifelines to operate successfully.

In general, interdependencies increase the vulnerability of lifelines to service disruptions. For example, telecommunications service can be disrupted on account of internal issues (e.g., damage to a switches or cell phone towers); however, because of interdependencies, service can also be disrupted on account of issues beyond the control of the telecommunications provider (e.g., power outages). Some of the vulnerabilities arising from these interdependencies can be mitigated through use of backup or emergency supplies of critical utilities. For example, a telecommunications center can install onsite diesel generators to supply emergency power to switches and other vital hardware if the electric power grid goes down. However, as a practical matter, not all interdependence-related vulnerabilities can be mitigated fully. Furthermore, under normal operating conditions, interdependencies can serve to increase the operational efficiency of lifelines.
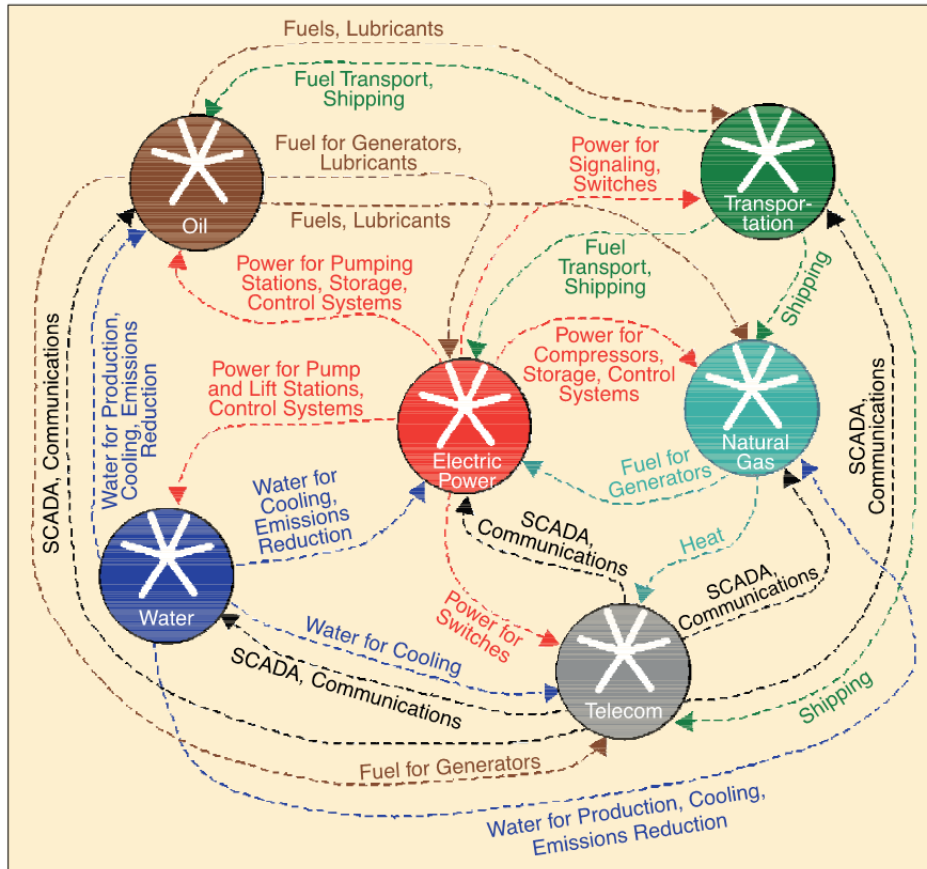
Figure 3.1   Examples of lifeline interdependencies [Rinaldi et al. 2001].

3.1.3 Correlation

As discussed in Section 2.2.1, correlation measures the relationship between the responses of two distinct objects. In a complex system like a community, correlation arises when a large number of its components have similar design or configuration—for example, a neighborhood of identical apartment buildings. While modular design and construction allows for greater economies of scale and efficiency, it also increases the vulnerability of the community to the effects of correlated failures. By incorporating diversity into the design and configuration of its components, a community can mitigate the impact of correlation.

The procedures developed and utilized by operators and organizations within a community play an important role in shaping the diversity of its components. For example, prescriptive provisions in a widely used engineering code or standard may, over time, produce a large number of structures within a community that have a similar flaw or defect. This phenomenon was observed in the aftermath of the 1994 Northridge earthquake when a significant number of welded joints in steel special moment resisting frames failed. These welded joints were approved for use by the Uniform Building Code (UBC), a national standard adopted by most communities in California at the time that has since been superseded by the IBC. In addition, prior to the mid-1970s, provisions in the UBC created a class of buildings,

referred to as nonductile concrete buildings, characterized by inadequate seismic detailing that can result in sudden collapse in an earthquake, therefore posing a serious threat to life and property [Anagnos et al. 2008; Comartin et al. 2008; Comartin et al. 2011] estimate there are approximately 17,000 nonductile concrete buildings in the 23 counties with the highest seismicity and exposure in California. As these examples have illustrated, unintended correlations that arise as the result of procedures enacted by a community can have significant impact on the performance of its components (e.g., structures and hardware) in an earthquake.

3.2   VULNERABILITY TO HAZARDS

Communities are vulnerable to a wide range of natural and human-made hazards, including earthquakes, hurricanes, tornados, floods, economic downturns, pandemics, and terrorist attacks. This section focuses primarily on earthquakes, which are especially challenging because of their unpredictability and widespread impact. In particular, the following subsections examine the types of effects produced by earthquakes, the direct consequences of these effects on communities, and the cascading consequences that often ensue. Much of the following discussion can be extrapolated to other types of hazards; however, this extrapolation is beyond the scope of this report.

3.2.1 Types of Effects

Earthquakes can produce many different effects, though the primary effect is ground shaking [Scawthorn 2003a]. Depending on the geology of the region, shaking can be felt at great distances—sometimes hundreds of miles—from the epicenter of an earthquake, though the intensity of shaking generally decreases as the distance from the epicenter increases. While ground shaking is typically the most widespread and devastating effect, earthquakes can produce additional harmful effects, including liquefaction, fault rupture, lateral spreading, landslides, and tsunamis. Furthermore, when an earthquake occurs, it usually triggers a series of aftershocks. Sometimes it can even induce additional earthquakes on nearby faults. These aftershocks and induced earthquakes, which themselves can be sizable, are particularly problematic because they strike when a community's built environment is in a weakened state.

3.2.2 Direct Consequences

The most direct consequence of earthquakes involves physical damage to the built environment of a community. For example, ground shaking can induce significant lateral displacements and accelerations that damage key structural elements in a building, possibly resulting in partial or total collapse of the structure. In addition, liquefaction can cause soil instability that ruptures buried pipelines and damages the foundations of structures. Furthermore, tsunamis can produce powerful waves that can obliterate entire city blocks. The extent of physical damage caused by earthquakes depends on many factors, including the location and magnitude of the earthquake and condition of the community's built environment. If the physical damage is severe, it can

disrupt a large number of a community's vital functions and result in a significant number of casualties.

3.2.3 Cascading Consequences

Cascading consequences refer to the sequences of events that result from physical damage to a community's built environment. Cascading consequences arise when the direct consequences of an earthquake cascade through a community, typically following the complex web of component interactions. For example, damage to gas pipelines can disrupt service to businesses and residences, and can even trigger large fires that destroy additional infrastructure, including the water, communication, and transportation systems that firefighters depend on to suppress fires. In addition, damage to a manufacturing facility can lead to costly downtime that could ultimately bankrupt the business and force workers to leave town in search of new employment. In turn, disruption to and potential closure of the plant can impact supply chains throughout the community, region, and even globe.

Due to an increasingly interconnected global economy, the cascading consequences caused by an earthquake can extend well beyond areas directly affected by it. The extent of these consequences depends on several factors, including the extent of the direct consequences and the importance of the affected community. For example, if an earthquake strikes a community and causes minor physical damage to its infrastructure, the cascading consequences will also likely be minor. On the other hand, if an earthquake strikes a city or region and causes extensive damage, the cascading consequences could be global, as they were following the 2011 Tohoku earthquake that struck northern Japan.

If the consequences are severe enough, a community may never fully recover after an earthquake. The combined impact of losses to housing, jobs, schools, and other services may be too much for a community to handle. Instead of rebuilding, residents may simply choose to leave and start over elsewhere. Even if the community eventually repairs or rebuilds damaged infrastructure, the disruption caused by an earthquake may result in irreversible harm to local businesses as global supply chains shift production to (unaffected) locations, as occurred in Kobe, Japan, after the 1995 Great Hanshin-Awaji earthquake [Olshansky et al. 2011]. Before the earthquake, the port of Kobe was the sixth busiest container port in the world. It suffered heavy damage as a result of the earthquake and, by the time its facilities were fully reconstructed in 1997, the port had dropped to seventeenth busiest [Chang 2000]. Fifteen years after the earthquake, the volume of containers handled at the port was only 90% of pre-earthquake levels [City of Kobe 2012].

3.3 CURRENT REGULATORY FRAMEWORK

It may not be possible to fully anticipate all of the cascading consequences, but mitigating the initial physical damage caused by an earthquake (or other hazard) significantly limits the consequences that can ensue. To this end, most communities in the United States have developed and enacted regulatory frameworks to mitigate the direct consequences of earthquakes and other

hazards. This section examines these frameworks, giving particular attention to building codes and other engineering standards that establish performance expectations, either explicit or implicit, for the built environment in earthquakes. Section 3.3.1 provides an overview of the current codes and standards for both buildings and lifelines, while Sections 3.3.2 and 3.3.3 describe the strengths and shortcomings, respectively, of these documents. Ultimately, it is these shortcomings that the engineering framework presented in this report aims to address.

3.3.1 Overview

The regulatory framework that dictates how a community's built environment (i.e., buildings and lifelines) should perform comprises a complex web of regulations, enforcement mechanisms, and guidance. Building codes and other engineering standards play an especially important role within this framework, specifying provisions and requirements for buildings and lifelines that ultimately determine how the built environment responds to earthquakes. Therefore, these documents are the focus of this subsection. It should be noted, however, that other regulations (e.g., zoning laws, retrofit ordinances, land-use plans) might also affect how a community's built environment performs in an earthquake. For example, the Alquist-Priolo Earthquake Fault Zoning Act, a bill signed into California law in 1972, prohibits construction of buildings on the surface trace of active earthquake faults with the intent to prevent damage caused by fault rupture. While important, the following two subsections focus on the codes and standards that establish performance expectations for buildings and lifelines, respectively, in earthquakes.

3.3.1.1 Buildings

At the heart of the current regulatory framework for buildings in the United States is the building code, a document that specifies minimum requirements for buildings and other structures in order to safeguard the health, safety, and general welfare of the public [ICC 2006]. Many communities in the United States use the IBC. The IBC is a consensus-based document developed and updated triennially by the International Code Council (ICC), a non-profit, non-governmental, membership association of engineers, architects, builders, contractors, elected officials, and others in the construction industry. While the IBC contains many provisions and requirements of its own, it also references other codes and standards, including ASCE 7 (Minimum Design Loads for Buildings and Other Structures) [ASCE 2006], ACI 318 (Building Code Requirements for Structural Concrete) [ACI 2011], AISC 360 (Specification for Structural Steel Buildings) [AISC 2010b], and AISC 341 (Seismic Provisions for Structural Steel Buildings) [AISC 2010a]. Once adopted by a city, county, or state, the IBC becomes law.

The IBC defines four occupancy categories for buildings: Occupancy Category I, which includes buildings representing low hazard to human life; Occupancy Category II, which includes most typical buildings; Occupancy Category III, which comprises high occupancy structures and buildings containing hazardous materials; and Occupancy Category IV, which includes facilities essential to emergency response and recovery operations [ICC 2006]. Table 3.1 provides more detailed descriptions of each category. The IBC specifies different design requirements for each occupancy category. These prescriptive requirements include minimum

lateral strength and stiffness for structural systems, as well as guidance for anchoring, bracing, and accommodation of structural drift for nonstructural systems [BSSC 2009]. In general, Occupancy Category III and IV buildings are required to have stronger and stiffer structural systems than Occupancy Category I or II buildings.

Building designs that satisfy the requirements of the IBC are implicitly expected to achieve certain levels of performance in different earthquake scenarios. These performance levels, however, are not explicitly stated in the IBC; instead they are discussed in the commentary to the NEHRP Recommended Provisions [BSSC 2004, 2009], which, via ASCE 7, serves as the basis for the seismic provisions of the IBC. The NEHRP Recommended Provisions define four seismic performance levels (operational, immediate occupancy, life safety, and collapse prevention) and three earthquake hazard scenarios or ground motions (frequent, design basis, and maximum considered), resulting in twelve possible performance objectives, where a performance objective comprises a performance level and hazard scenario. Table 3.2 provides a detailed description of each of the four seismic performance levels.

Figure 3.2 displays the set of performance objectives implicitly assumed for each occupancy category in the IBC. Again, these performance objectives are not explicitly stated in the IBC. Figure 3.2 displays three separate lines: one corresponding to Occupancy Category II buildings (labeled "OC II: Ordinary"); one corresponding to Occupancy Category III buildings (labeled "OC III: High Occupancy"); and one corresponding to Occupancy Category IV buildings (labeled "OC IV: Essential"). Each line contains three points, with each point representing a different performance objective for the particular occupancy category. Therefore, structures designed in accordance with the provisions of the IBC are expected to satisfy multiple (three in this case) performance objectives. For example, Occupancy Category IV buildings are expected to achieve the following three performance objectives: operational performance following a frequent earthquake; immediate occupancy performance following the design earthquake; and life safety performance following the maximum considered earthquake (MCE). As Figure 3.2 demonstrates, the set of performance objectives specified for Occupancy Category IV buildings are the most stringent, reflecting the essential nature of the functions performed by these buildings (see Table 3.1).

Table 3.1   Occupancy categories for buildings (adapted from ASCE [2006] and ICC [2006]).

Category	Nature of occupancy
I	Buildings and other structures that represent a low hazard to human life in the event of failure
II	All buildings and other structures except those listed in Occupancy Categories I, III, and IV
III	Buildings and other structures that represent substantial hazard to human life in the event of failure, including, but not limited to: • Buildings where more than 300 people congregate in one area • Buildings with daycare facilities with a capacity greater than 150 • Buildings with elementary school or secondary school facilities with a capacity greater than 250 • Buildings with a capacity greater than 500 for colleges or adult education facilities • Health care facilities with a capacity of 50 or more resident patients, but not having surgery or emergency treatment facilities • Jails and detention facilities Buildings and other structures, not included in Occupancy Category IV, with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure, including, but not limited to: • Power generating stations • Water or sewage treatment facilities • Telecommunication centers Buildings and other structures not included in Occupancy Category IV containing sufficient quantities of toxic or explosive substances to be dangerous to the public if released
IV	Buildings and other structures designated as essential facilities, including, but not limited to: • Hospitals and other health care facilities having surgery or emergency treatment facilities • Fire, rescue, ambulance, and police stations and emergency vehicle garages • Designated earthquake, hurricane, or other emergency shelters • Designated emergency preparedness, communication, and operation centers and other facilities required for emergency response • Power generating stations and other public utility facilities required in an emergency • Ancillary structures (communication towers, fuel storage tanks, cooling towers, fire water storage tanks, etc.) required for operation of Occupancy Category IV structures during an emergency • Aviation control towers, air traffic control centers, and emergency aircraft hangars • Water storage facilities and pump structures required to maintain water pressure for fire suppression • Buildings and other structures having critical national defense functions Buildings and other structures containing highly toxic substances where the quantity of the material exceeds a threshold quantity established by the authority having jurisdiction

Table 3.2   Descriptions of the four seismic performance levels implicitly assumed in the IBC [BSSC 2004].

Performance level	Description
Operational	Represents the least level of damage to the structure. Structures meeting this level when responding to an earthquake are expected to experience only negligible damage to their structural systems and minor damage to nonstructural systems. The structure will retain nearly all of its pre-earthquake strength and stiffness and all mechanical, electrical, plumbing, and other systems necessary for the normal operation of the structure are expected to be functional. If repairs are required, these can be conducted at the convenience of the occupants. The risk to life safety during an earthquake in a structure meeting this performance level is negligible. Note, that in order for a structure to meet this level, all utilities required for normal operation must be available, either through standard public service or emergency sources maintained for that purpose. Except for very low levels of ground motion, it is generally not practical to design structures to meet this performance level.
Immediate occupancy	Similar to the operational level although somewhat more damage to nonstructural systems is anticipated. Damage to the structural systems is very slight and the structure retains all of its pre-earthquake strength and nearly all of its stiffness. Nonstructural elements, including ceilings, cladding, and mechanical and electrical components, remain secured and do not represent hazards. Exterior nonstructural wall elements and roof elements continue to provide a weather barrier, and to be otherwise serviceable. The structure remains safe to occupy; however, some repair and clean up is probably required before the structure can be restored to normal service. In particular, it is expected that utilities necessary for normal function of all systems will not be available, although those necessary for life safety systems would be provided. Some equipment and systems used in normal function of the structure may experience internal damage due to shaking of the structure, but most would be expected to operate if the necessary utility service was available. Similar to the operational level, the risk to life safety during an earthquake in a structure meeting this performance level is negligible. Structural repair may be completed at the occupants' convenience, however, significant nonstructural repair and cleanup is probably required before normal function of the structure can be restored.
Life safety	Significant structural and nonstructural damage has occurred. The structure may have lost a substantial amount of its original lateral stiffness and strength but still retains a significant margin against collapse. The structure may have permanent lateral offset and some elements of the seismic force resisting system may exhibit substantial cracking, spalling, yielding, and buckling. Nonstructural elements of the structure, while secured and not presenting falling hazards, are severely damaged and cannot function. The structure is not safe for continued occupancy until repairs are instituted as strong ground motion from aftershocks could result in life threatening damage. Repair of the structure is expected to be feasible, however, it may not be economically attractive to do so. The risk to life during an earthquake in a structure meeting this performance level is very low.
Collapse prevention	A structure has sustained nearly complete damage. The seismic-force resisting system has lost most of its original stiffness and strength and little margin remains against collapse. Substantial degradation of the structural elements has occurred including extensive cracking and spalling of masonry and concrete elements and buckling and fracture of steel elements. The structure may have significant permanent lateral offset. Nonstructural elements of the structure have experienced substantial damage and may have become dislodged creating falling hazards. The structure is unsafe for occupancy as even relatively moderate ground motion from aftershocks could induce collapse. Repair of the structure and restoration to service is probably not practically achievable.
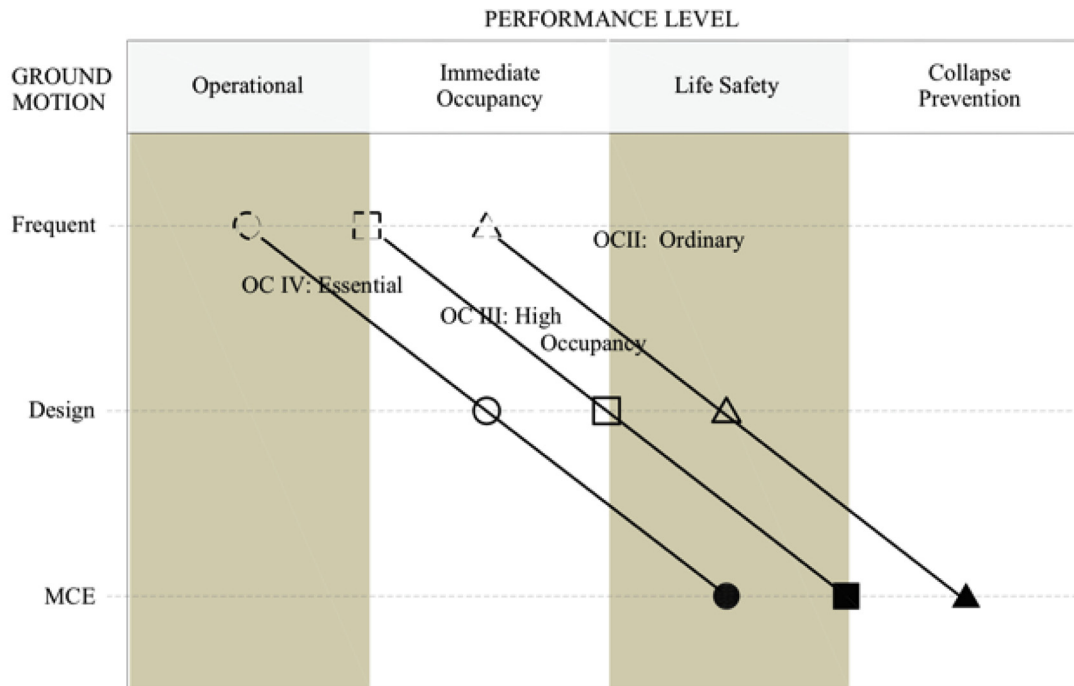
PERFORMANCE LEVEL

Figure 3.2   Implicit performance objectives corresponding to IBC occupancy categories [BSSC 2009; ASCE 2000].

In summary, the primary intent of the IBC is to "prevent, for typical buildings and structures, serious injury and life loss caused by damage from earthquake ground shaking" [BSSC 2009]. Because most earthquake-related injuries and deaths are caused by structural collapse of buildings, the focus of code provisions centers on preventing collapse during ground shaking associated with the maximum considered earthquake (MCE). Specifically, building designs that satisfy the provisions and requirements of the IBC are expected to have a 1% probability of collapse in 50 years, which is roughly equivalent to a 10% probability of collapse in MCE ground shaking [BSSC 2009].

Another important piece of a community's regulatory framework is the local department or agency that enforces the building code and its provisions. While the exact structure of these departments varies from community to community, their duties typically include reviewing plans and drawings, issuing permits, and inspecting buildings and other structures during and after construction. Without proper enforcement, building designers and constructers may choose to ignore certain code requirements if they consider them too onerous or costly. The resulting buildings will likely have lower quality and less reliable performance in an earthquake than code-compliant structures. While enforcement is an important component, this report focuses primarily on the regulations in a framework (i.e., building codes and other documents).

Often a community's regulatory framework also includes a local hazard mitigation plan. Federal law requires a community to develop such a plan as a condition for receiving certain types of non-emergency disaster aid. In general, a hazard mitigation plan provides a long-term strategy for a community to reduce the risks arising from natural hazards. It must contain, among

other things, a risk assessment and a mitigation strategy [USNARA 2009]. A risk assessment identifies the natural hazards that can affect a community and describes their impact. A mitigation strategy provides a blueprint for reducing the potential losses identified in the risk assessment, including a description of mitigation goals to reduce or avoid long-term vulnerabilities to hazards, an analysis of specific mitigation projects being considered, and an action plan for prioritizing and implementing the identified projects. Once it is approved, however, a hazard mitigation plan is not legally binding, unlike the adopted building code.

3.3.1.2 Lifelines

The current regulatory framework that establishes performance expectations for lifelines in earthquakes is not as easy to characterize as the one for buildings. Figure 3.3 summarizes the patchwork of codes and standards that currently exist for the different types of lifelines. Barkley [2009] provides an excellent summary of the current regulatory framework for lifelines:

> *Guidelines, standards, and code requirements for the seismic performance of lifelines vary widely. The range of functions and designs of these systems, as well as the range of potentially damaging hazards, necessitates sector and hazard specific approaches to reducing damage, ensuring safety, and facilitating system restoration. Consequently, development of these standards occurs among numerous code development entities, other professional organizations and private sector entities, and Federal, state, and local government agencies. These entities have made great strides in developing standards to reduce risk to lifeline systems in all sectors.*
>
> *Most sectors have progressed to system-based approaches in order to assess risk and reduce disruptions the performance of systems and delivery of services to customers. Nevertheless, achieving a consistent level of resilience is complicated by the many different regulating bodies to which system operators must answer. The general tendency toward sector and hazard specific development of standards results in the following problems:*
>
> - *A lack of commonly understood definitions for acceptable seismic performance*
>
> - *Different standards for performance among different sectors*
>
> - *A lack of inter-sector coordination for the development of standards, setting of priorities, and implementation of mitigation*
>
> - *Limited understanding by political leadership and the general public of the potential performance of lifelines during an earthquake – and whether the performance of lifelines will meet expectations*
>
> *The sector specific natural hazards provisions are generally based on varying levels of risk (for example, in terms of the design earthquake or probability of occurrence). Additionally, most sectors do not have standards for reliability – that is, practices that have been developed to ensure system restoration in accordance with goals set by stakeholders. According to the American Lifelines Alliance, such standards have been developed only for highways/roads, ports, and railroads [ALA 2004].*

OIL PRODUCTS SYSTEMS

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Buried Pipelines	ASME/ANSI B31.4	none[2]	none	
	ASCE TCLEE 1984	earthquake	earthquake	●
Aboveground Piping	ASME/ANSI B31.4	none[2]	none	
	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	API 2510			
	API 2508			
	ASCE TCLEE 1984	earthquake	none	●
Pumping Station Piping	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	ASME/ANSI B31.4	none[2]	none	
	API 2510			
	ASCE TCLEE 1984	earthquake	none	●
Well Facilities	ASME/ANSI B31.4	none[2]	none	
	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	API RP 14E			
Refineries	API 2508			
	ASCE Petrochem.	earthquake, wind	earthquake, wind	●
	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	ASME BPV[3]	none[2]	earthquake, wind, ice	
Storage Tanks	API 620	earthquake, wind	earthquake, wind	●
	API 650	earthquake, wind	earthquake, wind	●
	NFPA 59			
	API 2508			
	ASCE TCLEE 1984	earthquake	earthquake	●

NATURAL GAS SYSTEMS

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Buried Pipelines	ASME/ANSI B31.8	none[2]	none	
	PRCI (2000)	earthquake	earthquake	●
	ASCE TCLEE 1984	earthquake	earthquake	●
Aboveground Piping	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	ASME/ANSI B31.8	none[2]	none	
	ANSI Z223.1	none[2]		
	NFPA 54, SGC, IFGC	none[2]		
	ASCE TCLEE 1984	earthquake	none	●
Compressor Station Piping	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
	ASME/ANSI B31.8	none[2]	none	
	ASCE TCLEE 1984	earthquake	none	●
Well Facilities	ASME/ANSI B31.8	none[2]	none	
	API RP 14E			
LNG Facilites / System Reliability[6] / Piping / Storage Tanks	NFPA 59A	earthquake	earthquake	
	NFPA 59A	earthquake	earthquake	
	API 620	earthquake, wind	earthquake, wind	
	API 650	earthquake, wind	earthquake, wind	
	ASME BPV[3]	none[2]	earthquake, wind, ice	
	NFPA 59A	earthquake, ref. ANSI A58.1 for wind and snow	earthquake, ref. ANSI A58.1 for wind and snow	
	ASCE 1984	earthquake	earthquake	

WATER SYSTEMS (Potable & Raw)

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Buried Pipelines	AWWA M11	none[2]	none	
	ASCE TCLEE 15	earthquake	earthquake	●
Aboveground Pipelines	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
Pumping Plants	ASME B31.3	none[2]	earthquake, wind, ice	
Storage Tanks	ACI 350	earthquake	earthquake	●
	AWWA D[5]	earthquake, wind, snow	earthquake, wind, snow	●
	ASCE 1984	earthquake	earthquake	●
Well Facilities				
Canals				

WASTE WATER SYSTEMS

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Buried Pipelines	AWWA M11	none[2]	none	
	ASCE TCLEE 15	earthquake	earthquake	●
Aboveground Pipelines	ASME/ANSI B31.3	none[2]	earthquake, wind, ice	
Treatment Plants	ASME B31.3	none[2]	earthquake, wind, ice	●
	WEF	earthquake, flood		●
Storage Tanks	ACI 350	earthquake	earthquake	●
	AWWA D[5]	earthquake, wind, snow	earthquake, wind, snow	●
	ASCE 1984	earthquake	earthquake	●

ELECTRIC POWER SYSTEMS

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Substations	IEEE-693	earthquake	earthquake	●
	RUS 1724e*	wind, ice, earthquake	wind, ice, earthquake	●
	ASCE Manual 96	earthquake	earthquake	●
Transmission Towers & Poles	ASCE-10*	wind, ice, earthquake	wind, ice, earthquake	●
	ASCE Manual 72*	wind, ice, earthquake	wind, ice	●
	ASCE Manual 74	wind, ice, earthquake[2]	wind, ice	●
	ASCE Manual 91*	wind, ice, earthquake	wind, ice, earthquake	●
	ASCE Concrete Poles*	wind, ice, earthquake	wind, ice, earthquake	●
	PCI Prest. Conc. Poles*	wind, ice, earthquake	wind, ice, earthquake	●
	RUS 1724e*	wind, ice, earthquake	wind, ice, earthquake	●
	IEEE 605*	wind, ice, earthquake	wind, ice, earthquake	●
	IEEE 691*	none	none	●
	IEEE 693	earthquake	earthquake	●
	NESC	wind, ice, earthquake	wind, ice	●
Distribution Poles	NESC	wind, ice, earthquake	wind, ice	●
	RUS 160-2*	wind, ice, earthquake	wind, ice, earthquake	●
Buried Conduits				

TELECOMMUNICATION SYSTEMS

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]				
Towers, Masts and Poles	TIA/EIA 222G (2003)	earthquake, wind, ice	earthquake, wind, ice	●
	TIA/EIA 222F	wind, ice	wind, ice	●
Buried Cables	Bell Core	earthquake, flood	earthquake, flood	
Underwater Cables				
Aboveground Cables	Bell Core	earthquake, wind, ice, snow	Earthquake, wind, ice, snow	
Switching Equipment	Bell Core	earthquake, fire	earthquake, fire	
Cable Trays	SMACNA	none	earthquake	
	BSP (Bell System Practice)	none	earthquake	
	ASCE 7	earthquake, wind, ice, snow	earthquake, wind, ice, snow	

PORTS AND INLAND WATERWAYS

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]	ASCE TCLEE 12	earthquake		●
Piers/Wharves	NCEL R-939	earthquake	earthquake	
	NAVFAC DM-25.1			
	ASCE TCLEE 12	earthquake	earthquake	●
	NFESC TR-2069SHR	earthquake	earthquake	
Breakwaters/Jetties	NCEL R-939	earthquake	earthquake	
	ASCE TCLEE 12	earthquake	earthquake	●
Sea Walls	NCEL R-939	earthquake	earthquake	
	ASCE TCLEE 12	earthquake	earthquake	●
Container Handling	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	ASCE TCLEE 12	earthquake	earthquake	●
	AISC	none[2]	earthquake, wind, snow, ice	
Cargo Movement	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	ASCE-ASCE TCLEE 12	earthquake	earthquake	●
Marine Oil Terminals	CSLC	earthquake	earthquake	
	NFESC, TR-2103-SHR	earthquake	earthquake	
	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	NFPA[4]	earthquake	earthquake	

HIGHWAYS AND ROADS

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]	FHWA 106	earthquake	earthquake	
Bridges	AASHTO	earthquake, wind, snow, Ice, flood	earthquake, wind, snow, Ice, flood	●
	CALTRANS	earthquake, wind, snow, Ice, flood	earthquake, wind, snow, Ice, flood	●
	FHWA-RD-94-052	earthquake	earthquake	●
	FHWA 106	earthquake	earthquake	●
Embankments	CALTRANS	earthquake	earthquake	●
Road Beds				
Culverts	AASHTO	none[2]	none	
	CALTRANS	none[2]	none	
Tunnels	AASHTO	none[2]	none	
	CALTRANS	none[2]	none	
Retaining Walls	FHWA 106	earthquake	earthquake	
Signs	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	

RAILROAD

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
System Reliability[6]	AREMA Ch. 9			
Bridges	AREMA Ch. 7	wind	wind	
	AREMA Ch. 8	wind, ice	wind, ice	●
	AREMA Ch. 9	earthquake	earthquake	●
	AREMA Ch. 15	wind	wind	●
Embankments	AREMA Ch. 9	earthquake	earthquake	earthquake
Rails, Ties, and Ballast	AREMA Ch. 9	earthquake	earthquake	earthquake
Culverts	AREMA Ch. 9	earthquake	earthquake	earthquake
Tunnels	AREMA Ch. 9	earthquake	earthquake	earthquake
Signs	ASCE-7	earthquake, wind, snow, ice	earthquake, wind, snow, ice	
	IBC, SBC, UBC	earthquake, wind, snow, ice	earthquake, wind, snow, ice	

ELECTRICAL, MECHANICAL, AND ARCHITECTURAL COMPONENTS

COMPONENT	GUIDE/STANDARD[1]	LOADING	DESIGN	EXISTING[7]
Elect./Mech. Equip	ASCE-7	earthquake, wind, ice	earthquake, wind, ice	
	ASCE TCLEE 1984	earthquake	earthquake	●
	ASME BPV[3]	none[2]	earthquake, wind	
	NFPA[4]	earthquake	earthquake	
	IBC, SBC, UBC	earthquake, wind	earthquake, wind	
	SMACNA	earthquake	earthquake	●
Suspended Ceilings	IBC, SBC, UBC	earthquake	earthquake	
Elevated Floors				

NOTES

1. Documents in by **bold italics** indicate that the guidelines were not produced by a consensus process as defined for SDO's approved by the American National Standards Institute

2. "none" applies if a guideline or standard does not specifically identify how loads are to be obtained; if a group of standards is referenced, the natural hazard listed may be only covered in one document

3. ASME BPV refers to the ASME Boiler and Pressure Vessel Code that typically governs the design of all pressurized containers

4. NFPA refers to various NFPA standards governing fire protection systems

5. AWWA D refers to various AWWA standards governing water storage tanks

6. "System Reliability" is a component of design referring to practices that are specifically developed to provide reasonable assurance that consequences of a natural hazard on system service will meet the goals established by stakeholders (owners, operators, regulators, insurers, customers, and users). Consequences are defined by multiple performance requirements but typically include impact on public safety, duration of service interruption, and costs to repair damage.

7. **Existing** indicates that analysis or design procedures (NOT LOADS) could be applied for existing components

8. **Loading** refers to whether or not specific loads for various natural hazards are defined; "Design" refers to the existence of design and/or analysis procedures that account for loads arising from natural hazards

Figure 3.3   Matrix of standards and guidelines for lifelines [ALA 2004].

3.3.2 Strengths

One of the strengths of the current regulatory framework involves the efficacy in which it reduces the risk to life. As detailed in Table 3.2 and Figure 3.2, buildings designed in accordance with the provisions of the IBC are expected to respond to earthquakes in a manner that poses very low risk to life. Occupancy categories II, III, and IV all achieve life safety performance or better for earthquakes as severe as the design basis scenario, which has an expected return period of 475 years.

Recent earthquakes highlight the dramatic improvement in life safety provided by the current regulatory framework and, in particular, the building code. On 12 January 2010, a magnitude 7.0 earthquake struck near Port-au-Prince, the heavily populated capital of Haiti. The city lacks both a modern building code and a means to enforce it [DesRoches et al. 2011]. As a result, nearly half the buildings in Port-au-Prince, many of which were constructed using materials and methods prohibited in the IBC, collapsed during the earthquake. While an exact estimate may never be possible, the resulting destruction claimed the lives of approximately 300,000 Haitians [DesRoches et al. 2011]. In contrast, the magnitude 6.3 earthquake that struck Christchurch, New Zealand on 22 February 2011 claimed the lives of approximately 180 people [EERI 2011]. Despite both earthquakes having similar intensity, the casualties in New Zealand were a small fraction of those experienced in Haiti. The stark difference in the performance stems largely from the New Zealand building code, which closely resembles the IBC and is strictly enforced.

Another strength of the current regulatory framework involves the risk-based approach it uses to establish design requirements for buildings. Instead of specifying a universal set of provisions that apply to all structures, the building code assigns requirements based on a structure's risk to the health, safety, and general welfare of the public. The IBC requires all structures normally occupied by people (i.e., Occupancy Categories II, III, and IV) to remain safe during an earthquake, where safe is defined as collapse prevention performance or better. However, for buildings that pose greater risk or provide vital community services (e.g., Occupancy Category III or IV buildings), the IBC requires enhanced performance (see Figure 3.2). Table 3.1 lists examples of buildings in Occupancy Categories III and IV.

3.3.3 Shortcomings

In spite of these strengths, the current regulatory framework has several significant shortcomings. First, it does not employ an integrated, coordinated, and comprehensive approach (i.e., expansionist or top-down). Instead, it approaches the design and evaluation of a community on a component-by-component basis, often treating each component as if it does not interact with or depend on other components in the community. This approach produces communities in which most individual components behave as intended during an earthquake; however, when aggregated, the performance of components can result in unacceptable outcomes for the community.

As discussed in Section 3.3.1, the provisions contained in the IBC produce individual buildings that achieve implicit levels of performance (see Figure 3.2). However, these performance levels are not tied to broader performance objectives for the community, making it difficult to understand exactly how the community will perform in an earthquake. For example, if all of the residential buildings in a community achieve life safety performance after a major earthquake (see Table 3.2), the number of casualties should be small. However, it is less clear how many residents will be displaced and how long it will take to repair damaged homes.

The local hazard mitigation plan, despite taking a more expansive view, also fails to establish more detailed performance objectives for a community beyond simply reducing potential earthquake losses. Consequently, neither it nor the IBC looks at a community systematically to establish a framework that details exactly how it should perform in an earthquake. An integrated, coordinated, and comprehensive framework would first specify performance objectives for the community and then, using these objectives, would establish targets for individual subsystems and components.

Second, the current regulatory framework is not declaratively performance-based. Instead, it is highly prescriptive, specifying a large number of requirements and provisions for a building without first establishing explicit performance objectives for it. The performance objectives in Figure 3.2 are implicit in nature, meaning that if the prescriptive provisions in the IBC are satisfied, the building is expected to achieve its corresponding performance objectives. The IBC, however, does not require an explicit performance evaluation to verify whether these objectives have been satisfied. Furthermore, the prescriptive requirements of the IBC only ensure that a typical building (i.e., Occupancy Category II) remains safe after a major earthquake. They do nothing to address the functionality or reparability of the structure after an earthquake [Karlinsky 2009]. This makes it difficult to communicate with the public regarding exactly how individual buildings are expected to perform in an earthquake. Most people believe that a building designed in accordance with the current building code is "earthquake proof." In general, this is not true.

Third, the current regulatory framework fails to account for certain types of risk (i.e., it is not fully risk-informed). As discussed in Section 3.3.1, the current building code focuses on safeguarding the health, safety, and general welfare of the public. Consequently, its provisions allow significant structural and nonstructural damage to occur, provided it does not threaten the safety of the building's occupants. While the resulting damage may pose minor risk to life safety, it can significantly impact the functionality of the building and, ultimately, the entire community. As detailed in Table 3.2, a building that achieves life safety performance in an earthquake is not safe for continued occupancy until repairs are made. While repair of the structure is expected to be feasible, it may not be economically attractive to do so [BSSC 2004]. As a result, residents may be forced out of their homes for extended periods of time, imposing significant financial burden on both the families who must relocate and the government agencies that must shelter them. Similarly, businesses may be forced to close for lengthy periods of time, straining the finances of business owners, employees, and those who depend on their goods and services (e.g., other businesses). A significant outmigration of businesses and people may prevent a community from fully recovering after an earthquake.

Finally, the current framework fails to account for important components and interactions within a community. Buildings, which fall under the purview of the building code, are but one piece of a community's physical infrastructure. Lifelines also play a crucial role in a community's ability to function, both on a daily basis and in the aftermath of an earthquake. In spite of this, performance standards for lifelines vary widely and are not tied to generally applicable public policies for reducing risk in the face of a major earthquake [Barkley 2009; Poland et al. 2009]. Furthermore, the standards that do exist are not performance-based, making it difficult to determine exactly how these crucial systems will respond and interact with other components in the community [Barkley 2009]. This, in turn, makes it difficult to fully understand how a community will perform.

The engineering framework presented in subsequent chapters of this report addresses these shortcomings. It employs a transparent, performance-based, risk-informed methodology in order to establish performance targets for the numerous subsystems and components within the built environment that are consistent with broad resilience goals for the community. The proposed engineering framework is an adaptation of the regulatory framework used to design and evaluate the safety of nuclear power plants in the United States. This nuclear framework is described in the next chapter.

4 Nuclear Design Philosophy

The regulatory framework currently used to design, analyze, and regulate commercial nuclear power plants in the United States offers a promising template for communities to follow. Despite obvious differences in function and configuration, both communities and nuclear power plants are multi-faceted, dynamic systems comprising many interacting subsystems and components that cut across a diverse range of disciplines and professions. The current nuclear regulatory framework handles these numerous subsystems and components in a consistent and logical manner, informed partly by an explicit set of system-level performance expectations for the nuclear power plant. Furthermore, the tools and procedures employed by the current nuclear regulatory framework have been implemented successfully and refined extensively over the past several decades, resulting in significant improvements in the understanding of how these complex, dynamic systems behave.

This chapter examines the regulatory framework used to design and analyze nuclear power plants and their numerous subsystems and components. This examination is by no means exhaustive; instead it focuses on the parts of the framework with the most potential applicability to communities. Section 4.1 provides a brief overview of the current regulatory framework for nuclear power plants. Section 4.2 defines important nuclear terms and concepts that will be used throughout this chapter. Section 4.3 describes the design philosophy codified in current regulations. Section 4.4 discusses several important performance evaluation tools used to analyze the response of nuclear power plants, including probabilistic risk assessments (PRAs), event trees, and fault trees.

The engineering framework presented in Chapters 5, 6, and 7 of this report adapts the nuclear framework for use in a community setting. In particular, Chapter 5 describes how the nuclear concepts defined in Section 4.2 can be reinterpreted, subsequently providing a more transparent, integrated, and consistent basis for the design and evaluation of communities. Chapter 6 presents a set of event trees that can be used to link community-level resilience goals to specific performance objectives for individual components and subsystems within the built environment. This set of event trees, together with the definitions presented in Chapter 5, forms the foundations of the engineering framework proposed in this report. Finally, Chapter 7 demonstrates two potential applications of the proposed engineering framework using conceptual examples.

4.1   OVERVIEW

A nuclear power plant is a complex, multi-faceted, dynamic system. The focus of this chapter, however, is not the configuration or inner workings of the plant itself but rather the regulatory framework that dictates how it is designed, analyzed, constructed, and operated. More specifically, it is the general design and analysis philosophy codified in the current regulatory framework that is of particular interest. This philosophy, which is described in more detail in the following sections, provides a structured methodology for evaluating and mitigating the impact of natural hazards and other adverse events on the safety of a nuclear power plant. It also handles these numerous subsystems, components, and interactions in a consistent and logical manner, informed partly by an explicit set of system-level performance expectations for the nuclear power plant. It is this general methodology that will be adapted and applied to communities in subsequent chapters of this report.

In summary, the nuclear design philosophy begins at the system level, defining undesired outcomes whose occurrence should be avoided to the extent possible. It then identifies both the vital plant functions that must be maintained in order to prevent these undesired outcomes from occurring and the components and subsystems within the plant that support these vital functions. Next, it establishes performance targets for both the overall nuclear power plant system and, subsequently, its numerous subsystems and components. Finally, in order to ensure the plant satisfies these targets, the philosophy requires a detailed analysis of the system and its components in order to verify that the plant design satisfies the required system-level performance targets.

4.2   DEFINITIONS

The following subsections explain important terms and concepts from the nuclear regulatory framework, including undesired outcomes, accidents and accident sequences, vital functions, and frontline and support systems. In Chapter 5 these concepts will be extrapolated to communities.

4.2.1 Undesired Outcomes

In general, an undesired outcome represents a situation that inhibits the ability of a system to maintain functionality, the consequences of which can adversely impact the safety and welfare of the general public and surrounding environment. As such, a primary focus of the regulatory framework that governs the design and operation of such systems should involve minimizing the occurrence of these undesired outcomes to the extent possible. A wide range of events, including natural and human-made hazards, can trigger these undesired outcomes.

The nuclear regulatory framework defines two such undesired outcomes: core damage and large release of radioactivity. Core damage refers to damage to the nuclear fuel assemblies in the reactor core. It occurs when the reactor core losses sufficient cooling, resulting in heating of the core to the point that it damages the nuclear fuel [ANSI and ANS 2003]. Core damage ranges in severity depending on the length of time the core goes without cooling. If enough of the core

is damaged, large amounts of radioactive material can be released from the reactor core and, possibly, into the surrounding environment. Subsequently, core damage is a necessary precursor to a large release of radioactivity. Large release represents the worst-case outcome for a plant, not only dooming future operation of the plant, but also resulting in offsite contamination, casualties, and other adverse health effects. This hierarchy of undesired outcomes (i.e., core damage followed by large release) serves as the basis for many of the provisions and requirements that regulate the design and operation of nuclear power plants.

It is important to note that core damage and large release events may still take place (e.g., the nuclear accident at Fukushima Daiichi nuclear power plant after the 2011 Tohoku earthquake). However, these events should occur infrequently, depending in part on the risk targets codified in the regulatory framework.

4.2.2 Accidents and Accident Sequences

The International Atomic Energy Agency (IAEA) broadly defines an accident as "any unintended event, including operating errors, equipment failures and other mishaps, the consequences or potential consequences of which are not negligible from the point of view of protection or safety" [IAEA 2007]. An accident sequence is the representation of an accident as a series of events that may or may not result in a specified undesired outcome or end state, which for a nuclear power plant is either core damage or large release. The first event in an accident sequence, referred to as the initiating event, is any event, either internal or external, that perturbs normal operations of the plant, whether operating or not [ANSI and ANS 2003]. Initiating events include random subsystem and component failures, earthquakes, floods, fires, tornadoes, and aircraft impact, to name a few. The initiating event triggers a sequence of events that, depending on the combination of component, function, and operator failures or successes, may or may not result in the specified undesired outcome. If the undesired outcome does not result at the end of an accident sequence, the plant has avoided core damage or large release and is in a safe state.

For the purposes of illustration, Figure 4.1 displays a graphical representation of a simple accident sequence resulting in core damage. The sequence, which begins with an initiating event, comprises three additional events: Component A fails, Component B fails, and Component C fails. Core damage results only if all three events occur. Therefore, in this particular example, the accident sequence describes a simple parallel configuration with three components, A, B, and C. In a parallel configuration, all components must fail for the system to fail (i.e., core damage occurs). In contrast, in a series configuration, the system will fail if any one of its components fails. Note that Figure 4.1 represents only one of a potentially large number of accident sequences for the system being analyzed. These other sequences can involve additional components within the system, and can also feature both parallel and series configurations of components.
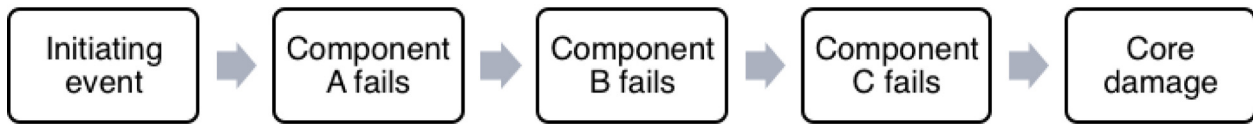
Figure 4.1   Graphical representation of a simple accident sequence.

Accident sequences can also be represented using Boolean expressions. A Boolean expression is mathematical construct that uses logical operators (intersection, union, etc.) to combine and give order to the events in an accident sequence. The symbol $\cap$ represents the intersection logical operator and denotes the occurrence of both events (i.e., both event X and event Y occur). The symbol $\cup$ represents the union logical operator and denotes the occurrence of either event (i.e., event X or event Y occurs).

Equation (4.1) shows the Boolean expression for the accident sequence in Figure 4.1. In words, Equation (4.1) says that if Component A fails and Component B fails and Component C fails, then core damage results. Again, note that Equation (4.1) represents only one of many potential accident sequences for the system. Accident sequences will be discussed further in Section 4.4.2, which describes event trees.

$$\left(\text{Component A fails}\right)\cap\left(\text{Component B fails}\right)\cap\left(\text{Component C fails}\right) \tag{4.1}$$

4.2.3 Vital Functions

When an initiating event occurs at a nuclear power plant, three vital safety functions need to be maintained in order to prevent core damage and subsequent large release [IAEA 2009]. The first vital function involves reactivity control: the self-sustaining chain reaction in the reactor core must be shut down. For most reactors, this involves insertion of control rods that absorb neutrons and prevent further fission. The second vital function involves cooling the fuel. Once the chain reaction is shut down, heat generated by the fuel needs to be removed from the core to ensure that the core does not incur damage such as melting, which would release radioactivity. In most reactors, this requires circulating a steady supply of cool water through the reactor core for several months, possibly longer. The third and final vital function involves confinement: radioactive material must not be allowed to escape into the environment. This typically involves relieving pressure in the core to ensure the steel reactor vessel does not rupture or the concrete containment structure does not crack. Failure to perform one of these functions does not necessarily result in core damage and/or large release; however, maintaining all of them ensures that these undesired events do not occur.

4.2.4 Frontline and Support Systems

Most nuclear power plant designs feature multiple redundant systems to perform each vital plant function. Depending on their role in an accident, these systems can be classified as either frontline or support systems. In a nuclear power plant, frontline systems are the engineered safety systems that deal directly with preventing an accident [Fullwood 2000]. In other words, they directly enable the vital functions in a nuclear power plant. Support systems, on the other hand, refer to those systems that support frontline systems and even other support systems. For example, the containment spray system, a frontline system that prevents over-pressurization of the containment structure, depends on several support systems, including electrical and water systems. Most nuclear power plant designs feature multiple redundant frontline systems for each vital safety function, as well as multiple redundant support systems for each frontline system. For example, for frontline systems requiring power, there are typically several support systems available to provide electricity, including offsite AC power, onsite AC power (often via diesel generators), and onsite DC power.

4.3 DESIGN AND REGULATORY PHILOSOPHY

In the context of this report, the structure of the regulatory framework currently used to design and analyze nuclear power plants is not as important as the philosophy that developed and shaped it because it is this philosophy that will be referred to and used in subsequent chapters of this report. Therefore, this section focuses primarily on the design and regulatory philosophy used in the nuclear industry in the United States. This philosophy has evolved substantially since the first nuclear power plants were built in the 1960s; the traditional, prescriptive, deterministic approach has given way (partly) to a more risk-informed, performance-based, probabilistic approach. The following subsections discuss two key concepts: defense-in-depth and risk-informed regulation.

4.3.1 The Concept of Defense-in-Depth

The concept of defense-in-depth is central to the current nuclear design and regulatory philosophy. Despite its fundamental role, there exists no official or preferred definition of the term [Sorenson et al. 1999]. The concept has evolved and expanded significantly since its initial development in the 1950s. One common interpretation defines defense-in-depth as the multiple physical barriers that prevent escape of radioactive material. These barriers typically include cladding on the fuel assemblies, the steel reactor vessel, and the concrete containment structure. Another common interpretation defines defense-in-depth as the high-level lines of defense in a nuclear power plant. These lines of defense are typically threefold: preventing the initiation of accident sequences; rapidly terminating those sequences that do occur; and mitigating the consequences of sequences that cannot be terminated successfully. A common thread in both interpretations is the deployment of successive levels of defense to ensure that safety of the plant is not dependent on only a single function or system [Sorenson et al. 1999]. This idea of multiple levels of protection is the central feature of defense-in-depth [INSAG 1999].

Table 4.1   Levels of defense-in-depth [INSAG 1999].

Level	Objective	Essential means
1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
2	Control of abnormal operation and detection of failures	Control, limiting, and protection systems and other surveillance features
3	Control of accidents within the design basis	Engineered safety features and accident procedures
4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
5	Mitigation of radiological consequences of significant releases of radioactive material	Offsite emergency response

Over the years the concept has expanded into an overall safety strategy for the nuclear industry. When applied properly, defense-in-depth ensures that no single human or equipment failure will lead to harm to the public, and even most combinations of failures will result in little or no harm [INSAG 1999]. Defense-in-depth is structured in five levels. Table 4.1 describes the objective of each level and the essential means for satisfying each objective. The five levels of defense are successive in that failure of one level calls into action the subsequent level. Events like earthquakes and fires, however, can impair multiple levels of defense simultaneously. For this reason, these hazards typically receive special consideration in order to limit their impact.

The current regulatory framework embodies the defense-in-depth strategy [Sorenson et al. 1999]. Its regulations are derived by repeated application of the question: what if a particular barrier or safety feature fails? The resulting set of provisions, which is prescriptive and deterministic in nature, ensures that nuclear power plants have multiple lines of defense for each barrier or safety feature, regardless of the probability that it may be required. In general, this conservative approach has served the nuclear industry in the United States well in terms of safety; however, in certain instances, it has resulted in excessive regulatory burden [Sorenson et al. 1999].

4.3.2 Risk-Informed Regulation

While most of its regulations are prescriptive and deterministic in nature, the Nuclear Regulatory Commission (NRC), the government agency that oversees commercial nuclear power plants in the United States, has been working over the past few decades to make the current nuclear regulatory framework more risk-informed. This change stems from the need to better understand and quantify the risks posed by current and future nuclear power plants to the health and safety of the public, where risk is defined as the product of two quantities: (1) the probability or

likelihood of an event occurring (i.e., equipment failure or human error) and (2) the consequences associated with its occurrence. As mentioned in the previous subsection, most current regulations were developed through consideration of questions that focus on only the second half of the risk equation: namely, what can go wrong and what are the consequences? Risk-informed regulation, on the other hand, involves asking a third question: how likely is it that something goes wrong? This third question helps ensure that the various burdens imposed by regulations are appropriate to their importance in protecting the health and safety of the public and the environment.

As an initial step towards a more risk-informed framework, the NRC issued a policy statement in 1986 that established an acceptable level of radiological risk to the public from nuclear power plant operation. In support of this risk target, the statement specifies two qualitative safety goals, which, in turn, are supported by two quantitative health objectives [USNRC 1986]. The two qualitative safety goals are:

- Individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear no significant additional risk to life and health.

- Societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risks.

The two quantitative health objectives are:

- The risk to an average individual in the vicinity (within one mile) of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of 1% (0.1%) of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed.

- The risk to the population in the area near (within ten miles) a nuclear power plant of cancer fatalities the might result from nuclear power plant operation should not exceed one-tenth of 1% (0.1%) of the sum of cancer fatality risks resulting from all other causes.

These qualitative safety goals and quantitative health objectives can be thought of as system-level performance targets for a nuclear power plant. The qualitative safety goals provide the basis for the quantitative health objectives, which in turn provide the basis for more specific numerical performance targets that focus specifically on the avoidance of core damage and large release. Core damage frequency (CDF) measures the number of core damage occurrences expected per year of operation for an individual reactor. The CDF for a plant is calculated using the probabilistic risk assessment (PRA) methodology, which is discussed more detail in Section 4.4.1. Similarly, large release frequency (LRF) measures the number of large release occurrences expected per year of operation. The LRF for a plant is also calculated using a PRA. The NRC has set as a target the expectation that all operating nuclear power plants have mean CDFs less than

1×10^{-4} per reactor-year and mean LRFs less than 1×10^{-5} per reactor-year [USNRC 2002]. This translates into less than one core damage event for every 10,000 reactor-years and less than one large release event for every 100,000 reactor-years, where a reactor-year refers to a year of plant operation. In philosophy, these targets can be considered equivalent to implicit performance expectation that buildings designed according to the provisions of the IBC have a 1% probability of collapse in 50 years [BSSC 2009].

Development in the mid-1980s of these system-level targets for nuclear power plants was driven primarily by the capabilities of the technology that existed at the time, not by a public policy decision as to what might be adequately safe, although this consideration did play a role. The NRC developed the targets using results from PRAs of several nuclear power plants built before 1980. As a result, most nuclear reactors designed and constructed before the NRC established these targets were expected to satisfy them and, when evaluated, they all did. New plants, whose designs include a variety of advanced technology features, will likely perform better than the NRC targets; however, like previously constructed plants, they are not required to meet a specific risk target.

While they do not replace the deterministic regulations based on defense-in-depth principles, the system-level goals and targets help provide a more rational and transparent foundation for the current regulatory framework for nuclear power plants. In other words, they represent the expected level of performance achieved by satisfying the prescriptive requirements of the current framework. All nuclear power plants currently operating in the U.S. meet these goals and objectives with considerable margin. Crucially, if it were to be found that a reactor did not meet one of these safety goals or health objectives, the NRC and the reactor owner/operator would perform a detailed investigation to understand the reason in order to achieve enough improvements to bring the reactor back in compliance with the specified requirements.

Since the 1986 policy statement, the NRC has gradually been updating its regulations to make them more risk-informed, though currently most regulations are still deterministic in nature. This is due primarily to reluctance to rely fully on the results of PRAs. In spite of this, the PRA methodology has been an essential tool in facilitating the gradual shift from a deterministic to a more risk-informed regulatory structure. In 1995, the NRC issued a policy statement addressing the use of PRA in nuclear regulatory activities. It states: "The use of PRA technology should be increased in all regulatory matters to the extent supported by the state-of-the-art in PRA methods and data and in a manner that complements the NRC's deterministic approach and supports the NRC's traditional defense-in-depth philosophy" [USNRC 1995].

While the 1995 policy statement clearly embraces the increased use of PRA, it does so with caution. Limitations of the PRA methodology, coupled with uncertainty and incompleteness in the understanding of how nuclear power plants behave during severe accidents, make the NRC reluctant to trust fully the results obtained from PRAs. Consequently, the NRC uses defense-in-depth to compensate for these shortcomings in understanding. This approach has resulted in a regulatory framework that is risk-informed rather than risk-based. A risk-informed framework uses risk information to develop regulations for those items most important to safety; however, it

reserves the right to impose additional regulations (i.e., extra lines of defense) in order to compensate for any potential uncertainty and/or incompleteness of knowledge.

4.4   PERFORMANCE EVALUATION TOOLS

In order for a regulatory framework to establish and successfully implement quantitative design targets, adequate performance evaluation tools must be available. Since its conception in the mid-1970s, the PRA methodology has gained increasing prominence in the nuclear industry as one such analysis tool. The following subsections describe the methodology in detail, focusing on key elements that will be used later in this report to evaluate communities.

4.4.1 Probabilistic Risk Assessment

In general, a PRA tries to answer the three following questions: (1) what can go wrong; (2) how likely it is; and (3) what are the consequences if it occurs [Kaplan and Garrick 1981]. For a complex system like a nuclear power plant, the answers to these questions can be highly uncertain, stemming primarily from limitations in our knowledge of how the systems behave during severe accidents. The PRA methodology provides a rational, consistent framework by which to evaluate these uncertainties and, ultimately, produce an estimate of risk.

The scope of a PRA depends on the nature of the risk being evaluated. The nuclear industry uses the PRA methodology to estimate three different levels of risk: a Level 1 PRA evaluates the risk of core damage at a plant; a Level 2 PRA estimates the risk of radioactive release at a plant; and a Level 3 PRA, or consequence analysis, quantifies the risk of radiation exposure to the public and the environment arising from plant operation [ANS and IEEE 1983]. Figure 4.2 shows the relationship between the three levels of PRA. As can be seen in the figure, a Level 3 PRA uses results from a Level 2 PRA, which in turn uses results from a Level 1 PRA.

In principle, the PRA methodology is relatively straightforward. After establishing the scope of the analysis (i.e., Level 1, 2, or 3 PRA), the first step involves identifying initiating events that have potential to disrupt steady-state operation of the reactor. Initiating events can be either internal or external to the plant. Internal initiating events typically involve operator errors and random failures of important equipment and components. External initiating events include earthquakes, hurricanes, tornados, fires, floods, and aircraft impact. Incomplete or ill-defined initiating events can lead to inaccuracies in the PRA results; therefore a great deal of emphasis must be placed on selecting a comprehensive and appropriate set of initiating events.

The second step in the PRA methodology involves identifying all frontline and support systems (including component failure rates, fragilities, and dependencies) that can be called upon during an accident sequence. As discussed in Section 4.2.4, frontline systems directly enable the basic safety functions in a plant, while support systems enable the frontline systems. Once all relevant systems have been identified, dependency matrices can be developed. A dependency matrix portrays any direct dependencies that exist between frontline and support systems or

among different support systems. These matrices will be used in the next step to determine how the failure of certain systems impacts the availability of others.

The third step in the PRA methodology involves performing a systems analysis of the plant to enumerate all possible accident sequences that can result from the initiating events identified in the first step. Each accident sequence involves a different series of events that, depending on the combination of component, function, and operator failures or successes, may or may not result in the specified undesired outcome (i.e., core damage or large release). There can be thousands or even millions of sequences for a plant. Accident sequences are portrayed graphically using event trees, which are described in more detail in Section 4.4.2.
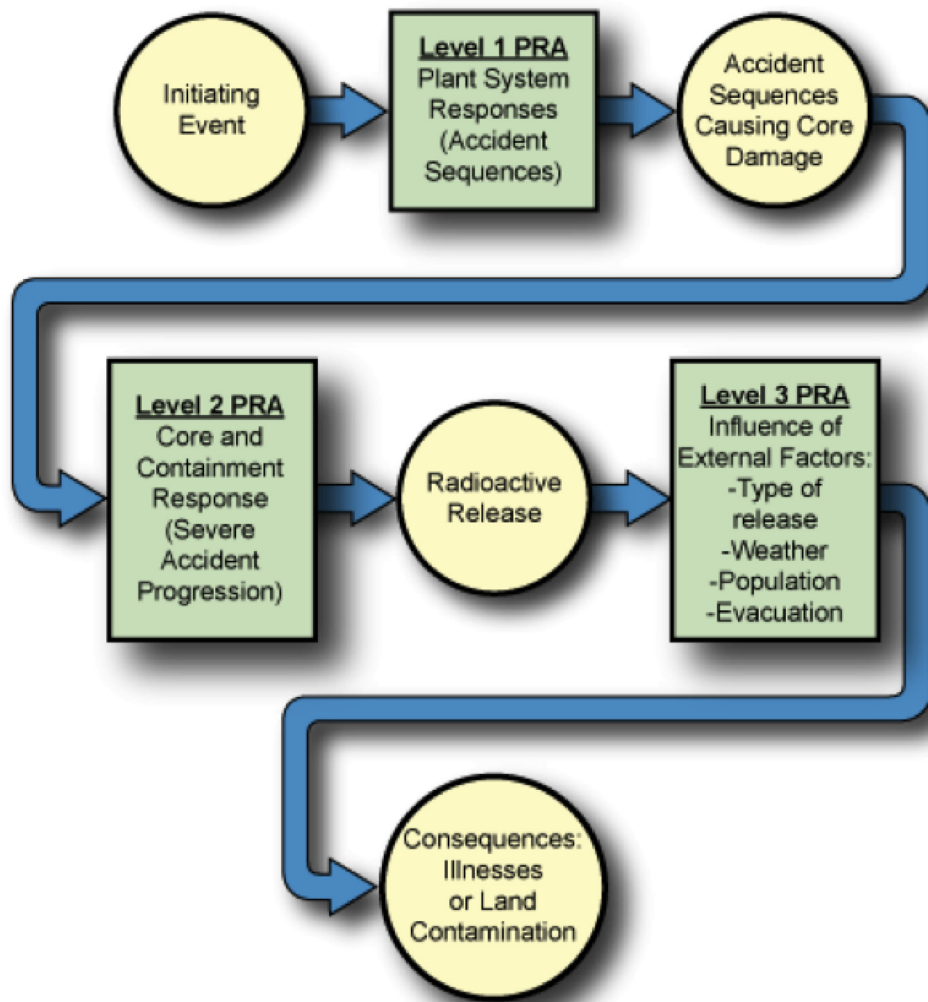
Figure 4.2   **The three levels of PRA used in the nuclear industry [USNRC 2012a].**

The final step in the PRA methodology involves compiling the information obtained in previous steps to produce an estimate of risk. For a Level 1 PRA, this means computing the CDF for the plant, which is obtained by summing the frequencies of all core damage accident sequences identified in the third step. For a Level 2 PRA, this involves computing the LRF for the plant. And for a Level 3 PRA, this means estimating the consequences (e.g., physiological, environmental, and economical issues) of core damage and large release on the surrounding environment and the population in neighboring communities. When these consequences are considered together with the CDF and LRF, an estimate of risk can be obtained.

While in principle the methodology is relatively straightforward, in practice, performing a PRA can be quite difficult. Much of this difficulty stems from limitations in current knowledge (i.e., epistemic uncertainty). Table 4.2 lists several of these limitations. It is important to emphasize, however, that these are not limitations in the PRA methodology itself, but rather limitations associated with its use and application. In other words, PRAs have made these shortcomings more transparent. Over time, with increased knowledge and better data, many of these limitations can be overcome. In the meantime, by exposing these limitations, performing a PRA serves as an effective way in figuring out areas where current knowledge needs most improvement.

Table 4.2   Limitations associated with the use of the PRA methodology.

	Limitation
1	Inability to anticipate fully all possible initiating events and their subsequent effects
2	Insufficient data to quantify accurately the frequency of occurrence of initiating events
3	Insufficient understanding of the failure mechanics and modes for systems and components
4	Insufficient data to quantify accurately the failure rates or fragilities of components
5	Inability to anticipate fully all possible dependencies among systems and components
6	Inability to enumerate fully all potential accident sequences
7	Inability to understand fully the consequences of severe accidents

4.4.2 Event Trees

An event tree is a graphical representation of the various accident sequences that can occur as a result of an initiating event [USNRC 2012b]. It is an essential tool in analyzing whether a nuclear power plant satisfies its system level design targets (i.e., CDF and LRF targets). It provides a rational framework for enumerating and, subsequently, evaluating the myriad events and sequences that can affect a nuclear power plant.

The top half of Figure 4.3 shows a simple example of an event tree and will be used to explain its basic structure and logic. While the event tree in Figure 4.3 is much simpler than one

for an actual nuclear power plant, the principles remain the same. All event trees begin with an initiating event—in this example, jumping from an airplane (see the red box in Figure 4.3). In general, for a nuclear power plant, an initiating event is anything that perturbs steady-state operation (e.g., an earthquake, fire, flood, etc.). After the initiating event, a series of top events follows (see the yellow box in Figure 4.3). Each top event corresponds to a subsystem or component required to prevent the undesired outcome from occurring. In this example, the undesired outcome involves injury or death of the person jumping from the airplane. For a plant, it is typically core damage or large release.

The event tree in Figure 4.3 comprises two top events. The first involves the main parachute while the second involves the reserve chute. After the initiating event occurs, the main parachute is called upon. This first top event can either fail or succeed. A downward branch in an event tree indicates that the corresponding top event has failed to occur, while an upward branch indicates the event has occurred successfully. In this example, a downward branch means the main parachute fails. An upward branch, on the other hand, means the main chute succeeds. Note that the upward branch results in the jumper landing safely, which is the first of three possible outcomes shown in Figure 4.3.

After the first top event, the second top event is called upon. Note, however, that for this particular example, if the first event is successful then the second top event is not called upon. In other words, the jumper does not need the reserve chute if the main one succeeds; only if the main parachute fails will the reserve chute be called upon. This second top event can either fail or succeed. Again, a downward branch represents failure and an upward branch success. If the reserve chute succeeds, the jumper lands safely (the second outcome in Figure 4.3). If, on the other hand, the reserve chute fails, the undesired outcome results, which is the third outcome shown in Figure 4.3.

In the end, the event tree in Figure 4.3 contains three accident sequences, with one resulting in the undesired outcome (i.e., injury or death of the jumper). This failure sequence is represented by the Boolean expression in Equation (4.2).

$$\left(\text{Main chute fails}\right) \cap \left(\text{Reserve chute fails}\right) \tag{4.2}$$

In order to compute the probability of the undesired outcome, P_f, we need to compute the probability of the accident sequence in Equation (4.2). If the two events are independent, P_f is simply:

$$P_f = P_{f,mc} \cdot P_{f,rc} \tag{4.3}$$

Where $P_{f,mc}$ is the probability the main chute fails and $P_{f,rc}$ is the probability the reserve chute fails. In order to compute these two quantities, we need to perform analyses of both the main and reserve chutes. Fault trees, which are discussed in the next subsection, provide one such methodology for doing so.
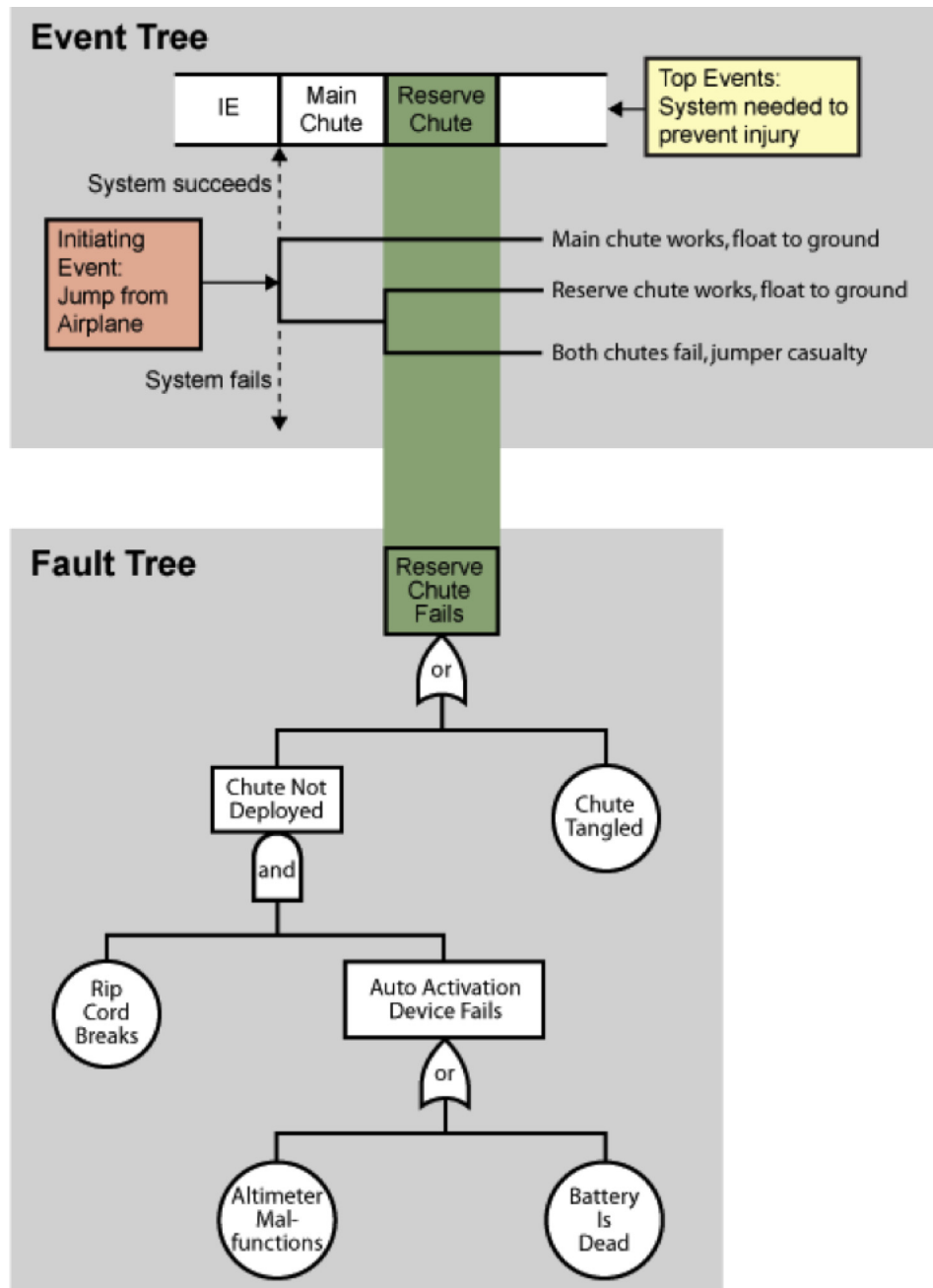
Figure 4.3   Example of a simple event and fault tree [USNRC 2012a].

4.4.3 Fault Trees

A fault tree is an analytical model that graphically depicts the logical combinations of faults (i.e., hardware failures and/or human errors) that can lead to an undesired state (i.e., failure mode) for a particular subsystem or component [Vesely et al. 1981]. This undesired state serves as the topmost event in the fault tree and usually corresponds to a top event in an event tree. Thus, a fault tree provides a rational framework for identifying the combinations of hardware failures and/or human errors that can result in a particular failure mode of a subsystem or component.

Once fully developed, a fault tree can be used to evaluate the subsystem or component quantitatively.

The bottom half of Figure 4.3 shows a simple example of a fault tree and will be used to explain its basic structure and logic. While the tree in Figure 4.3 is much simpler than one for an actual subsystem in a nuclear power plant, the principles remain the same. As mentioned in the previous paragraph, the topmost event in a fault tree corresponds to a top event in an event tree. The green box in Figure 4.3 explicitly highlights this connection. The top event in this example involves failure of the reserve chute. From the topmost event, the reader works downward through the fault tree. Directly beneath the top event is an OR-gate. To pass through an OR-gate, one or more of the events directly connected to the gate must occur. In this example, there are two connected events: "Chute Not Deployed" and "Chute Tangled." In other words, the reserve chute will fail if it does not deploy or if it gets tangled.

Directly beneath the "Chute Not Deployed" event in Figure 4.3 is an AND-gate. To pass through an AND-gate, all events directly connected to the gate must occur. In this example, there are two connected events: "Rip Cord Breaks" and "Auto Activation Device Fails." Both of these events must occur for the reserve chute to not deploy. Lastly, beneath the "Auto Activation Device Fails" event is another OR-gate, which is connected to two events: "Altimeter Malfunctions" and "Battery Is Dead." If either of these events occurs, the auto activation device will fail.

The fault tree in Figure 4.3 can be represented using a Boolean expression. See Equation (4.4). Table 4.3 explains the symbols used in Equation (4.4).

$$T = A \cup E_1 = A \cup (B \cap E_2) = A \cup \left[B \cap (C \cup D) \right] = A \cup (B \cap C) \cup (B \cap D) \tag{4.4}$$

According to Equation (4.4), the top event (failure of the reserve chute) will occur if any one of the following occurs: the chute tangles; the ripcord breaks and the altimeter malfunctions; or the rip cord breaks and the battery is dead. In Section 4.4.2, we were interested in computing $P_{f,rc}$, the probability that the reserve chute fails. Using the Boolean expression in Equation (4.4), we can now do so. See Equation (4.5).

$$P_{f,rc} = P\left(A \cup \left[B \cap (C \cup D)\right]\right) = P(A) + P\left(B \cap (C \cup D)\right) - P\left(A \cap \left[B \cap (C \cup D)\right]\right) \tag{4.5}$$

After some manipulation, Equation (4.5) expands to the following:

$$\begin{aligned} P_{f,rc} = P(A) + P(B \cap C) + P(B \cap D) - P(B \cap C \cap D) - P(A \cap B \cap C) - \\ P(A \cap B \cap D) + P(A \cap B \cap C \cap D) \end{aligned} \tag{4.6}$$

If we assume A, B, C, and D are all independent, Equation (4.6) simplifies to the following:

$$P_{f,rc} = P_A + P_B \cdot P_C + P_B \cdot P_D - P_B \cdot P_C \cdot P_D - P_A \cdot P_B \cdot P_C - P_A \cdot P_B \cdot P_D + P_A \cdot P_B \cdot P_C \cdot P_D \tag{4.7}$$

where $P_A = P(A)$ is the probability the chute tangles; $P_B = P(B)$ is the probability the ripcord breaks; $P_C = P(C)$ is the probability the altimeter functions; and $P_D = P(D)$ is the probability the battery is dead. These quantities can be estimated from historical data, laboratory testing, and/or analytical modeling.

In summary, the event and fault trees presented Figure 4.3 provide a structured, rational methodology for identifying and quantifying the risk associated with a particular activity (in this case, jumping out of an airplane). These performance evaluation tools have been implemented successfully in the design and analysis of nuclear power plants for several decades. In the next two chapters, these tools will be extended and applied to communities in order to create an engineering framework that explicitly links community-level resilience goals to specific performance targets for individual components and subsystems within the built environment.

Table 4.3 **Explanation of the symbols used in Equation (4.4).**

Symbol	Event
T	Reserve chute fails (i.e., top event)
$\cap$	AND-gate (i.e., intersection)
$\cup$	OR-gate (i.e., union)
E_1	Chute not deployed
E_2	Auto activation device fails
A	Chute tangled
B	Ripcord breaks
C	Altimeter malfunctions
D	Battery is dead

5   Adaptation of Nuclear Design Philosophy

This chapter marks the beginning of the presentation of the proposed engineering framework. The need for this framework arises from the observation that, under the current regulatory framework for communities, performance objectives for components and subsystems within the built environment are not tied to broader performance goals for the community. To remedy this shortcoming, the engineering framework presented in this chapter and the next seeks to develop an integrated, comprehensive, and consistent methodology for establishing performance targets for individual components. This methodology properly accounts for both the numerous interactions among components and subsystems and also broader community resilience goals.

The proposed engineering framework adapts parts of the regulatory framework used in the United States to design, analyze, and regulate commercial nuclear power plants. In particular, it extends and applies the general design philosophy described in the previous chapter to communities. In summary, this philosophy, as adapted to communities, comprises three main steps. The first step defines undesired outcomes for a community whose occurrence should be avoided to the extent practical. The second step identifies both the vital community functions that must be maintained in order to prevent these undesired outcomes from occurring and the frontline and support systems within the built environment that support these vital functions. Lastly, the third step establishes performance targets for both the overall community and, subsequently, its numerous frontline and support systems.

This chapter focuses on the first two steps in the above philosophy: Section 5.2 discusses the range of potential undesired outcomes that can affect a community; Section 5.3 identifies and describes the vital community functions that prevent the undesired outcomes from occurring; and Section 5.4 lists the frontline and support systems within the built environment that enable the vital community functions. Chapter 6 focuses on the last step of the philosophy, outlining a methodology that can be used to link community-level performance goals to specific performance targets for individual components and subsystems within the built environment. Section 5.5 helps set the stage for Chapter 6, describing how the performance evaluation tools presented in Chapter 4 are adapted for use in a community setting.

5.1   CAVEATS

Before describing the conceptual foundations of the proposed engineering framework, it is important to recognize that not all of the concepts presented in Chapter 4 lend themselves perfectly to extension to communities. Important differences exist between nuclear power plants and communities. One distinction involves physical scale. Communities occupy much larger geographic areas than nuclear power plants, meaning certain subsystems and components in a community, especially lifelines, can be spatially distributed over a potentially large area. As a result, it becomes necessary to account for partial failures of these subsystems and components. For example, an earthquake may cause damage to portions of a community's electric power grid, resulting in service disruptions to particular neighborhoods or city blocks. The evaluation of nuclear power plants does not account for partial failures: in the safety analysis of these plants, the assumption is generally that a particular subsystem or component is either functional or has failed completely.

Another distinction involves external boundaries of the system. Most components and subsystems in a nuclear power plant reside within the well-defined physical boundaries of the plant. A community, on the other hand, can rely on components and subsystems that fall outside its jurisdictional boundaries. For example, a community's electric power grid may draw electricity from a generating station hundreds of miles away. An event that disrupts the functionality of the station may cause service disruptions in the community, even though its electric power grid is not directly affected by the event. In general, these types of interactions do not exist in nuclear power plants.

The final distinction involves time scale. A community's built environment is constructed over time, expanding and evolving over the course of decades or even centuries as the community's population grows and/or its needs change. Consequently, individual components within the built environment have likely been designed and constructed using substantially different specifications and standards, meaning that the expected performance of similar components (e.g., residential buildings or highway bridges) within a community can vary drastically. In comparison, nuclear power plants are built over a relatively short period of time, with most of their components and subsystems being designed and constructed using a common set of specifications and standards.

In spite of these differences, the nuclear design philosophy, with appropriate modification, is still suitable for use in a community setting. The next four sections, which detail how several key nuclear concepts and tools are adapted, also discuss how the above differences can be addressed.

5.2   UNDESIRED OUTCOMES

As described in Section 4.2.1, an undesired outcome is one that inhibits the ability of a system (e.g., a nuclear power plant or a community) to maintain functionality, the consequences of which can adversely impact the safety and welfare of the general public and surrounding

environment. As such, a primary focus of the regulatory framework that governs the design and operation of such systems should involve minimizing the occurrence of these undesired outcomes to the extent possible. The nuclear regulatory framework defines two undesired outcomes, core damage and large release, and specifies performance targets that establish numerical limits regarding the likelihood of their occurrence (i.e., less than one core damage event in 10,000 years).

The first step in adapting the nuclear design philosophy to communities involves identifying possible undesired outcomes for a community. Because of their diverse nature, undesired outcomes will likely vary from community to community. This report focuses on one particular undesired outcome: a significant and rapid outmigration of residents. This outcome is particularly problematic because residents serve as both a community's workforce and customer base. If a large number of residents leave suddenly, the effects can ripple through the community and its economy. Businesses lose both workers and customers. In response, some might close permanently or decide to relocate, taking additional workers with them. As businesses and residents disappear, tax revenue for local government shrinks, forcing layoffs and cuts to essential community programs. This, in turn, might induce even more residents to leave.

It is important to reiterate that a community may choose whatever undesired outcome (or outcomes) it feels is appropriate given its particular circumstances. This report focuses on a significant and rapid outmigration of residents because this phenomenon has been observed (to varying degrees) following several major natural disasters. After the 1995 Great Hanshin earthquake, the population of Kobe, Japan, shrank by 2.5% and took 10 years to return to pre-earthquake levels [Chang 1996, 2010; Horwich 2000]. A year following Hurricanes Katrina and Rita, the population of New Orleans, Louisiana, was approximately 9% to 21% lower than pre-hurricane levels, though in certain neighborhoods it was significantly lower [Hori et al. 2009; Olshansky and Johnson 2010]. This report makes no attempt to define numerical boundaries for what constitutes a significant outmigration of residents, as these boundaries will likely vary from community to community. Consequently, individual communities need to determine thresholds that are appropriate for them.

5.3 VITAL FUNCTIONS

As detailed in Section 4.2.3, three vital safety functions stand in the way of core damage and large release during an accident at a nuclear power plant. In a similar fashion, this section identifies four vital community functions that prevent a significant and rapid outmigration of residents caused by an earthquake or other natural disaster. These four vital functions include public services, housing, employment, and education (adapted from Poland et al. [2009], SERRI and CARRI [2009], Twigg [2009], and Cutter et al. [2010]). It is important to note that these four items refer to functions, not physical infrastructure; the frontline and support systems that physically enable these vital functions are described in Section 5.4. If a community chooses an undesired event other than an outmigration of residents, then the corresponding vital community functions will likely need to be modified. The following four subsections describe each vital function in more detail.

5.3.1 Public Services

The first vital community function involves providing essential public services to the residents of a community, where public services refer to those services considered so important to a modern society that they are typically provided, subsidized, or regulated directly by the government. They commonly include police, fire and rescue, emergency medical care, non-emergency health care, food, water, energy, transportation, communication, banking, sanitation, and other essential community services (including building permit and inspection, planning, government finance and taxation, social services, defense, mail delivery, and recordkeeping). This list focuses on those services most crucial to disaster response and recovery because they play a fundamental role in protecting the physical health, safety, and security of the general public both in day-to-day operations and in the aftermath of a disaster.

In the immediate aftermath of a major accident or event, certain public services are critical to emergency response operations. For example, emergency services like police, fire, and medical are especially important in the first few hours and days, as they are responsible for rescuing and treating injured residents, extinguishing fires, evacuating unsafe areas, and maintaining general law and order. These services need to be at or near full capacity immediately following an initiating event in order to respond successfully to the potentially significant increase in demand caused by the accident or event.

Furthermore, certain public services play important roles in recovering from a major accident or event. For example, inspection services provided by the local building department will likely be required for a substantial number of a community's buildings before they can be reoccupied. In addition, mass transit systems need to be operational so residents can commute to and from work. Other public services are less critical to the disaster response and recovery process. For example, most residents can go without access to public libraries or museums for several months. However, this should not downplay the importance of these services beyond the response and recovery phases. Often, libraries, museums, and similar institutions play a vital role in preserving a community's history and culture. In some cases, they can also serve as major tourist attractions and thus play an important role in the local economy.

In the long term, failure to provide any public service after an event is unacceptable, representing a significant breakdown in one of the most fundamental functions of society. However, in the immediate aftermath of a major disaster, the public services most important to the response and recovery process must be given highest priority. Chapters 6 and 7 will discuss this prioritization in more detail.

5.3.2 Housing

The second vital community function involves providing housing to the residents of a community. Housing is particularly important because it helps keep in place both the workforce and customer base of a community's local economy. In a modern society, housing also includes basic utilities typically available at a residence, including water, sanitation, electricity, natural gas, and communications (e.g., telephone, Internet, and/or television). The building code

stipulates various provisions and requirements that establish minimum habitability requirements for residential buildings [ICC 2006; BSSC 2004; BSSC 2009], many of which pertain to the availability of essential utilities like water, power, and sanitation.

In the aftermath of a major accident or event, it is ideal for residents to shelter-in-place in their own homes [Poland et al. 2009; SPUR 2012]. Shelter-in-place is a new performance level for buildings developed by SPUR that proposes to relax certain habitability requirements during emergency periods. Whereas the building code would prohibit residents from occupying buildings without electricity or water, the SPUR shelter in place performance level would allow residents to shelter in such buildings provided they are structurally safe and important utilities are restored within a specified time period. Neighborhood support centers would provide shelter-in-place residents with interim access to important utilities.

However, for many different reasons, not all residential buildings will be safe to occupy after a major accident. If residents cannot shelter in place, the next best option is to move them to emergency shelters in their original neighborhoods. If this is not possible, then the next best option is to locate them somewhere else in the community, preferably in adjacent neighborhoods. And if this is not possible and residents are forced to leave, then it is important for the community to develop a plan for their return [Johnson and Eckroad 2001].

5.3.3 Employment

The third vital community function involves providing adequate employment opportunities to the residents of a community. Private employment is important because it is the primary driving force behind a local economy, servings two crucial functions (note that public employment is captured in the public services basic safety function). First, employment is responsible for producing, distributing, and selling many of the goods and services required by residents, local governments, businesses, and organizations in the community. Second, employment provides residents with a source of income to purchase the goods and services provided by the local economy.

In the immediate aftermath of a major accident or event, certain types of employment are more important than others. For example, engineers, contractors, and materials suppliers play critical roles in repairing and replacing damaged infrastructure after a disaster. Banks, insurance agencies, and other financial institutions finance these reconstruction projects. Therefore, these (and other) types of employment need to be available quickly following an initiating event.

If employment is disrupted for an extended period of time following an initiating event, some residents may struggle to afford even basic necessities like food, water, energy, and health care. In response, some will leave the community in search of employment elsewhere. As their customer base shrinks, businesses that sell goods and services to local residents may start to fail, initiating a potentially adverse cycle of further outmigration and additional business failures.

Globalization complicates this process. The growing interconnectedness of local economies means that certain types of businesses are less dependent on the residents of local communities to serve as their workforce and/or customer base. For example, if an earthquake

disrupts operations at a local factory, the owner might decide to shift production, either temporarily or permanently, to a location unaffected by the earthquake. Similarly, a local business that exports its goods and services is less vulnerable to a collapse in local demand caused by a major disaster than a business that sells only to local residents. However, these export businesses are now vulnerable to disasters outside their local community. In spite of these complications, employment remains a crucial function that communities must maintain in order to prevent disruption to the local economy and significant outmigration of residents.

5.3.4 Education

The fourth vital community function involves providing residents with adequate access to schools and education. A community's education system is an important factor in attracting potential residents. It also plays a crucial role in preventing residents from leaving the community after a major incident. Without functional schools or day care facilities for their children, some residents will be unable to return to work. If the disruption lasts long enough, some will leave the community to enroll their children elsewhere. Education can also play an important role in a community's local economy. Colleges, universities, and trade schools train and educate a community's workforce, which attracts businesses and other employers eager to leverage this highly skilled workforce.

5.4   FRONTLINE AND SUPPORT SYSTEMS

As discussed in Section 4.2.4, frontline systems in a nuclear power plant refer to those systems that directly enable its vital safety functions. Sometimes, frontline systems can support multiple functions. Frontline systems, in turn, are supported by support systems. Support systems are especially important because they often support multiple frontline systems, as well as other support systems, meaning that their failure can have widespread impact on the vital safety functions in a nuclear power plant.

In general, in a community, frontline systems refer to buildings while support systems refer to lifelines. Table 5.1 lists some of the frontline systems that support each of the four vital functions in a typical community. Table 5.2 lists the support systems in a typical community (adapted from PCCIP [1997], Rinaldi et al. [2001], ALA [2004], and Barkley [2009]). These lists are by no means exhaustive, but rather give a general indication of the types of components in each system.

Table 5.1   Frontline systems for each vital function in a community (adapted from ASCE [2006] and Poland et al. [2009]).

Vital community function	Frontline systems
Public services	• Hospitals, clinics, medical provider offices, and other health care facilities • Fire, police, rescue, and ambulance stations • Dispatch and emergency operations centers • City hall and other administrative offices • Military bases and other defense facilities • Grocery stores and pharmacies

Housing	• Permanent residences
	    ○ Single-family housing (including mobile homes)
	    ○ Multi-family housing (apartments, condominiums, dormitories, public housing)
	    ○ Institutional housing (nursing homes, assisted living facilities, correctional facilities, prisons, rehabilitation facilities)
	• Short-term residences
	    ○ Transient housing (hotels, motels, boarding houses)
	    ○ Emergency housing (community centers, schools, convention centers, arenas, other designated emergency shelters)
	    ○ Interim housing (FEMA trailers, tents)

Employment	• Commercial buildings (offices, retail shops, restaurants, banks, warehouses) • Industrial buildings (factories, hazardous facilities)
Education	• Preschools and day care facilities • Primary and secondary schools (elementary, middle, and high schools) • Post-secondary schools (universities, colleges, trade schools, institutes)

Table 5.2   **Support systems in a community (adapted from Rinaldi et al. [2001], Barkley [2009], PCCIP [1997], and ALA [2004]).**

Support system	Components
Electric power	Generation stations; transmission substations, towers, lines, and conduits; distribution substations, towers, lines, and conduits; control centers
Natural gas	Well facilities; processing plants; compressor stations; storage facilities; pipelines; control centers
Oil	Well facilities; pumping stations; refineries; storage facilities; pipelines; control centers
Solid fuels	Mines; processing/preparation plants; storage facilities
Roads and highways	Bridges; tunnels; roadways; traffic signs and signals; embankments; culverts; retaining walls; operation and control centers; maintenance facilities
Mass transit	*Buses*: stations; operation and control centers; fuel, dispatch, and maintenance facilities *Light rail*: tracks; bridges; tunnels; DC power substations; dispatch and maintenance facilities
Railways	Tracks; bridges; tunnels; stations; signs and signals; fuel, dispatch, and maintenance facilities
Airports	Runways; control towers; terminal buildings; hangars; fuel and maintenance facilities
Ports and waterways	Waterfront structures (docks, piers, wharves, sea walls, breakwaters, jetties); cranes and cargo handling equipment; warehouses; fuel facilities; locks and other engineered waterways
Water	Well facilities; desalination plants; dams; reservoirs; canals; pipelines; pumping stations; treatment facilities; storage tanks
Waste water	Pipelines; pumping/lift stations; treatment facilities
Solid waste	Transfer stations; materials recovery facilities; waste combustion facilities; disposal sites
Telecommunications	Central offices; data centers; network operations centers; transmitter stations; towers and poles; cables, lines, and conduits; satellite dishes

5.5   PERFORMANCE EVALUATION TOOLS

The following three subsections explain how the performance evaluation tools presented in Section 4.4 are adapted for use in a community setting. Specifically, Section 5.5.1 describes dependency matrices, Section 5.5.2 describes event trees, and Section 5.5.3 describes fault trees.

5.5.1 Dependency Matrices

As briefly mentioned in Section 4.4.1, dependency matrices provide a simple, convenient way to capture the interactions among the various systems in a nuclear power plant. Dependency

matrices can be used in a similar fashion in a community. Figure 5.1 displays a simple dependency matrix developed for the lifelines (i.e., support systems) depicted in Figure 3.1. The matrix is constructed one row at a time, with an "x" mark indicating a dependency between the two systems under consideration. For example, as shown in Figure 3.1, the transportation lifeline depends on oil (for fuels and lubricants), electric power (for power to signals and switches), and telecommunications [for supervisory control and data acquisition (SCADA) and communication]. Therefore, the transportation row of the dependency matrix in Figure 5.1 contains three "x" marks corresponding to these three dependencies.

	Oil	Water	Electric power	Transportation	Natural gas	Telecom	
Oil		x	x	x		x	4
Water			x			x	2
Electric power	x	x		x	x	x	5
Transportation	x		x			x	3
Natural gas	x	x	x	x		x	5
Telecom	x	x	x	x	x		5
	4	4	5	4	2	5	

Figure 5.1   Dependency matrix corresponding to the support systems portrayed in Figure 3.1.

A dependency matrix not only captures the direct dependencies between each of the systems included in the analysis, but also provides a relative indication of which systems are most important and which are most vulnerable. By summing the number of "x" marks in each column, a general measure of the importance of each system can be ascertained. In Figure 5.1, both electric power and telecommunications systems support five lifelines, meaning a service disruption to either of these systems can have widespread impact on other lifelines. In contrast, a disruption to the natural gas lifeline would only affect two other systems (electric power and telecom). Similarly, by summing the number of "x" marks in each row, a general indication of the vulnerability of each system can be obtained. In Figure 5.1, electric power, natural gas, and telecommunications systems each depend on five other lifelines, meaning they are more vulnerable to disruptions caused by disruptions to other systems. In contrast, the water support

system only relies on two other systems (electric power and telecommunications), meaning it is less susceptible to disruptions caused by external systems.

As Figure 5.1 demonstrates, dependency matrices make for useful planning tools. They can be adapted to fit other situations: for example, analyzing the interactions between frontline systems and support systems or between individual components within a particular system. In spite of these many potential applications, dependency matrices have a few important limitations. First, they do not capture the type of dependence (e.g., physical, cyber, geographic, or logical) between the systems (see Table 2.6). Second, they do not capture the strength of dependence between the systems. For these reasons, when performing in-depth analyses of community systems and their interactions, dependency matrices should only be used during the preliminary stages to identify general interactions.

5.5.2 Event Trees

The framework proposed in Chapter 6 makes extensive use of event trees. Traditionally, event trees have been used to analyze the response of a system or component (i.e., the analysis side of the equation); however, in this report they will be used to link broad performance goals for a community to specific performance targets for an individual component or subsystem (i.e., the design side of the equation). Regardless, the event trees described in Chapter 6 function in the same fashion as described in Section 4.4.2, with one key difference in how they are constructed. In a nuclear power plant, the response of frontline and support systems is binary: each system either fails or succeeds. In a community, the response of frontline and support systems (i.e., buildings and lifelines) is not as binary. Due to their spatial distribution, some systems can fail partially. For example, damage to a community's electric power system caused by an earthquake may disrupt service to only a small number of neighborhoods. Event trees can be easily modified to account for these partial failures, as will be demonstrated in Chapter 6.

5.5.3 Fault Trees

As detailed in Section 4.4.3, fault trees can be used to evaluate the failure modes of specific subsystems and components within a nuclear power plant. They can be used in a similar fashion to analyze particular subsystems and components within a community. However, this report does not demonstrate this extension for the following reason: unlike event trees, fault trees cannot be adapted for use in a generic fashion. For example, a fault tree cannot be developed for a generic electric power system because the structure of the fault tree requires detailed information about the system's components and configuration, which can be obtained only after selecting a particular system to study (e.g., the electric power grid in San Francisco). At this stage of development, the engineering framework presented in this chapter and the next is kept purposefully generic in order to maximize its applicability and also demonstrate its benefits more readily.

6   Community Event Trees

This chapter presents and describes a set of event trees that forms the backbone of the proposed engineering framework. To this end, Section 6.1 outlines the conditions under which the event trees should be used, while Section 6.2 discusses their general structure and organization. Section 6.3 introduces the event trees and details the rationale used to develop each one. Section 6.4 synthesizes and combines the event trees from the previous section into a single tree.

The event trees presented in this chapter can be used for many different purposes. For example, they can be used as an analysis tool to quantify the vulnerability of a community and its built environment to natural hazards. In addition, they can be used as a design tool to link community-level resilience goals to specific performance objectives for individual components and subsystems (e.g., buildings and lifelines) within the built environment. This application is given particular attention in Chapter 7, which presents a conceptual example demonstrating how to develop seismic performance targets for a new residential building from a community-level performance objective.

6.1   APPLICABILITY

A primary objective in developing the event trees presented in this chapter is to maximize their applicability. In general, the event trees can be used to evaluate a wide range of communities and hazards; however, several important limitations must first be acknowledged.

First, the event trees have been developed with earthquakes in mind. Earthquakes are unique for several reasons. Unlike most other natural hazards, they offer little or no advance warning. Hurricanes, on the other hand, can be forecast several days before landfall, allowing residents sufficient time to perform last-minute mitigation activities and evacuate to safer land. Even tornadoes give a few minutes of warning in most cases. In addition to their unpredictability, earthquakes can have extremely widespread impact. Tornadoes, in contrast, affect a much narrower geographic area. Furthermore, large-magnitude earthquakes are typically followed by sizable aftershocks, some of which can be as devastating as the initial shock, especially since the built environment is already in a weakened state. As a result of these unique factors, the event trees developed in this chapter may require some modification in order to apply to other natural hazards.

Second, the event trees have been developed for hazards that have the potential to affect an entire community. As a result, the event trees should not be used to evaluate the impact of small-scale hazards, like an isolated windstorm that damages an office building or a landslide that destroys two or three houses. Instead, the event trees should be used to evaluate hazards with more widespread impact, like hurricanes, earthquakes, and large tornadoes, wildfires, and floods.

Third, the event trees have been developed for application at the level of the community, which can range in size from large towns to major metropolises. For larger communities, the event trees presented in this chapter can also be used at the neighborhood level. However, at further levels of refinement (e.g., city block or parcel level), the event trees presented in this chapter begin to lose applicability. Additional refinement is possible, but it will likely require that a new set of event trees be developed, which is beyond the scope of this report. In the opposite direction, the event trees can be used to evaluate clusters of nearby communities or geographic regions (e.g., the San Francisco Bay Area). However, the event trees require modification in order to be applied at the state or national level. Again, this extrapolation is beyond the scope of this report.

And fourth, the event trees have been developed for mitigation and planning purposes only. More specifically, they have been developed to quantify the vulnerability of communities to hazards and, consequently, to help communities make better-informed policy decisions to address this vulnerability before a disaster strikes, through, for example, modifications to locally-adopted building codes, development of retrofit programs, and/or improved land use regulations. The event trees should not be used to track or assess the real-time response of a community during an actual disaster or accident.

6.2   GENERAL STRUCTURE

Event trees provide a structured framework for enumerating and, subsequently, evaluating the numerous combinations of events that can result in undesired outcomes for a system. In a nuclear power plant, they help identify specific combinations of events, or accident sequences, that can produce core damage and/or large release. The event trees presented in this chapter are developed for a similar purpose: to identify the combinations of events that can result in a significant and rapid outmigration of residents from a community. As described in Section 5.3, four vital functions stand in the way of this undesired outcome: public services, housing, employment, and education. Therefore, this chapter develops an individual event tree for each of the four vital community functions.

Figure 6.1 illustrates the general structure of an individual event tree. In essence, the tree describes the range of possible outcomes for a single vital function following an initiating event, which in the context of communities can range from natural phenomena like earthquakes, hurricanes, and floods to human-made events like terrorist attacks, economic downturns, and random system or component failures. This report, however, focuses primarily on earthquakes. The event tree in Figure 6.1 comprises three top events, each defined in terms of a different limit

on a tracking variable. As a result of this construction, these three top events enable the tree to capture partial failure of the vital community function.

The tracking variable in Figure 6.1 refers to a quantifiable parameter that describes the status of the vital function after the initiating event. This variable must be chosen carefully so that it adequately captures and summarizes the overall status of the vital community function. Using a single variable to track a complex, multi-faceted process carries with it inherent limitations; however, because the primary intent of the event tree is to serve as a summary of the impact of damage on the chosen vital function, a single variable, when chosen carefully, is appropriate.

The three top events in Figure 6.1 produce four distinct outcomes. Outcome #1 results if the first top event fails to occur (i.e., the parameter fails to satisfy Limit #1). Outcome #2 results if the first top event occurs but the second one does not (i.e., the parameter satisfies Limit #1 but fails to satisfy Limit #2), and so on. In general, Outcome #1 represents a worst-case scenario, one that has catastrophic impact on the vital community function, hence the red color. Outcome #4, on the other hand, represents a best-case scenario, one that has minor impact on the availability of the vital function, hence the green color. Outcomes #2 and #3 fall between these two extremes. Additional branches can be added to the event tree if more than four outcomes are desired. However, if chosen correctly, three top events should adequately encompass the range of possible outcomes for a vital community function, while at the same time limiting the complexity of the tree.

Figure 6.2, which portrays the event tree for the housing vital community function, helps make these concepts and ideas more concrete by providing a specific tracking variable and top events. The tracking variable for the event tree is the percentage of residents displaced from their homes. The first top event in the tree asks whether less than 20% of residents have been displaced from their homes. Figure 6.2, which portrays the event tree for the housing vital community function, helps make these concepts and ideas more concrete by providing a specific tracking variable and top events. The tracking variable for the event tree is the percentage of residents displaced from their homes. The first top event in the tree asks whether less than 20% of residents have been displaced from their homes. If the answer to this question is no (i.e., more than 20% of residents are displaced), the resulting outcome has catastrophic impact on the housing vital community function, potentially resulting in a significant and rapid outmigration of residents from the community, especially if other vital community functions suffer similar levels of disruption. If, on the other hand, the answer to this question is no (i.e., less than 20% of residents have been displaced), the second top event is called upon, which asks whether less than 10% of residents have been displaced. If yes, the resulting outcome has significant impact on the housing vital function; if no, the third top event is called upon, which asks whether less than 2% of residents have been displaced. Section 6.3.2 discusses this event tree in additional detail.
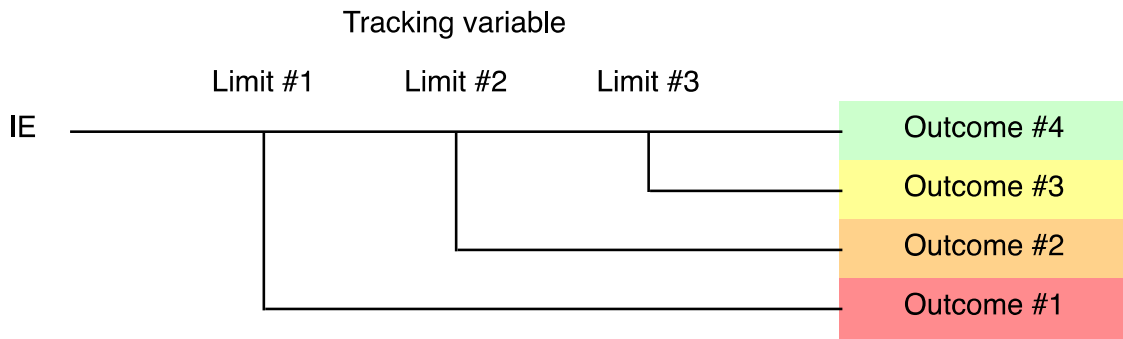
Figure 6.1   Example of an event tree for an individual vital community function.
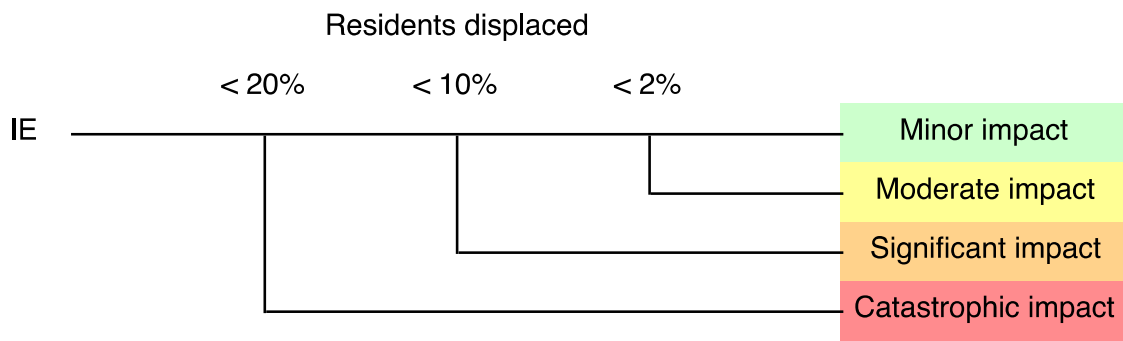
Figure 6.2   Housing event tree.

6.3   EVENT TREES

In general, when an initiating event such as an earthquake occurs, it causes damage to a community's built environment. More specifically, the initiating event causes physical damage to components (e.g., structures and hardware) within a community's frontline and support systems. The extent and scale of damage depends on many factors, including the characteristics of the initiating event (e.g., magnitude and location of the earthquake) and the vulnerability of the built environment. This damage has several immediate consequences. First, it can cause serious physical and psychological harm to residents in the community. For example, debris may fall on people, or buildings may collapse on their inhabitants. And second, damage to structures and equipment can cause frontline and support systems in the community to partially or completely fail. Through a complex web of interdependencies and interactions, these direct failures can cause additional systems to fail. Ultimately, if the initiating event causes enough direct and indirect system failures, it can disrupt one or more of the vital functions of a community.

The event trees presented and described in the following subsections aim to quantify and summarize the extent to which an initiating event impacts the vital functions of a community. Four event trees are described, one for each of the four vital community functions (public services, housing, employment, and education). The following subsections describe each tree in

more detail, including discussion of the rationale for selecting both the tracking variable and top events for each tree.

6.3.1 Public Services

The public services event tree, depicted in Figure 6.3, captures the effect of damage to frontline and support systems on the availability of the public services vital function. Specifically, the event tree tracks the percentage of capacity disrupted by the initiating event, where capacity is benchmarked to pre-event service levels. This measure is an aggregation of the disruption to individual public services. Only the most essential public services for response and recovery should be included in this aggregation. Recall that public services refer to those services considered so important to a modern society that they are typically provided, subsidized, or regulated directly by the government. Section 5.3.1 enumerates a baseline set of public services, including police, fire and rescue, emergency medical care, non-emergency health care, food, water, energy, sanitation, transportation, communication, banking, and other essential community services (including building permit and inspection, planning, government finance and taxation, social services, defense, mail delivery, and recordkeeping). Some of these services are provided by the private sector but are included in this formulation due to their extremely important nature.

Because of the diversity of services included in the public services vital community function, the tracking variable needs to be an aggregation. Of course, this aggregation could be avoided by developing a separate event tree for each public service, but the complexity involved with doing so is not appropriate at this stage of development and would likely overwhelm the analyst or decision maker. Furthermore, since the framework in this chapter has been developed for application at the community level, there is benefit to describing the public services vital function with a single measure.

In addition, the selected tracking variable is appropriate because it can capture disruptions to the capacity of public services arising from several different sources. First, frontline systems (i.e., buildings) may suffer structural damage to the extent that they are not safe to occupy. For example, a hospital that sustains significant permanent lateral displacement after an earthquake will be rendered unusable due to the collapse risk it poses. Second, frontline systems may lose access to important utilities due either to nonstructural damage to the buildings themselves or to damage to external support systems (i.e., lifelines). For example, a hospital's water supply can be disrupted if pipes and conduits throughout the hospital break, or if damage to a community's water infrastructure causes a service disruption to the hospital. And third, support systems may suffer physical damage. For example, damage to a community's water infrastructure can disrupt water service to certain neighborhoods, which can inhibit the ability of firefighters to battle blazes. The chosen tracking variable is robust enough to capture all of these effects.

At the same time, it is important to recognize a limitation associated with the choice of tracking variable presented in Figure 6.3. Because it aggregates the performance of many different services, the tracking variable does not capture the source or nature of the disruption.

For example, consider a situation in which 10% of capacity is disrupted. This disruption could be the result of a 10% disruption to each individual service, or it could be the result of a 100% disruption to one particular service (assuming there are 10 individual services and each is weighted equally in the aggregation). As this simple example demonstrates, the tracking variable obscures which services have been disrupted and the extent to which each has been impacted. Again, this limitation can be overcome by simply creating separate event trees to track each public service.

The three top events displayed in Figure 6.3 establish four possible outcomes for the public services vital function. The top outcome, less than 5% capacity disrupted, represents a situation that has limited impact on the community's ability to provide public services to its residents. The bottom outcome, more than 50% of capacity disrupted, on the other hand, represents a scenario that can have catastrophic impact on public services. It is important to note, however, that the numerical limits corresponding to each top event in Figure 6.3 may require refinement in order to properly distinguish the range of possible outcomes. Currently, insufficient data exists to verify the appropriateness of these numerical targets (i.e., whether a disruption of more than 50% of capacity actually represents a catastrophe). In addition, these targets may need to be adjusted on a community-by-community basis. However, at this stage of development, the structure of the public services event tree is more important than the numerical targets associated with its top events, as the numbers can be refined further in the future.
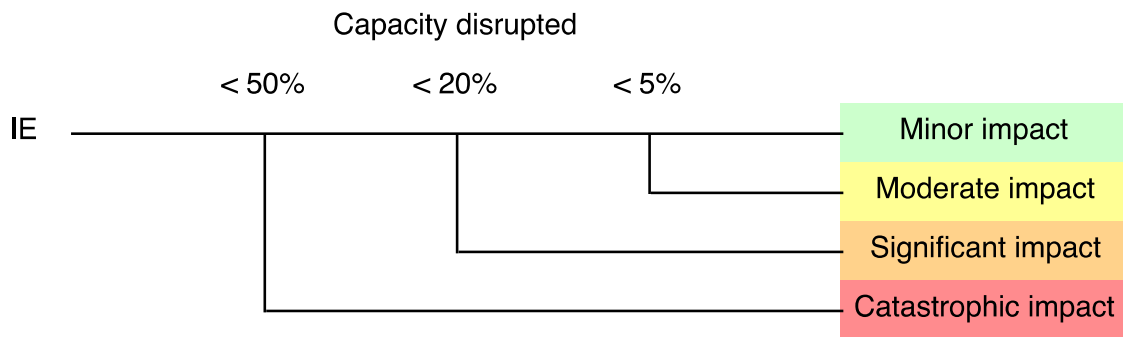
Figure 6.3   Public services event tree.

6.3.2 Housing

The housing event tree, depicted in Figure 6.2, captures the effect of damage to frontline and support systems on the availability of the housing vital community function. Specifically, the event tree tracks the percentage of residents displaced by the initiating event. This tracking variable captures the two main reasons residents can be displaced. First, frontline systems (i.e., residential buildings) may suffer structural damage to the extent that they are not safe to occupy following an initiating event. However, even if a residence is safe to occupy, some residents might still choose to leave for personal or psychological reasons, while others might be forced out by landlords who want to make repairs before allowing residents to reoccupy. Second, frontline systems may lose access to important utilities, due either to nonstructural damage to the buildings themselves or to damage to external support systems (i.e., lifelines). This second

reason is especially applicable to multi-family housing (e.g., apartments and condominiums) and institutional housing. After an initiating event, landlords may not want tenants occupying apartments that lack power or water for liability reasons, while certain types of institutional housing (e.g., nursing homes) may require utilities in order to remain operational. The chosen tracking variable is robust enough to capture these effects.

In addition, the percentage of residents displaced is an appropriate choice of tracking variable because in the days, weeks, and months following a major disaster, a primary concern of community leaders and decision makers involves sheltering displaced residents. Unlike tracking variables that focus on the physical damage to a community's housing stock, the percentage of displaced residents provides a direct measure of the affected population, which is important for emergency response and recovery planning (e.g., determining the number of public shelters required, preparing emergency food supplies, etc.).

Despite its appropriateness, it is important to recognize the limitations of the chosen tracking variable. First, it does not capture which residents are displaced. Vulnerable populations within a community are more likely to seek shelter at public facilities than affluent, well-connected populations [Yelvington 1997; Wisner et al. 2003]. Therefore, it is helpful for communities to know which types of residents are displaced so that they can plan accordingly. Second, the chosen tracking variable does not capture the reason each resident is displaced. As detailed in the first paragraph of this subsection, residents can be displaced for several reasons, the implications of which have varying impact on housing recovery. For example, it typically takes more time to repair buildings with significant structural damage than those with minor nonstructural issues [Comerio 1998; SPUR 2012; ATC 2010]. Knowing the nature of the physical damage to the housing stock helps a community determine (approximately) how long residents will be displaced. Third, the chosen tracking variable does not capture which types of housing are damaged. Again, the implications of this affect recovery time. For example, multi-family housing typically takes longer to restore than single-family housing [Comerio 1998; ATC 2010; SPUR 2012]. However, because the primary intention of event tree is to summarize the overall impact of damage on the housing vital function, these limitations are secondary in nature.

The three top events displayed in Figure 6.2 establish four possible outcomes for the public services vital function. The top outcome, less than 2% of residents displaced, represents a situation that has limited impact on the community's ability to provide housing to its residents. The bottom outcome, where more than 20% of residents are displaced, represents a scenario that has catastrophic impact on housing. These numerical targets are based on data from SPUR [2012]. However, they may need to be adjusted on a community-by-community basis. In general, the first top event (20%) corresponds to a percentage of the population that substantially exceeds the community's emergency shelter capacity; the second top event (10%) corresponds to the community's emergency shelter capacity; and the third top event (2%) corresponds to the community's vacancy rate, which refers to the percentage of rental units that are unoccupied. In the aftermath of an earthquake, these vacant units can be made available to displaced residents, provided they are not rendered uninhabitable from damage caused by the earthquake.

6.3.3 Employment

The employment event tree, depicted in Figure 6.4, captures the effect of damage to frontline and support systems on the availability of the employment vital function. Specifically, the event tree tracks the percentage of businesses disrupted by the initiating event. The tracking variable is appropriate because it can capture the many different reasons that businesses can be disrupted following an earthquake or other natural hazard. Table 6.1 summarizes several of these reasons. As the table demonstrates, there exist a wide variety of reasons a business can be disrupted, reflecting the high degree of interconnectedness within a community's local economy. Again, the chosen tracking variable is robust enough to capture these numerous sources of disruption.
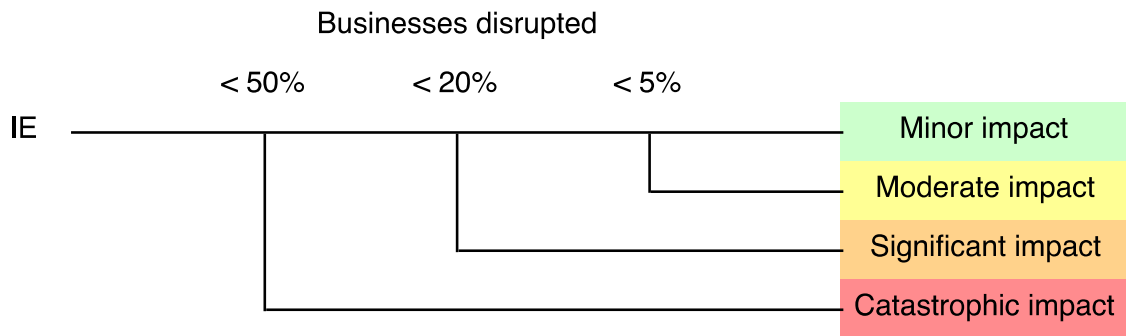
Figure 6.4   Employment event tree.

In addition, the percentage of businesses disrupted is an appropriate choice of tracking variable because businesses are drivers of the local economy. In the aftermath of a major disaster, it is usually business owners, not workers, who make decisions about closing or relocating, either temporarily or permanently. Therefore, the tracking variable should focus on the percentage of businesses disrupted, not the percentage of workers unemployed. Furthermore, a tracking variable like the unemployment rate would be unable to distinguish between those unemployed before the disaster and those unemployed because of the disaster.

Despite its appropriateness, it is important to note several limitations associated with the chosen tracking variable. First, it does not capture which businesses are disrupted. For example, consider a scenario in which 10% of businesses are disrupted after an earthquake. If the disrupted businesses include several large employers, it will impact more workers and likely have graver consequences for the community than if the disrupted businesses are small employers. In addition, if the disrupted businesses are concentrated in a single employment sector, the consequences will likely impact a community more profoundly than if the disrupted businesses are spread across all sectors. Furthermore, if the business disruption affects a critical industry or sector, the consequences will likely be more profound than if a less critical sector is disrupted. Second, the chosen tracking variable does not capture the nature of the business disruption. Table 6.1 lists several causes of business disruption, with each one having varying impact on the speed of recovery (if recovery is even possible). While important, these limitations are secondary in

nature, as the primary purpose of the employment event tree is to broadly summarize the impact of damage on businesses.

The three top events displayed in Figure 6.4 establish four possible outcomes for the employment vital community function. The top outcome, less than 5% of businesses disrupted, represents a situation that has limited impact on the community's ability to provide employment opportunities to its residents. The bottom outcome, where more than 50% of businesses are disrupted, represents a scenario that can have catastrophic impact on employment. It is important to note, however, that the numerical limits corresponding to each top event in Figure 6.4 may require refinement in order to properly distinguish the range of possible outcomes. Currently, insufficient data exists to verify the appropriateness of these targets (i.e., whether a disruption of more than 50% of businesses actually represents a catastrophe). In addition, these targets may need to be adjusted on a community-by-community basis. Again, at this stage of development, the structure of the employment event tree is more important than the numerical targets associated with its top events, as the numbers can be refined in future iterations.

Table 6.1   Reasons that businesses can be disrupted after an earthquake.

Description	Example
Frontline systems (i.e., buildings) may suffer structural damage to the extent that they are not safe to occupy	A restaurant suspends operations because its building suffers extensive damage (i.e., receives a red tag)
Frontline systems may lose access to important utilities, due either to nonstructural damage to the buildings themselves or to damage to external support systems (i.e., lifelines)	Loss of electricity from the power grid suspends operations at an otherwise undamaged factory
Support systems may suffer physical damage	Damage to roads and highways disrupts the transportation of goods and services, causing supply chains to shut down and preventing workers from commuting to work
Other businesses may be disrupted	A factory suspends activity because the building of one of its suppliers has suffered damage and, as a result, cannot supply a key input
Customers may relocate	A coffee shop near a large apartment complex closes because the apartment complex suffers extensive damage, forcing residents to seek shelter elsewhere
Workers may relocate	A factory shuts down because its workers, displaced from their homes, relocate at great distances from the factory

6.3.4 Education

The education event tree, depicted in Figure 6.5, captures the effect of damage to frontline and support systems on the availability of the education vital function. Specifically, the event tree tracks the percentage of students displaced by the initiating event. This tracking variable is appropriate because it can capture the many different reasons students can be displaced after an initiating event such as an earthquake. First, frontline systems (i.e., schools) may suffer structural damage to the extent that they are not safe for students to occupy. Second, frontline systems may lose access to important utilities, due either to nonstructural damage to the schools themselves or to damage to external support systems (i.e., lifelines). Additionally, support systems may suffer damage. For example, roads and highways may suffer damage that prevents students from getting to school. Furthermore, students may be displaced because their schools also serve as public shelters during a disaster or emergency. Lastly, students may be displaced if their homes are damaged and they are forced to move to locations that lack adequate schools. The chosen tracking variable is sufficiently robust to capture these effects. In contrast, variables that focus on physical damage to schools are unable to capture student displacement caused by external factors (e.g., damage to roads and highways, schools doubling as public shelters, etc.). Furthermore, these alternate tracking variables obscure important factors like the size of the schools damaged.

Despite its appropriateness, it is important to recognize two limitations associated with the chosen tracking variable. First, it does not capture which students have been displaced. For example, consider a scenario in which 15% of students have been displaced after an earthquake. If the majority of displaced students come from vulnerable neighborhoods, it will have different consequences than if most displaced students come from affluent neighborhoods. Similarly, if the majority of displaced students are in grade school, it will have different consequences than if displaced students are in high school or college, in part because younger children need constant care if not in school, meaning their parents will likely be unable to return to work until their children are back in school. Second, the chosen tracking variable does not capture why students have been displaced. As described above, students can be displaced for many reasons, each one having varying impact on how quickly students can get back in the classroom. However, because the primary intention of event tree is to summarize the overall impact of damage on the education vital function, these limitations are secondary in nature.

The three top events displayed in Figure 6.5 establish four possible outcomes for the education vital function. The top outcome (less than 5% of students displaced) represents a situation that has limited impact on the community's ability to provide educational opportunities to its residents. The bottom outcome (more than 20% of students displaced), on the other hand, represents a scenario that can have catastrophic impact on education. It is important to note, however, that the numerical limits corresponding to each top event in Figure 6.5 may require refinement in order to properly distinguish the range of possible outcomes. Currently, insufficient data exists to verify the appropriateness of these targets (i.e., whether displacing more than 20% of students actually represents a catastrophe). In addition, these targets may need to be adjusted on a community-by-community basis. Again, at this stage of development, the

structure of the education event tree is more important than the numerical targets associated with its top events, as the numbers can be refined in future iterations.
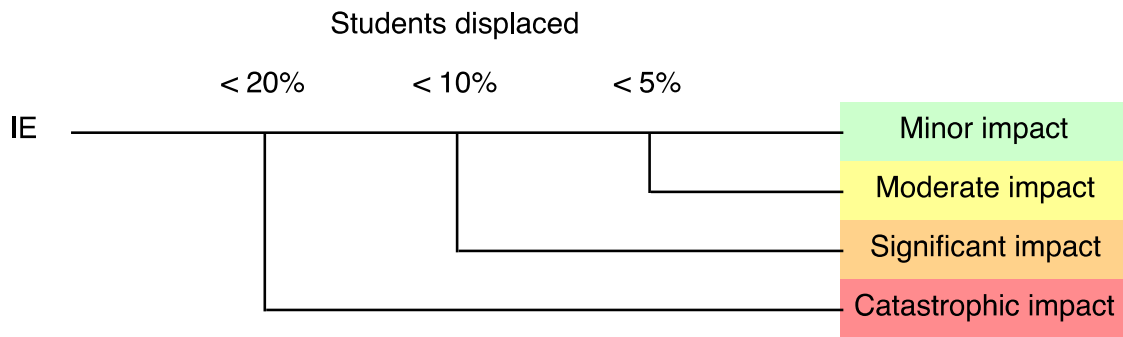
Students displaced

Figure 6.5   Education event tree.

6.4   SYNTHESIS

In order to obtain a complete picture of the impact of damage to frontline and support systems on the community, the four event trees need to be combined into a single tree. This combined event tree, which is depicted in Figure 6.6, summarizes the numerous outcomes possible in a community following an initiating event such as an earthquake. There are $4^4 = 256$ possible outcomes. The topmost outcome in Figure 6.6 results from the following sequence of events: less than 5% of public services capacity disrupted, less than 2% of residents displaced, less than 5% of businesses disrupted, and less than 5% of students displaced. Because each vital community function suffers only minor disruption, this outcome does not trigger a significant and rapid outmigration of residents from the community. In contrast, the bottommost outcome in Figure 6.6 will likely result in a significant and rapid outmigration of residents because each vital community function suffers catastrophic disruption: more than 50% of public services capacity disrupted, more than 20% of residents displaced, more than 50% of businesses disrupted, and more than 20% of students displaced.

The combined event tree in Figure 6.6 provides a structured methodology for identifying combinations of events that can result in a significant and rapid outmigration of residents (or any other undesired outcome of interest). Identification of these sequences is a crucial step in the proposed engineering framework, as it links damage to frontline and support systems to broader outcomes in a community. Because these sequences will likely vary from community to community, this report does not attempt to definitively identify them here. In general, sequences that trigger a significant and rapid outmigration of residents can be identified using data from previous disasters or, in its absence, the expert judgment of those with extensive knowledge of communities and the built environment (e.g., engineers, planners, policymakers, and economists).

The combined event tree in Figure 6.6 can be used for both design and analysis applications. On the analysis side, the combined event tree can be used to synthesize the results of separate analyses of frontline and support systems in order to determine the overall impact on

the community and its vital functions. For example, an analysis of the housing stock using HAZUS, FEMA's methodology for estimating potential losses from disasters, can be used in conjunction with the housing event tree (see Figure 6.2) to understand the contribution of potential housing losses to the likelihood of outmigration following an earthquake scenario. This report, however, does not demonstrate an application of this nature. Instead it focuses on design applications. Chapter 7 presents a conceptual example that uses the combined event tree to develop seismic design targets for a new residential building from a community-level performance goal. Ultimately, the combined event tree can serve as a mechanism for linking community-level resilience goals to specific design targets contained in building codes and other engineering standards for buildings and lifeline systems.
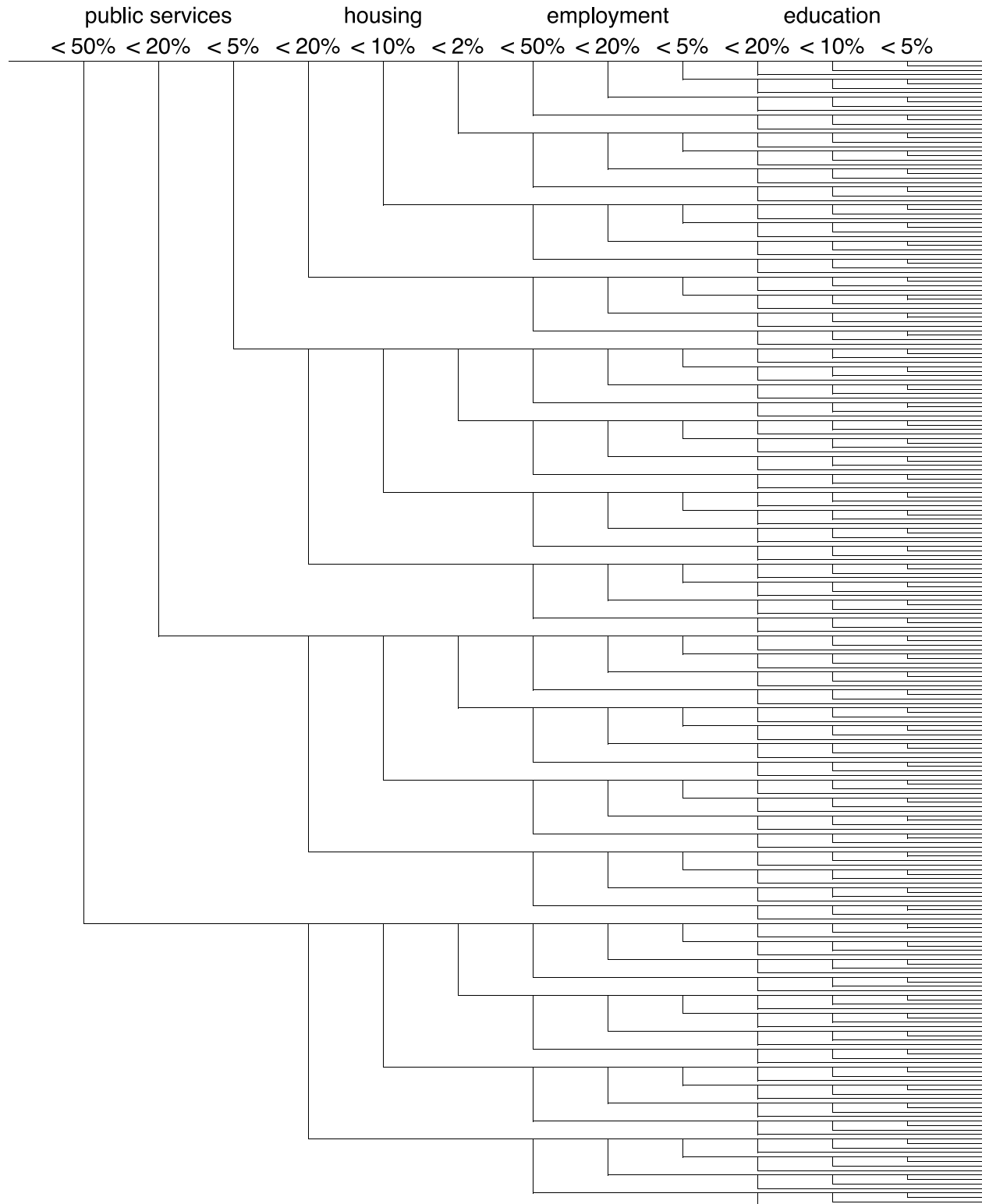
Figure 6.6   **Single event tree obtained from combining the public services, housing, employment, and education event trees.**

7   Example Applications

This chapter represents the culmination of the work in this report, presenting two conceptual examples that highlight potential applications of the framework described in Chapters 5 and 6. The first example, presented in Section 7.1, describes a methodology for establishing consistent performance targets for individual components from a community-level target using the event trees developed in the previous chapter. The second example, presented in Section 7.2, outlines a methodology for estimating the capacity of public services disrupted using dependency matrices.

7.1   EXAMPLE: ESTABLISHING CONSISTENT PERFORMANCE OBJECTIVES

The first example demonstrates how the event trees presented in the previous chapter can be used to develop consistent performance targets for individual components from a community-level target. In particular, the example shows how to develop seismic performance targets for a new residential building from a community-level performance objective using the combined event tree in Figure 6.6. Ultimately, this example outlines a procedure that can be used to modify the implicit performance objectives contained in building codes, or even to lay the conceptual foundations of a "community performance code," a proposed document that specifies explicit performance targets for a community and the numerous components and subsystems of its built environment (see Chapter 8 for further discussion).

The following subsections outline a basic methodology for creating a consistent hierarchy of performance objectives for a community. The first step, described in Section 7.1.1, establishes performance targets for the entire community. The second step, described in Section 7.1.2, uses these community-level targets together with the event trees presented in the previous chapter to determine performance objectives for each of the four vital community functions. The third step, outlined in Section 7.1.3, uses the objectives for each vital community functions to establish performance targets for frontline and support systems in the built environment. And the fourth step, discussed in Section 7.1.4, establishes targets for individual components within each frontline and support system. Several important simplifications and assumptions need to be made during each step; each one will be identified and detailed in the following subsections when appropriate.

7.1.1 Performance Targets for a Community

The first step in the methodology involves establishing a performance target (or targets) for the entire community. These targets can take many different forms. For a nuclear power plant, system-level performance targets take the form of a mean annual frequency of core damage and large release: less than 1×10^{-4} and 1×10^{-5} per reactor year, respectively (see Section 4.3.2 for additional detail). System-level performance targets for a community can mirror those for a nuclear power plant. In other words, community-level performance targets could take the form of a mean annual frequency of occurrence of an undesired outcome, which in the context of this report is a significant and rapid outmigration of residents.

The target chosen for the mean annual frequency of significant outmigration directly impacts the resilience of a community. In general, a community that selects a more stringent performance target (e.g., 1×10^{-4} instead of 1×10^{-3}) is less vulnerable to events that can cause a significant and rapid outmigration of residents, including earthquakes, hurricanes, and floods. Consequently, the mean annual frequency of significant outmigration can be considered a proxy for community resilience, with smaller targets equating to improved levels of resilience.

For the purposes of this example, we will assign a mean annual frequency of significant outmigration equal to 1×10^{-4} or less per year, which translates to one undesired outcome occurring every 10,000 years, on average. Note that this value represents a design target. As such, it does not reflect the actual level of performance achieved by the community as it currently exists. Instead, it represents the level of performance the community ultimately desires. If an evaluation reveals that the community and its existing built environment do not satisfy their specified performance targets, the community needs to make investments to retrofit or replace its infrastructure in order to improve performance.

It is essential that community stakeholders (e.g., politicians, engineers, and planners) establish these community-level performance targets in a public process so that they accurately reflect the level of risk acceptable to society. There are many considerations to weigh during this process, including the expected lifetime of individual subsystems and components within the built environment (e.g., buildings, bridges, power grid, etc.), the level of risk aversion of stakeholders, and sustainability/environmental issues. The mean annual frequency target chosen for this example, 1×10^{-4}, likely resides at the conservative end of the spectrum of possible targets, as it is the same as the target for averting core damage in a nuclear power plant.

In order to verify that a community satisfies the target chosen for this example, its performance needs to be evaluated across the entire range of possible hazard types and intensities (e.g., small-magnitude and large-magnitude earthquakes, frequent and rare floods, etc.). An explicit and comprehensive analysis of this scope and scale is not practical. Furthermore, engineers and planners traditionally use specific hazard scenarios when designing individual buildings or when modeling damage and loss at the community level. Therefore, to be consistent, the annualized performance target needs to be converted to targets corresponding to specific scenarios for each type of hazard that can impact a community. For each type of hazard, an appropriate number of scenarios should be selected. This number should enable an accurate

picture of response to emerge without burdening designers and analysts with unnecessary work. Furthermore, hazard scenarios should be well separated and effectively encompass the range of intensities with most potential to impact a community. For example, for most hazards, small magnitude events do not need to be considered.

In this example, we will make the following simplification: earthquakes are the only type of hazard that can affect the hypothetical community. Furthermore, to be consistent with the IBC, we will select only two earthquake scenarios. The first scenario, referred to as the design basis earthquake (DBE), has a 475-year mean recurrence interval, corresponding to an annual frequency of exceedence of 2×10^{-3}, or 10% probability of being exceeded in 50 years [BSSC 2004]. This scenario represents an earthquake that can reasonably be expected to occur during the lifetime of a building, which is typically assumed to be 50 years. The second scenario, referred to as the maximum considered earthquake (MCE), has a 2,450-year mean recurrence interval, corresponding to an annual frequency of exceedence of 4×10^{-4}, or 2% probability of being exceeded in 50 years [BSSC 2004]. This scenario represents the "worst-case" event expected during the lifetime of a structure. Note, however, that the MCE is not truly a worst-case event as larger-magnitude earthquakes are still possible, though they are very unlikely.

Once specific hazard scenarios have been selected, conditional probabilities of significant outmigration need to be chosen for each one. These conditional probabilities should be assigned in such a way that the original mean annual frequency of significant outmigration (1×10^{-4}) is satisfied. In this example, we will select the following conditional probabilities of significant outmigration: 1% for the 475-year earthquake and 10% for the 2450-year earthquake, which are similar in structure to the performance objectives selected for nuclear power plants in ASCE 43 (Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities) [ASCE 2005]. If we assume these two hazard scenarios (DBE and MCE) are independent, the mean annual frequency associated with these choices of conditional probabilities is:

$$P_f = 0.01\cdot 2\times10^{-3} + 0.10\cdot 4\times10^{-4} = 6\times10^{-5} < P_{f,target} = 1\times10^{-4} \qquad (7.1)$$

As Equation (7.1) demonstrates, the resulting mean annual frequency of significant outmigration for the community (6×10^{-5}) is less than the original target (1×10^{-4}) by a factor of 1.67. Because only two scenarios have been selected, this level of conservatism is warranted. Note that the ratio of $P_{f,target}$ to P_f can be interpreted as the confidence with which the original community-level performance target is satisfied. Consequently, values greater than one indicate higher confidence that the original community-level performance target is satisfied. Again, it is important to note that other combinations of numbers can be selected if desired, provided that the resulting P_f is less than $P_{f,target}$. Community stakeholders and policymakers can adjust this ratio as they see fit.

In summary, in this example, we have established two community-level performance objectives:

- 1% probability of significant outmigration in the 475-year earthquake
- 10% probability of significant outmigration in the 2450-year earthquake

These two community-level performance targets provide the foundation for the hierarchy of performance objectives developed in the next three subsections.

7.1.2 Performance Targets for the Vital Community Functions

The second step in the methodology involves establishing performance targets for each of the four vital community functions (public services, housing, employment, and education). To this end, the community-level performance objectives from the previous step (see Section 7.1.1) need to be translated into targets for each vital community function. The event trees presented in Chapter 6 and reproduced in Figure 7.1 provide the means for this translation. Specifically, the event trees can be used to identify the sequences of events that produce a significant and rapid outmigration of residents from a community. Once these sequences have been identified, probabilities can be assigned to each branch of the tree in such a way that the original community-level performance objectives are satisfied. These branch probabilities can then be used to establish performance objectives for each of the four vital community functions.

Continuing the example from the previous subsection, the two community-level performance objectives (1% probability of significant outmigration in the 475-year earthquake and 10% probability of significant outmigration in the 2450-year earthquake) need to be translated into targets for each vital function. In order to do so, the event trees in Figure 7.1 need to be combined into a single tree so that sequences that result in a significant and rapid outmigration of residents can be identified. Figure 7.2 shows this combined event tree. It comprises $4^4 = 256$ possible outcomes or accident sequences. Sequences that trigger a significant outmigration of residents can be identified using several different techniques, including expert judgment or data from previous disasters. In this example, we will identify these sequences using the following simple rule: a significant outmigration results either when at least two of the individual event trees in Figure 7.1 are "in the red" or when at least three are "in the orange." An individual event tree is "in the red" when its bottom outcome has occurred and "in the orange" when its second-from-the-bottom outcome has occurred. As a result of this rule, there are 104 sequences that trigger significant outmigration. In Figure 7.2, a red box at the end of a branch indicates such a sequence.

(a) Public services event tree

(b) Housing event tree

(c) Employment event tree

(d) Education event tree

Figure 7.1   **Individual event trees for the vital community functions.**

public services   housing   employment   education

< 50% < 20%   < 5%   < 20% < 10%   < 2%   < 50% < 20%   < 5%   < 20% < 10%   < 5%
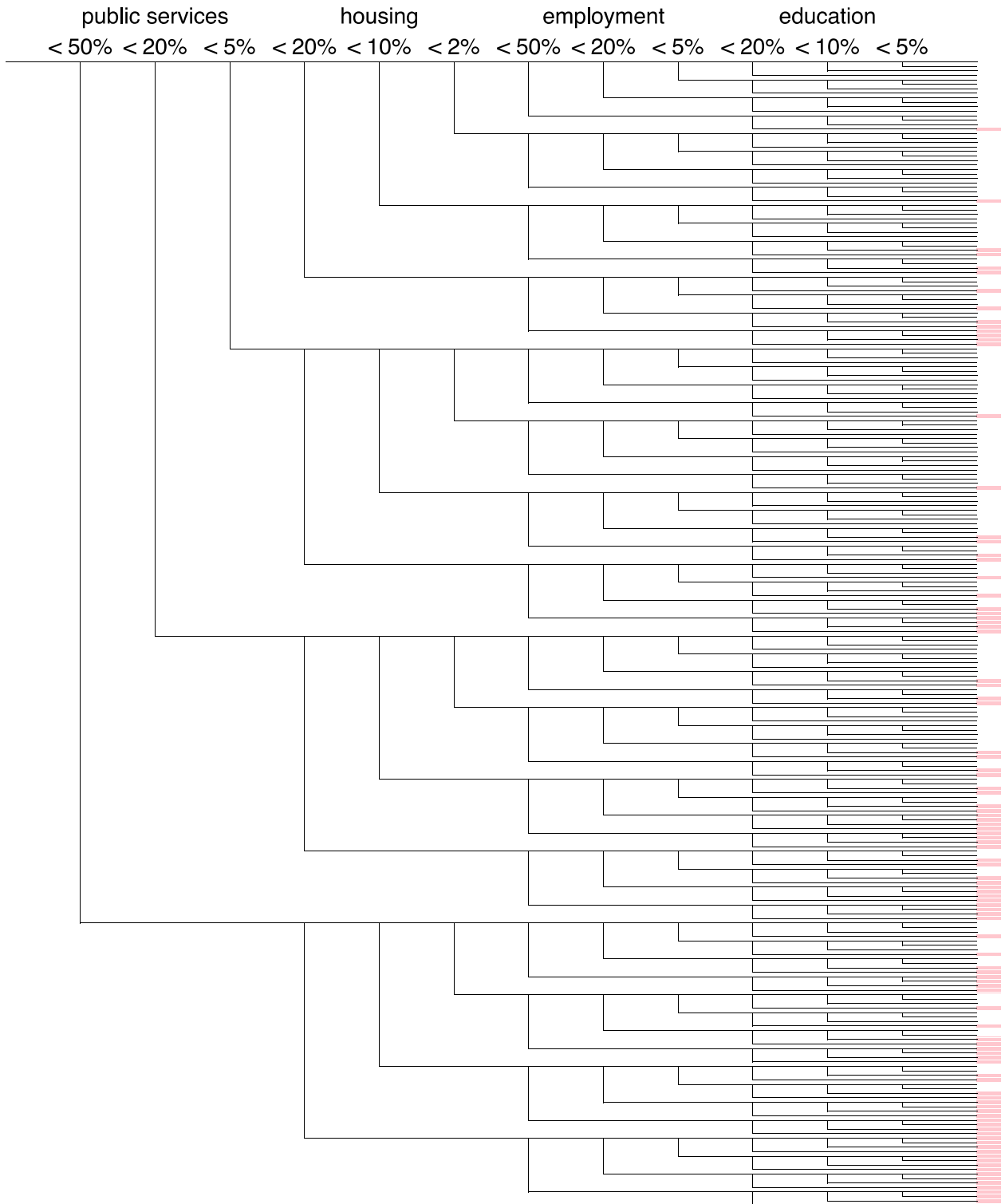
Figure 7.2   **Combined event tree (sequences that trigger significant outmigration
identified by red boxes at the end of the branches).**

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In order to compute the conditional probability of significant outmigration for a community in a specific hazard scenario (e.g., a DBE or MCE), the probability of each of the 104 significant outmigration sequences needs to be computed and then summed. Consider, for example, the bottom outcome in the combined event tree in Figure 7.2. This outcome, which is a sequence that triggers significant outmigration, can be represented with the following Boolean expression:

$$(C > 0.50) \cap (R > 0.20) \cap (B > 0.50) \cap (S > 0.20) \tag{7.2}$$

Where C is the fraction of capacity disrupted [i.e., the tracking variable in Figure 7.1(a)], R is the fraction of residents displaced, B is the fraction of businesses disrupted, S is the fraction of students displaced, and the Boolean symbol $\cap$ indicates the intersection of events (i.e., the occurrence of two or more events). Note that each of these tracking variables can be considered a random variable bounded between zero and one. In words, Equation (7.2) represents a sequence in which more than 50% of the capacity of public services has been disrupted, more than 20% of residents have been displaced, more than 50% of businesses have been disrupted, and more than 20% of students have been displaced. Equation (7.3) can be used to calculate P_{256}, the probability that this sequence—the 256th sequence—occurs.

$$P_{256} = P\left[(C > 0.50) \cap (R > 0.20) \cap (B > 0.50) \cap (S > 0.20)\right] \tag{7.3}$$

Similarly, Equation (7.4) can be used to compute P_{255}, the probability that the second-from-the-bottom outcome in Figure 7.2 occurs. This outcome is another sequence that results in a significant and rapid outmigration of residents.

$$P_{255} = P\left[(C > 0.50) \cap (R > 0.20) \cap (B > 0.50) \cap (0.10 < S \leq 0.20)\right] \tag{7.4}$$

Similar equations can be developed for the other 102 significant outmigration sequences.

Because each sequence is mutually exclusive, the conditional probability of significant outmigration for the community is simply the sum of these 104 equations. In this example, the sum needs to be less than 1×10^{-2} (1%) for the DBE and 1×10^{-1} (10%) for the MCE. In order to ensure these requirements are satisfied, an appropriate multivariate probability distribution for the tracking variables (C, R, B, and S) needs to be selected. A multivariate distribution is required because, in general, the tracking variables are not pair-wise independent. In other words, the tracking variables can be correlated. This correlated behavior arises from the fact that each of the four vital community functions commonly relies on a shared network of frontline and support systems in order to operate successfully. A multivariate distribution can capture this correlation.

In this example, however, we will assume that each of the tracking variables is independent of the others. As a result, a multivariate probability distribution is no longer required; instead, each tracking variable can be described individually with a separate univariate distribution. This assumption greatly simplifies the computations of Equation (7.3) and Equation (7.4); see Equation (7.5) and Equation (7.6), respectively, for the simplified expressions that

result. This assumption is justified because, while it impacts the final numbers, accuracy of results is not the focus of this example. Instead, the focus is on the process, which is not affected by the independence assumption. Future iterations of this example should address this assumption by using a multivariate probability distribution to capture correlation among the four tracking variables.
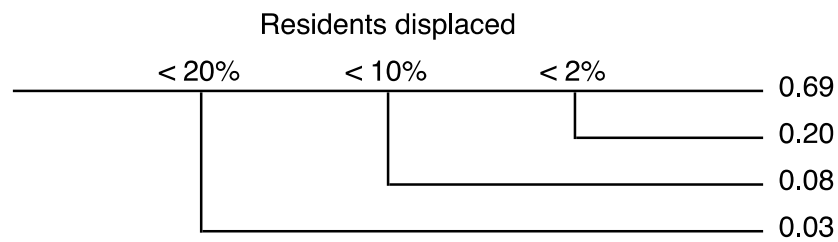
$$P_{256} = P(C > 0.50) \cdot P(R > 0.20) \cdot P(B > 0.50) \cdot P(S > 0.20) \tag{7.5}$$

$$P_{255} = P(C > 0.50) \cdot P(R > 0.20) \cdot P(B > 0.50) \cdot P(0.10 < S \le 0.20) \tag{7.6}$$

Employing these simplifications and assumptions, it is relatively straightforward to assign branch probabilities for each vital community function in a way that satisfies the conditional probability targets for significant outmigration (1% in the DBE or 10% in the MCE). There are many possible ways to assign branch probabilities. Again, community stakeholders and policymakers have the freedom to choose branch probabilities that most appropriately reflect the priorities and preferences of the community. Figure 7.3 and Figure 7.4 demonstrate one possibility.
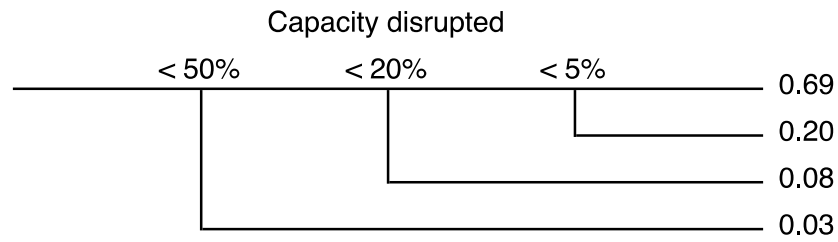
Capacity disrupted

< 50%   < 20%   < 5%
—————————————————————————————— 0.69
                              ———————— 0.20
                     —————————————————— 0.08
          ——————————————————————————————— 0.03

(a) Public services event tree

Residents displaced

< 20%   < 10%   < 2%
—————————————————————————————— 0.69
                              ———————— 0.20
                     —————————————————— 0.08
          ——————————————————————————————— 0.03

(b) Housing event tree

Businesses disrupted

< 50%   < 20%   < 5%
—————————————————————————————— 0.69
                              ———————— 0.20
                     —————————————————— 0.08
          ——————————————————————————————— 0.03

(c) Employment event tree

Students displaced

< 20%   < 10%   < 5%
—————————————————————————————— 0.69
                              ———————— 0.20
                     —————————————————— 0.08
          ——————————————————————————————— 0.03
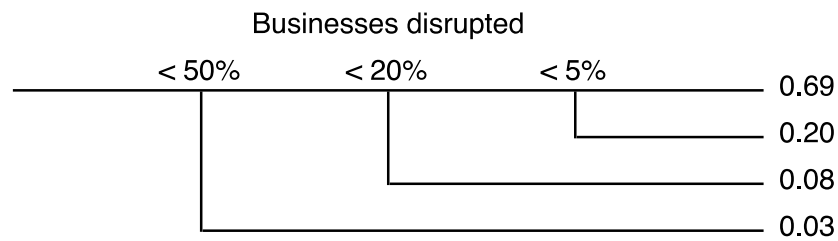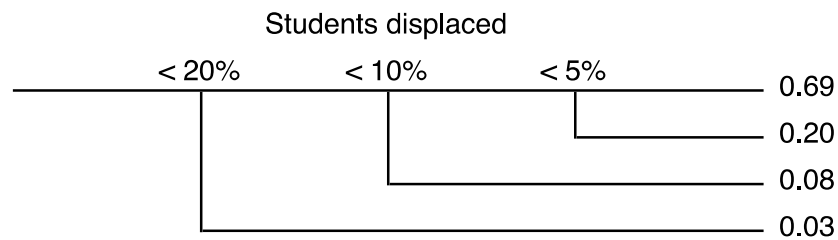
(d) Education event tree

Figure 7.3   **Branch probabilities corresponding to 1% probability of significant outmigration in the design basis earthquake.**
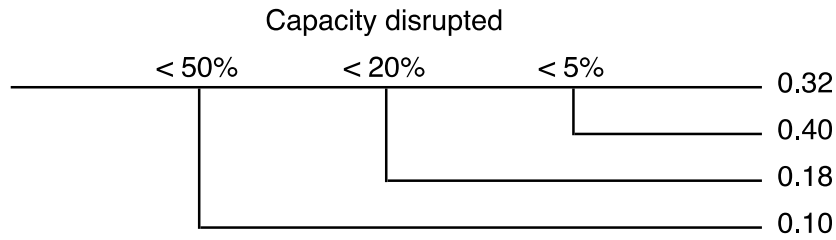
Capacity disrupted

< 50%	< 20%	< 5%	
			0.32
			0.40
			0.18
			0.10

(a) Public services event tree

Residents displaced

< 20%	< 10%	< 2%	
			0.32
			0.40
			0.18
			0.10

(b) Housing event tree

Businesses disrupted

< 50%	< 20%	< 5%	
			0.32
			0.40
			0.18
			0.10

(c) Employment event tree

Students displaced

< 20%	< 10%	< 5%	
			0.32
			0.40
			0.18
			0.10
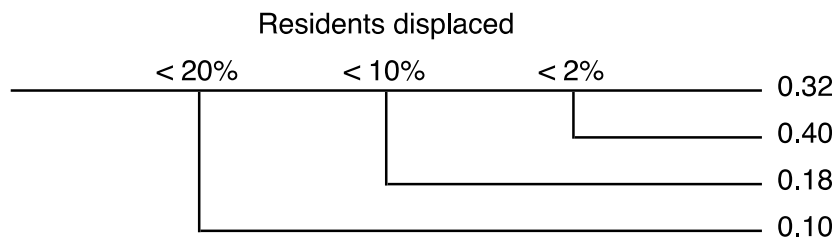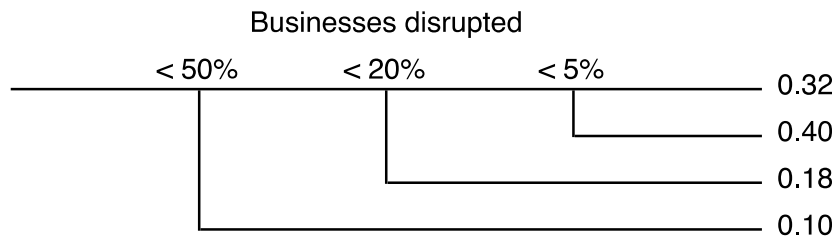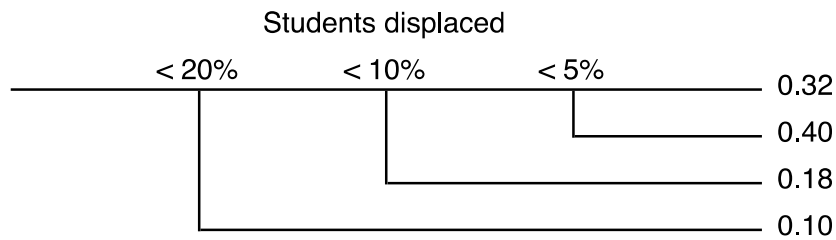
(d) Education event tree

Figure 7.4   **Branch probabilities corresponding to 10% probability of significant outmigration in the maximum considered earthquake.**

Figure 7.3 shows an example of branch probabilities that satisfy the specified target of 1% probability of significant outmigration in the DBE. Note that the sum of branch probabilities for each event tree must equal one. Also note that each vital community function is given equal importance. In other words, the corresponding branches for each vital function are assigned the same probability (e.g., the top outcome in each of the event trees in Figure 7.3 is assigned a probability of 0.69). Using these quantities, it is straightforward to compute the probability associated with each sequence. For example, Equation (7.5), which corresponds to the bottom sequence in Figure 7.2, computes to:

$$P_{256} = 0.03 \cdot 0.03 \cdot 0.03 \cdot 0.03 = 8.1 \times 10^{-7} \tag{7.7}$$

If this calculation is repeated for the other 103 sequences that trigger significant outmigration, the conditional probability of outmigration in the DBE can be computed by summing each probability. For the branch probabilities in Figure 7.3, the conditional probability of outmigration is 0.92%, which is less than the specified target of 1%. Recall, however, that Figure 7.3 depicts only one of many possible ways to assign branch probabilities. Community stakeholders may, for example, determine that housing is the most important vital community function and, subsequently, assign branch probabilities so that the combined likelihood of the two bottom outcomes in the housing event tree is smaller than the two bottom outcomes in the three other event trees.

Similarly, Figure 7.4 shows an example of branch probabilities that satisfy the specified target of 10% probability of significant outmigration in the MCE. As before, each vital community function is given equal importance (e.g., the top outcome in each of the event trees in Figure 7.4 is assigned a probability of 0.32). A similar procedure as outlined in the previous paragraph can be used to calculate the probability of each sequence and, subsequently, the conditional probability of significant outmigration in the MCE. For the branch probabilities in Figure 7.4, the conditional probability of outmigration is 10.05%, which is very close to the specified target of 10%. Again, Figure 7.4 depicts only one of many possible ways to assign branch probabilities.

Before proceeding, it is important to note that the branch probabilities in Figure 7.3 and Figure 7.4 represent design targets for each of the vital community functions and, subsequently, the built environment that supports them. As such, branch probabilities do not reflect the actual level of performance achieved by the built environment as it currently exists. Instead, they represent the level of performance the community ultimately desires. If an evaluation reveals that the existing built environment does not satisfy its specified performance targets, the community needs to make investments to retrofit or replace its infrastructure in order to improve performance.

The branch probabilities for each vital community function can be used to plot the cumulative distribution function for each tracking variable. Figure 7.5 displays the cumulative distribution function for each vital community function in both earthquake scenarios. It is important to note upfront that the curves in Figure 7.5 are not the same as seismic fragilities, as their interpretations are different. Seismic fragilities plot the conditional probability of failure of

a particular component or structure given a seismic demand parameter (e.g., peak ground acceleration). The next paragraph describes how the curves in Figure 7.5 are to be interpreted.

Figure 7.5(b) shows the cumulative distribution function for the housing vital community function in both the DBE and MCE. On the horizontal axis is r, the fraction of residents displaced, which ranges between zero and one. Note the difference between R and r. R refers to the random variable that describes the tracking variable, while r refers to a specific value that R can take. On the vertical axis is $F_R(r)$, the cumulative distribution function for R, which is the probability that R is less than or equal to r. To make these concepts more concrete, consider $r = 0.20$. From Figure 7.5(b), for the DBE, $F_R(0.20) = 0.97$, which means that the community requires a 97% probability that less than 20% of residents be displaced in the DBE, or a 3% probability that more than 20% of residents be displaced. Similarly, for the MCE, $F_R(0.20) = 0.90$, which means that the community requires a 90% probability that less than 20% of residents be displaced in the MCE, or a 10% probability that more than 20% of residents be displaced. These targets make sense: we would expect the probability of more than 20% of residents being displaced to be higher in the MCE (10%) than the DBE (3%).

(a) Public services

(b) Housing

(c) Employment

(d) Education
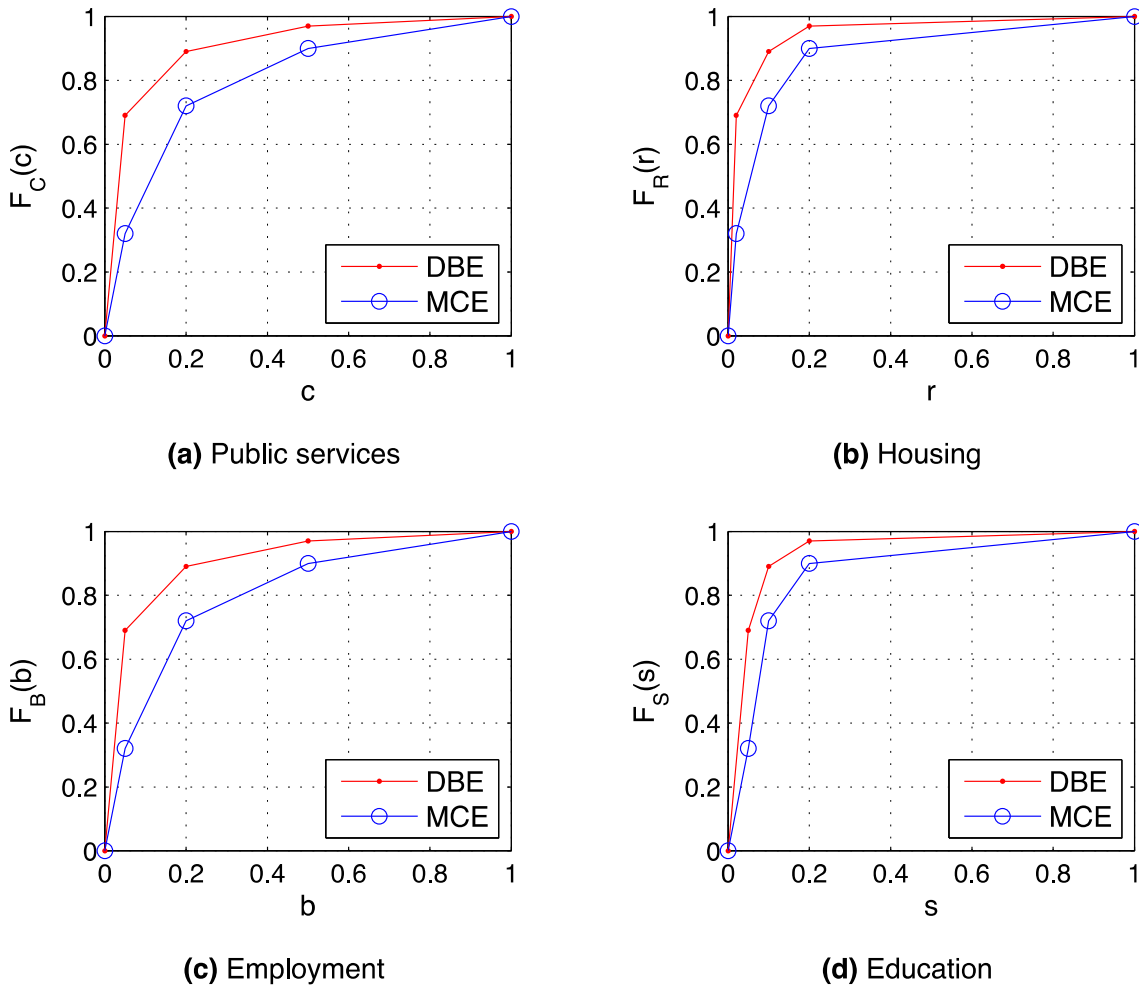
Figure 7.5   Cumulative distribution functions for each vital community function.

Again, the cumulative distribution functions in Figure 7.5 represent design targets for a community, and can serve as benchmarks either for measuring the performance of the vital community functions as they currently exist in a community or for evaluating the effect of engineering actions to improve their performance. Specifically, each cumulative distribution function can be used to compute the mean, median, standard deviation, or any other statistic for a particular tracking variable and hazard scenario. These statistics can, in turn, be used as the basis for establishing performance targets for the corresponding vital community functions—the ultimate goal of this subsection. In this example, we will use the mean to establish these design targets. In general, the mean, or expected value, of a continuous random variable X can be computed using the following equation:

$$E[X] = \int_{-\infty}^{\infty} x \cdot f(x) \, dx \tag{7.8}$$

Where $f(x)$ is the probability density function of X and $E[X]$ is the mean of X. If X is strictly positive ($P(X \geq 0) = 1$), the mean can be computed using the equivalent formula:

$$E[X] = \int_{0}^{\infty} \left[1 - F_X(x)\right] dx \tag{7.9}$$

Where $F_X(x)$ is the cumulative distribution function of X. In this example, because each tracking variable is bounded between zero and one, Equation (7.9) simplifies to:

$$E[X] = \int_{0}^{1} \left[1 - F_X(x)\right] dx = 1 - \int_{0}^{1} F_X(x) \, dx \tag{7.10}$$

Where the integral of the cumulative distribution function, the second term on the right-hand side of Equation (7.10), is simply the area under each of the curves in Figure 7.5. This area is a function of not only the assigned branch probabilities in Figure 7.3 and Figure 7.4, but also the specified branch limits (e.g., 2%, 10%, 20%, etc.). See Section 6.3 for a discussion of how the branch limits for each of the event trees in Figure 7.1 were selected.

Table 7.1 summarizes the performance targets for each vital community function in both hazard scenarios. These targets are based on the mean values of each tracking variable and were calculated using Equation (7.10). Alternatively, the median or other statistic may also be used to establish these design targets. From Table 7.1, we obtain the following two performance objectives for the housing vital community function: (1) less than 4.9% of residents be displaced in the DBE; and (2) less than 11.4% of residents be displaced in the MCE. Similar objectives can be formulated for the other vital community functions.

In review, the performance targets in Table 7.1 result from four primary choices:

- The original community-level performance target (1×10^{-4} mean annual frequency of significant outmigration)

- The hazard scenarios and corresponding conditional probabilities (1% probability of significant outmigration in the DBE; 10% probability of outmigration in the MCE)

- The technique for identifying sequences that trigger significant outmigration

- The event tree branch probabilities (Figure 7.3 and Figure 7.4)

Again, each of these choices is at the discretion of community stakeholders and policymakers. Changing any of the decisions made previously in this example will change the results in Table 7.1.

Table 7.1   Performance targets for each basic safety function (based on mean values).

Vital community function (tracking variable)	Public services (% of capacity disrupted)	Housing (% of residents displaced)	Employment (% of businesses disrupted)	Education (% of students displaced)
475-year earthquake	9.3	4.9	9.3	6.2
2450-year earthquake	19.6	11.4	19.6	12.5

7.1.3 Performance Targets for Frontline and Support Systems

The third step in the methodology involves establishing performance targets for each frontline and support system in the community. To this end, the performance objectives from the previous step (see Section 7.1.2) need to be translated into targets for each frontline and support system. Because the goal of this example involves developing performance targets for a new residential building, we only need to focus on the frontline and support systems related to the housing vital function.

Section 5.4 identified important frontline and support systems that support the housing vital function, including single-family housing, multi-family housing, and water, electric power, and natural gas lifelines (see Table 5.1 and Table 5.2). Physical damage to any of these systems can displace residents from their homes, as described in Section 6.3.2. For simplicity, in this example, we will assume that residents will be displaced from their homes only if the buildings are not structurally safe enough to occupy immediately following an earthquake. In other words, residents can stay in their homes even if they lack important utilities like water and power, provided they are structurally safe to occupy. This would be the case for a community that has adopted shelter-in-place performance requirements for its residential buildings [Poland et al. 2009; SPUR 2012]. As a result of this simplification, we only need to establish performance

objectives for frontline systems (i.e., the housing stock), while recognizing that an actual real-world example would be more complicated.

To this end, if we assume that the percentage of residents displaced is roughly equivalent to the percentage of the housing stock not safe to occupy, it is straightforward to establish performance targets for the housing stock. The equivalence of these two measures is true for communities with a large percentage of single-family homes, but starts to break down for communities with large concentrations of multi-family residences. For the purposes of this example, however, it is a sufficient approximation. As a result of this approximation, we now have two performance targets for the housing stock: (1) less than 4.9% of residences not structurally safe to occupy in the DBE; and (2) less than 11.4% of residences not structurally safe to occupy in the MCE.

7.1.4 Performance Targets for Individual Components

The final step in the methodology involves establishing performance targets for individual components within each frontline and support system. To this end, the performance objectives from the previous step (see Section 7.1.3) need to be translated into targets for individual components within each frontline and support system. In this example, the performance objectives for the housing stock need to be translated into targets for an individual residential building. On account of the assumptions and simplifications made in previous subsections, this is a straightforward task. If the performance target is that no more than 4.9% of a community's housing stock will be structurally unsafe to occupy after the DBE, then an individual residential building needs to have a 4.9% probability (or less) of being structurally unsafe. Similarly, if no more than 11.4% of a community's housing stock can be structurally unsafe to occupy after the MCE, then an individual residential building needs to have an 11.4% probability (or less) of being structurally unsafe.

In summary, we have established the following two performance targets for an individual residential building: (1) less than 4.9% probability of being structurally unsafe to occupy in the DBE; and (2) less than 11.4 % probability of being structurally unsafe to occupy in the MCE. These targets are consistent with the community-level performance objectives developed in Section 7.1.1.

7.1.5 Implications

The example described in prior subsections outlined a methodology for establishing a consistent hierarchy of performance objectives for a community and its built environment. Specifically, it developed a set of performance objectives for an individual residential building that, if achieved, will satisfy community-level performance targets. These performance objectives can be used to check whether the implicit performance levels achieved by the current building code (e.g., the IBC) are satisfactory from the perspective of the community. Figure 7.6 displays results from an analysis of the current building code performed by SPUR. Of the five performance categories defined in the figure, three (C, D, and E) represent outcomes in which a building is not usable

following an earthquake. SPUR estimates that the provisions of the current building code result in a new building having approximately 65% probability of being unsafe to occupy after the DBE, where 65% is the sum of the black bars corresponding to Categories C, D, and E in Figure 7.6.
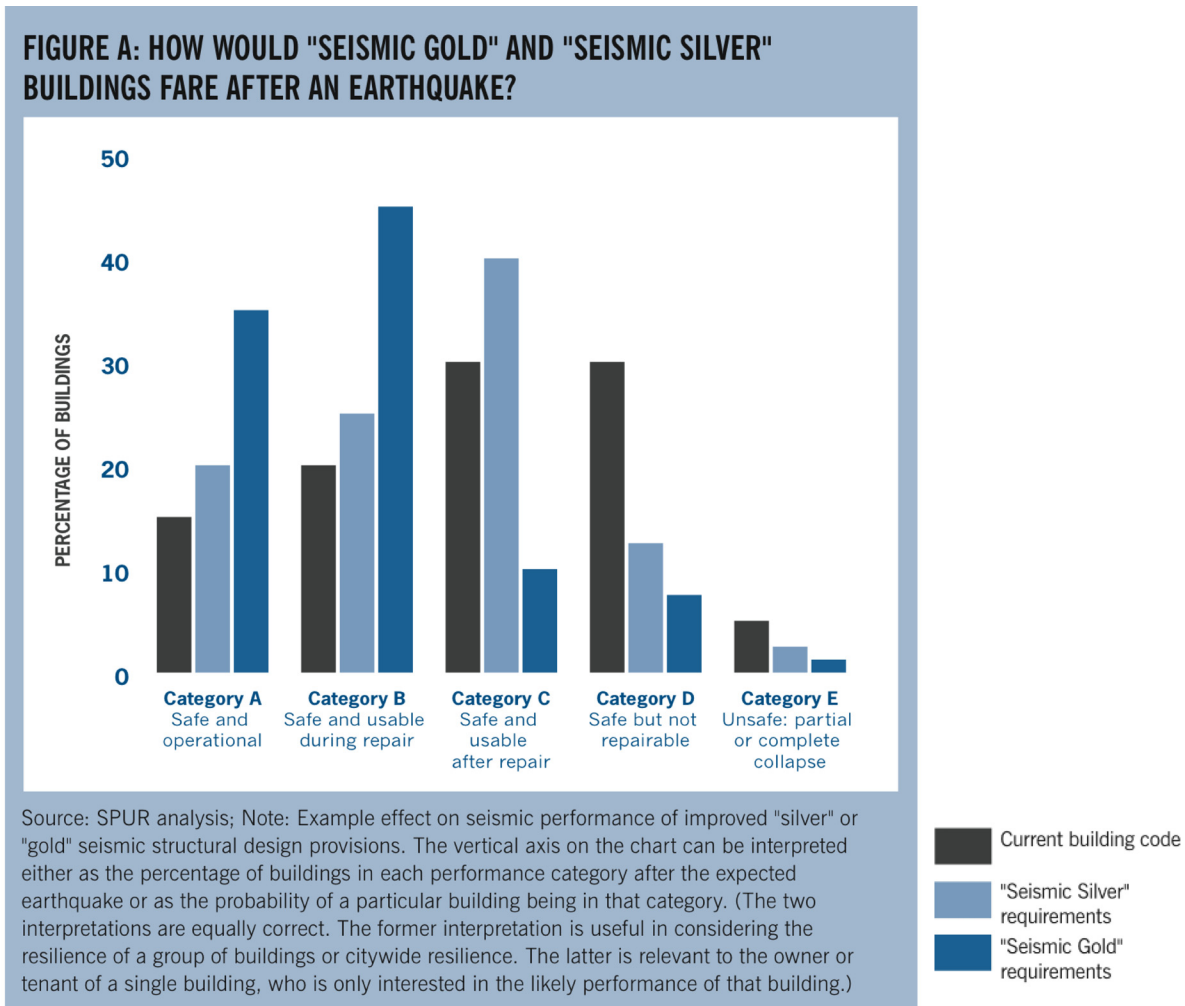

Figure 7.6 **SPUR analysis of the current building code [Poland et al. 2009].**

Recall that in the previous subsection we established the following performance target for a new residential building in the DBE: 4.9% probability of being structurally unsafe to occupy (or a 95.1% probability of being structurally safe to occupy). In light of this requirement, the provisions of the current building code are inadequate, as they provide only a 35% probability that a new building will be safe to occupy following the DBE (compared to the 95.1% requirement). This discrepancy is significant; however, many simplifications and assumptions were made in establishing the 95.1% requirement. Furthermore, the original community-level performance target (1×10^{-4} mean annual frequency of significant outmigration) is probably too conservative. A less stringent target for the community will likely lower the 95.1% requirement

for individual buildings in the DBE. Regardless, the example presented in this section illustrates the potential mismatch in performance objectives that can arise when broader performance goals for the community are ignored, as is the case in the IBC.

In summary, the methodology presented in this section can be used to create a set of performance objectives for a wide range of components and subsystems within the built environment, including not only residential buildings but also hospitals, factories, and electric power grids. Ultimately, this set of performance objectives can serve as the basis for revisions to the building code and can even provide the foundations for a "community performance code" (see Chapter 8).

7.2   EXAMPLE: COMPUTING DISRUPTION TO PUBLIC SERVICES

The second example outlines a methodology for estimating the capacity of public services disrupted following an initiating event. The methodology can be used for several purposes. First, a community can use it to estimate the vulnerability of its public services to different hazard scenarios, the results of which can be used to develop and implement targeted retrofit programs or other mitigation activities that address its most critical vulnerabilities. Second, the methodology can be used to calibrate the branch limits of the public services event tree [see Figure 6.3 or Figure 7.1(a)]. As mentioned in Section 6.3.1, the branch limits for the public services event tree may require refinement in order to properly distinguish the range of possible outcomes (i.e., minor impact, moderate impact, significant impact, and catastrophic impact). Using data from previous earthquakes and other hazards, the methodology outlined in this example can be used to compute the initial disruption to public services that occurred during these events. Once enough data have been compiled, the branch limits can be adjusted appropriately. As the example in Section 7.1 demonstrated, branch limits are important because they influence the performance objectives for each vital community function (see Section 7.1.2).

The methodology comprises six steps, as outlined in Table 7.2. The following subsections describe each step in more detail.

Table 7.2   Methodology to estimate the disruption to public services.

Step	Action
1	Define boundaries for the analysis
2	Determine the system importance matrix
3	Compute the system disruption matrix
4	Calculate the service disruption matrix
5	Determine the service importance matrix
6	Calculate the total disruption

7.2.1 Analysis Boundaries

The first step in the methodology involves defining appropriate boundaries for the analysis. Most importantly, the individual public services to be included in the analysis need to be identified. Table 7.3 lists the individual public services included in the analysis. It is adapted from Section 5.3.1 and reflects a baseline set of services essential both in normal, day-to-day operations and in the aftermath of a major disaster. If desired, the list in Table 7.3 can be expanded to include additional services. Note that essential community services, the last row in Table 7.3, include building permit and inspection, planning, government finance and taxation, social services, mail delivery, and public recordkeeping, to name only a few.

Once individual public services have been identified, the frontline and support systems (i.e., buildings and lifelines) that enable these services need to be identified. Table 7.4 lists the frontline and support systems included in the analysis (note that italics are used to differentiate support systems from frontline systems). The list, which draws from Table 5.1 and Table 5.2 in Section 5.4, can be expanded (or trimmed) if desired. Note that if a community has an auxiliary water system for firefighting purposes (separate from the system that delivers potable water), it needs to be added to the list. Also note that non-emergency medical facilities include medical provider offices, clinics, and other outpatient facilities, while government facilities include prisons, post offices, and administrative offices.

Table 7.3   Public services included in the analysis.

	Public service
1	Police
2	Fire and rescue
3	Emergency medical care
4	Non-emergency health care
5	Food
6	Water
7	Energy
8	Sanitation
9	Transportation
10	Communication
11	Banking
12	Essential community services

Table 7.4   Frontline and support systems included in the analysis.

	Frontline/*support* system
1	Police stations
2	Fire stations
3	Hospitals
4	Dispatch centers
5	Emergency operations centers
6	Non-emergency medical facilities
7	Grocery stores
8	Banks
9	City hall
10	Government facilities
11	*Water (potable)*
12	*Electric power*
13	*Natural gas*
14	*Oil*
15	*Solid fuels*
16	*Roads and highways*
17	*Mass transit*
18	*Railways*
19	*Airports*
20	*Ports and waterways*
21	*Telecommunications*
22	*Wastewater*
23	*Solid waste*

7.2.2 System Importance Matrix

The second step of the methodology involves developing the system importance matrix. The system importance matrix is an adaptation of the dependency matrix described in Section 5.5.1. Whereas a dependency matrix identifies the basic interactions among the systems in a community (see Figure 5.1), the system importance matrix also captures the strength of the interaction or dependence. Specifically, it captures the extent to which the public services identified in Table 7.3 depend on the frontline and support systems identified in Table 7.4.

The system importance matrix, I_{system}, is an $m \times n$ matrix, where m corresponds to the number of public services included in the analysis and n corresponds to the number of frontline and support systems. From Table 7.3 and Table 7.4, $m = 12$ and $n = 23$. Entries in I_{system} range between zero and one. $I_{system}(i,j) = 0$ indicates that the ith public service does not depend on the jth frontline or support system. On the other hand, $I_{system}(i,j) \neq 0$ indicates dependence to some degree, with values close to one representing strong dependence. The ith row of I_{system} describes the dependence of the ith public service on the frontline and support systems included in the analysis. The nonzero entries in the ith row must all sum to one.

The system importance matrix can be developed to capture basic dependencies either during normal, steady−state conditions or in the aftermath of a major disaster. In an emergency situation, certain public services may be able to operate in a limited capacity even if some of the frontline and support systems they normally depend on are unavailable. For example, under normal circumstances, banks serve as the headquarters for most of the banking services provided to residents; however, after a major earthquake, it may be possible to provide these services even if banking buildings are damaged and unsafe to occupy. For example, portable ATMs can be brought in to provide cash to residents. As a result, the banking services row in the system importance matrix might assign a smaller value for banks in the aftermath of a disaster than during normal, steady−state conditions.

Before developing the system importance matrix, it is helpful to construct a dependency matrix to first identify basic interactions. Figure 7.7 shows an example of a dependency matrix that captures the interactions among the public services in Table 7.3 and the frontline and support systems in Table 7.4. The matrix is constructed one row at a time, with an "x" mark indicating that a particular public service depends on the corresponding frontline or support system. The dependency matrix in Figure 7.7 is developed for application during a disaster scenario. Furthermore, it is developed for general applicability to a wide range of communities; therefore, the matrix will likely require adjustment in order to capture the interactions within a particular community. These adjustments should be made by community stakeholders who have intimate knowledge of particular public services (e.g., fire and police chiefs, utility operators, etc.).

The first row of the dependency matrix in Figure 7.7 shows that the police service depends on eight frontline and support systems: police stations, dispatch centers, emergency operations centers, government facilities (which include prisons), electric power, oil, roads and highways, and telecommunications. Police stations serve as the primary frontline systems in law enforcement operations in a community. To remain fully operational, they require access to basic utilities like electricity and telecommunications. However, a significant percentage of police services involve responding to emergencies throughout the community. Therefore, dispatch centers and emergency operations centers, which direct officers to where they are needed, also impact the availability of police services. Furthermore, the condition of transportation (in particular, roads and highways), energy (in particular, oil/gasoline to fuel patrol vehicles), and telecommunications infrastructure is vitally important in determining the disruption to the police service.

	police stations	fire stations	hospitals	dispatch centers	emergency operations centers	non-emergency medical facilities	grocery stores	banks	city hall	government facilities	water (potable)	electric power	natural gas	oil	solid fuels	roads and highways	mass transit	railways	airports	ports and waterways	telecommunications	wastewater	solid waste	
police	x			x	x					x		x		x		x					x			8
fire and rescue		x		x	x						x	x		x		x					x			8
emergency medical care			x	x	x						x	x	x	x		x					x	x	x	11
non-emergency health care						x					x	x	x								x	x	x	7
food							x				x	x	x	x		x		x		x	x		x	10
water											x	x	x								x	x		5
energy											x	x	x	x	x	x		x		x	x	x		10
sanitation											x	x				x					x	x	x	6
transportation												x		x	x	x	x	x	x	x	x			9
communication											x	x				x					x			4
banking								x				x				x					x			4
essential community services					x				x	x	x	x				x					x			7
	1	1	1	3	4	1	1	1	1	2	9	12	5	6	2	10	1	3	1	3	12	5	4	

Figure 7.7   **Dependency matrix for public services and frontline and support systems.**

Figure 7.8 shows an example of a system importance matrix developed using the dependency matrix in Figure 7.7. The specific values assigned in the matrix will vary from community to community and, again, should be developed by stakeholders who have intimate knowledge of particular public services. If the values in each column of the matrix are summed, a measure of the importance of each frontline and support system can be obtained. As Figure 7.8 demonstrates, support systems like telecommunications, electric power, roads and highways, and water feature some of the highest totals, reinforcing the crucial role these lifelines play in supporting multiple public services. For illustrative purposes, the rows of the matrix in Figure 7.8 sum to 100 instead of one.

	police stations	fire stations	hospitals	dispatch centers	emergency operations centers	non-emergency medical facilities	grocery stores	banks	city hall	government facilities	water (potable)	electric power	natural gas	oil	solid fuels	roads and highways	mass transit	railways	airports	ports and waterways	telecommunications	wastewater	solid waste	
police	25	0	0	5	5	0	0	0	0	5	0	5	0	5	0	25	0	0	0	0	25	0	0	100
fire and rescue	0	20	0	5	5	0	0	0	0	0	20	5	0	5	0	20	0	0	0	0	20	0	0	100
emergency medical care	0	0	25	5	5	0	0	0	0	0	10	20	5	5	0	5	0	0	0	0	10	5	5	100
non-emergency health care	0	0	0	0	0	30	0	0	0	0	15	25	5	0	0	0	0	0	0	0	15	5	5	100
food	0	0	0	0	0	0	25	0	0	0	10	10	5	10	0	15	0	5	0	5	10	0	5	100
water	0	0	0	0	0	0	0	0	0	0	40	25	5	0	0	0	0	0	0	0	20	10	0	100
energy	0	0	0	0	0	0	0	0	0	0	5	20	15	15	15	5	0	5	0	5	10	5	0	100
sanitation	0	0	0	0	0	0	0	0	0	0	15	10	0	0	0	15	0	0	0	0	10	25	25	100
transportation	0	0	0	0	0	0	0	0	0	0	0	10	0	5	5	30	10	10	10	10	10	0	0	100
communication	0	0	0	0	0	0	0	0	0	0	10	30	0	0	0	10	0	0	0	0	50	0	0	100
banking	0	0	0	0	0	0	0	20	0	0	0	40	0	0	0	10	0	0	0	0	30	0	0	100
essential community services	0	0	0	0	5	0	0	0	25	30	5	15	0	0	0	10	0	0	0	0	10	0	0	100
	25	20	25	15	20	30	25	20	25	35	130	215	35	45	20	145	10	20	10	20	220	50	40	

Figure 7.8   **System importance matrix for public services and frontline and support systems.**

7.2.3 System Disruption Matrix

The third step in the methodology involves computing the system disruption matrix, D_{system}, which measures the disruption to frontline and support systems caused by an initiating event. It is an $n \times 1$ matrix, where n is the number of frontline and support systems included in the analysis. In this example, $n = 23$. The disruption to each system is represented by a single variable, as shown in Equation (7.11). These variables can range between zero and one, where zero indicates no disruption to the system and one represents complete disruption.

$$D_{system} = \begin{bmatrix} D_{police\ stations} \\ D_{fire\ stations} \\ D_{hospitals} \\ D_{dispatch\ centers} \\ D_{emergency\ operations\ centers} \\ D_{non-emergency\ medical\ facilities} \\ D_{grocery\ stores} \\ D_{banks} \\ D_{city\ hall} \\ D_{government\ facilities} \\ D_{water\ (potable)} \\ D_{electric\ power} \\ D_{natural\ gas} \\ D_{oil} \\ D_{solid\ fuels} \\ D_{roads\ and\ highways} \\ D_{mass\ transit} \\ D_{railways} \\ D_{airports} \\ D_{ports\ and\ waterways} \\ D_{telecommunications} \\ D_{wastewater} \\ D_{solid\ waste} \end{bmatrix} \qquad (7.11)$$

An analysis of each frontline and support system must be performed in order to fully determine the system disruption matrix. The nature of each analysis will depend on the overall purpose of the study and the particular frontline or support system under consideration. For example, if the purpose of the study is to calibrate the branch limits in the public services event tree, then the analysis of each frontline and support system will require corresponding data sets from previous disasters. On the other hand, if the purpose of the study involves identifying a community's vulnerabilities before disaster strikes, then analysis tools like HAZUS or the lifeline interdependency models listed in Section 2.1.2 can be used to estimate the disruption expected for each system. For example, the disruption to the hospitals frontline system can be measured by the fraction of hospitals in the community that are not operational following an initiating event, or, alternatively, by the fraction of hospital beds unavailable. See Equation (7.12).

$$D_{hospitals} = \frac{\text{number of beds unavailable}}{\text{total number of beds}} \qquad (7.12)$$

7.2.4 Service Disruption Matrix

The fourth step in the methodology involves computing the service disruption matrix, $D_{service}$, which measures the disruption to individual public services caused by disruptions to frontline and support systems. It is the product of the system importance matrix, I_{system}, and the system disruption matrix, D_{system}. See Equation (7.13).

$$D_{service} = I_{system} \cdot D_{system} \qquad (7.13)$$

$D_{service}$ is an $m \times 1$ matrix, where m is the number of public services included in the analysis ($m = 12$ in this example). Equation (7.14) shows the individual entries of $D_{service}$.

$$D_{service} = \begin{bmatrix} D_{police} \\ D_{fire\ and\ rescue} \\ D_{emergency\ medical\ care} \\ D_{non-emergency\ health\ care} \\ D_{food} \\ D_{water} \\ D_{energy} \\ D_{sanitation} \\ D_{transportation} \\ D_{communication} \\ D_{banking} \\ D_{essential\ community\ services} \end{bmatrix} \qquad (7.14)$$

Each entry in $D_{service}$ can be considered a weighted average or aggregation of the disruptions to frontline and support systems, with the weights being specified in the system importance matrix. For example, disruption to the police service, D_{police}, is a weighted average of the disruption to police stations, dispatch centers, emergency operations centers, government facilities (i.e., prisons), electric power, oil, roads and highways, and telecommunications. See Equation (7.15).

$$\begin{aligned} D_{police} = {} & 0.25 \cdot D_{police\ stations} + 0.05 \cdot D_{dispatch\ centers} + \\ & 0.05 \cdot D_{emergency\ operations\ centers} + 0.05 \cdot D_{government\ facilities} + \\ & 0.05 \cdot D_{electric\ power} + 0.05 \cdot D_{oil} + 0.25 \cdot D_{roads\ and\ highways} + \\ & 0.25 \cdot D_{telecommunications} \end{aligned} \qquad (7.15)$$

As can be seen in Equation (7.15), even a significant disruption to dispatch centers, emergency operations centers, government facilities, electric power, or oil infrastructure has only minor impact on D_{police}. In contrast, an extensive disruption to police stations, roads and highways, or telecommunications infrastructure can have a substantial effect on D_{police}. Again, the specific weights assigned to each frontline and support system (via the system importance matrix) will likely require refinement in order to better reflect the interactions within a particular community.

7.2.5 Service Importance Matrix

The fifth step in the methodology involves determining the service importance matrix, $I_{service}$, which measures the relative importance of each public service to the community. It is a $1 \times m$ matrix, where m is the number of public services included in the analysis ($m = 12$ in this example). The sum of all entries in $I_{service}$ must equal one. Similar to the system importance matrix, the service importance matrix can be developed to reflect the importance of individual public services either during normal, steady state conditions or during the emergency response phase after a major disaster. Figure 7.9 displays an example of each. During normal, steady state conditions [Figure 7.9(a)], each service is weighted approximately the same. In contrast, during the emergency response phase [Figure 7.9(b)], services like police, fire and rescue, and emergency medical care are assigned higher weights because of their importance in responding to an emergency. As elsewhere, the numbers presented in Figure 7.9 can be adjusted to reflect the priorities and preferences of stakeholders in a particular community.

police	fire and rescue	emergency medical care	non-emergency health care	food	water	energy	sanitation	transportation	communication	banking	essential community services
0.07	0.07	0.06	0.08	0.08	0.08	0.12	0.08	0.10	0.10	0.08	0.08

(a) Normal, steady state conditions

police	fire and rescue	emergency medical care	non-emergency health care	food	water	energy	sanitation	transportation	communication	banking	essential community services
0.14	0.15	0.16	0.04	0.12	0.12	0.08	0.04	0.05	0.05	0.02	0.03

(b) Emergency response phase

Figure 7.9   Examples of a service importance matrix.

7.2.6 Total Disruption

The final step in the methodology involves computing the total disruption to public services, D_{total}, which is an aggregation of the disruption to individual public services. Note that D_{total} is equivalent to C, the fraction of capacity disrupted (as defined in Section 7.1.2), which, in turn, is equivalent to the tracking variable in the public services event tree for the initial damage phase [see Figure 6.3 or Figure 7.1(a)]. D_{total} is the product of the service importance matrix and the service disruption matrix. See Equation (7.16). It can be considered a weighted average of the

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disruptions to each individual public service, with the weights coming from the service importance matrix.

$$D_{total} = I_{service} \cdot D_{service} \tag{7.16}$$

If Equation (7.13) and Equation (7.16) are combined, Equation (7.17) results.

$$D_{total} = I_{service} \cdot I_{system} \cdot D_{system} \tag{7.17}$$

In summary, D_{total}, as computed using Equation (7.16) or Equation (7.17), can be used to determine the branch of the public services event tree on which a community resides ([see Figure 6.3 or Figure 7.1(a)]. For example, if $D_{total} = 0.36 = 36\%$, the community resides on the third branch of the public services event tree, which indicates the initial disruption to public services will have significant impact on the community.

7.2.7 Implications

Previous subsections have outlined a methodology that aggregates the disruption to public services using a single measure, D_{total}. In spite of its simplicity, the implications of the methodology are significant. As discussed at the beginning of Section 7.2, it can be used to calibrate the branch limits of the public services event tree for the initial damage phase [see Figure 6.3 or Figure 7.1(a)]. This calibration process requires development of an extensive database of observations gathered from a wide range of previous disasters. The development of this database, while beyond the scope of this report, is one of the future tasks identified in Section 8.2. Proper calibration of the branch limits in the public services event tree will enable communities to more accurately gauge the expected performance of their public services. In other words, it will allow them to get a better sense of whether the total disruption to public services (computed using the methodology outlined in previous subsections) has catastrophic, significant, moderate, or minor impact.

Furthermore, the methodology can be used to measure the effect of different mitigation strategies once a community has estimated the total disruption expected to its public services. For example, consider a community that performs an analysis that estimates each of its frontline and support systems will have 25% of its capacity disrupted in a particular hazard scenario (i.e., $D_{system}(i,1) = 0.25$ for $i = 1, 2, \ldots , n$). Using the system importance matrix in Figure 7.8, the service importance matrix in Figure 7.9(b), and Equation (7.17), an estimate of D_{total} can be computed. In this example, because $D_{system}(i,1) = 0.25$ for $i = 1, 2, \ldots , n$, D_{total} is simply 0.25. In order to decrease the overall vulnerability of its public services (i.e., D_{total}), the community can perform a wide range of mitigation activities that reduce the vulnerability of various frontline and support systems (i.e., the entries in D_{system}). The methodology can be used to measure and compare the effectiveness of each of these mitigation activities. Figure 7.10 shows the effectiveness of reducing the disruption to each frontline system from 0.25 to zero on D_{total}. Similarly, Figure 7.11 displays the effectiveness of reducing the disruption to each support system from 0.25 to zero.
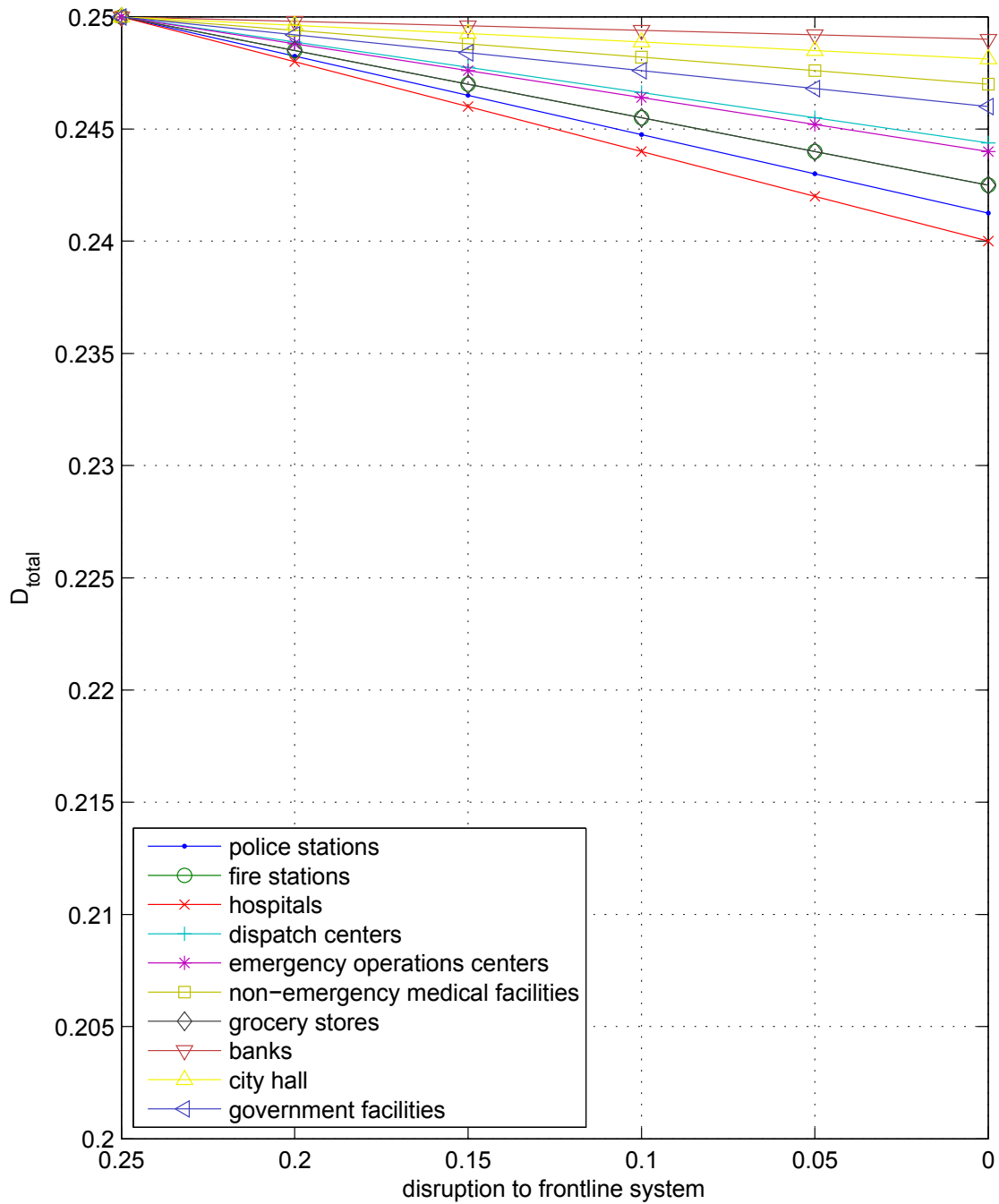
Figure 7.10 Effectiveness of decreasing the vulnerability of individual frontline systems.
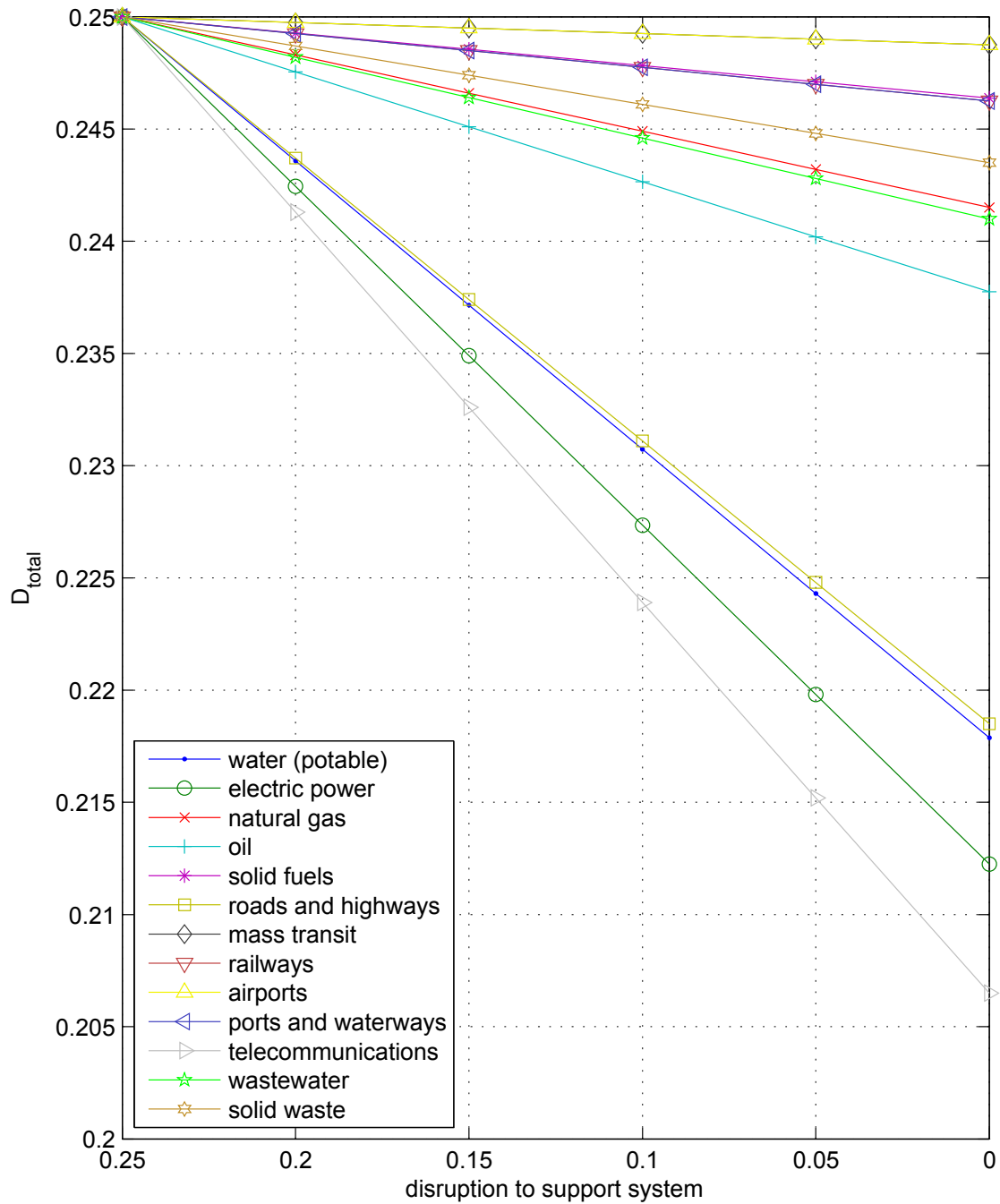
Figure 7.11   Effectiveness of decreasing the vulnerability of individual support systems.

In this example, the effect of decreasing the vulnerability of frontline systems is not as significant as decreasing the vulnerability of support systems (see Figure 7.10 and Figure 7.11). Even so, improving the performance of hospitals, police stations, and grocery stores has the most

effect. However, the most effective way to reduce D_{total} is to decrease the vulnerability of telecommunications, electric power, roads and highways, and water support systems. Therefore, if faced with limited resources for mitigation activities, a community should focus efforts on retrofitting or replacing these particular systems, at least in this example.

However, it is important to note that additional factors, including cost, environmental impact, and political or legal constraints, need to be considered when choosing among potential mitigation activities. For example, while it might produce significant reductions to D_{total}, upgrading a community's water infrastructure is typically expensive and disruptive to nearby residents and businesses, as it may require replacement of lengthy sections of pipeline buried under city streets. Furthermore, sometimes the water infrastructure within a community can be part of a larger network that serves other communities, meaning an individual community may have limited control over retrofit decisions.

In summary, the example presented in this section outlines a straightforward methodology for capturing the interdependencies that exist between a community's public services and its frontline and support systems to estimate the total disruption to a community's public services. This methodology, when combined with analysis tools like HAZUS-MH, may be used to make better decisions regarding how to address the seismic vulnerabilities of a community's built environment. In addition, it may be used to calibrate the public services event tree in order to improve the rigor of the performance objectives established for a community and the numerous components and subsystems within its built environment.

8   Conclusions

A community is a dynamic system of people, organizations, and patterned relationships and interactions [Alesch 2005]. Structures and hardware, referred to as the built environment in this report, play a particularly important role in enabling a community to successfully function, providing the physical foundations for much of the economic and social activities that characterize a modern society [O'Rourke 2007]. The built environment is a complex, dynamic, interdependent network of engineered subsystems and components, including buildings, bridges, pipelines, and other structures. Natural hazards such as earthquakes, hurricanes, and floods can damage a community's built environment, which in turn may disrupt the security, economy, safety, health, and welfare of the public. In response, many communities have developed and implemented regulatory frameworks to ensure minimum levels of performance for individual parts of the built environment. For buildings subject to earthquakes, these minimum levels of performance center on preventing collapse during very rare, intense seismic ground motion [BSSC 2009].

This report has examined the regulatory framework currently used in the United States to design and evaluate a community's built environment to withstand the effects of earthquakes and other natural hazards. Using the attributes of an ideal regulatory framework as a guide, it has identified and described several important shortcomings. The most significant shortcoming of the current regulatory framework involves its lack of an integrated, coordinated, and comprehensive approach to establishing performance expectations for individual components of the built environment. Consequently, performance objectives for individual components within the built environment are not tied to broader performance targets for the community. This divergence results in a community in which most individual components behave as intended; however, when aggregated, the performance of and interaction among components can result in unacceptable outcomes for the community (i.e., insufficient levels of resilience).

To address the shortcomings of the current regulatory framework, this report has studied the philosophy used in the United States to design and analyze nuclear power plants and has adapted it for use in a community setting. Most crucially, the nuclear design philosophy features an integrated, coordinated, and comprehensive approach. It begins at the system level, specifying performance objectives that result in a small probability of unacceptably large radiation release affecting the nearby population. The framework then identifies the vital safety functions that must be available during a postulated accident in order for a nuclear power plant to avert core

damage and/or large release of radioactivity. It then identifies the frontline and support systems that enable each vital safety function to operate successfully. This systematic, top-down approach ensures that performance requirements for individual components and subsystems are consistent with system-level performance targets. In order to verify that a nuclear power plant satisfies these performance objectives, nuclear engineers use tools like probabilistic risk assessments, event trees, and fault trees to analyze the response of the plant and its various components and subsystems.

In adapting the nuclear design philosophy to communities, this report has drawn extensively from the rapidly evolving fields of community resilience and lifeline interdependency. The adaptation begins with defining undesired outcomes for a community whose occurrence, because of their adverse consequences, should be minimized to the extent possible. This report has selected a significant and rapid outmigration of residents as the undesired outcome of interest because it has been observed in the aftermath of several major disasters, including the Great Hanshin earthquake in 1995 and Hurricane Katrina in 2005. Using the work of Poland et al. [2009], SERRI and CARRI [2009], Twigg [2009], and Cutter et al. [2010], the report has identified four vital functions, public services, housing, employment, and education, that a community must maintain in the aftermath of a major earthquake or other natural hazard in order to prevent a significant and rapid outmigration of residents. It then identifies the many frontline and support systems within the built environment that enable each vital function to operate successfully. This list was adapted from PCCIP [1997], Rinaldi et al. [2001], ALA [2004], ASCE [2006], Barkley [2009], and Poland et al. [2009]. In summary, these vital community functions and their corresponding frontline and support systems prevent a significant and rapid outmigration of residents from occurring in a community after an initiating event (e.g., earthquakes, hurricanes, and floods).

Furthermore, this report has developed a set of event trees for a community that can be used to identify combinations or sequences of events that result in a significant and rapid outmigration of residents. The event trees track the status of each vital function after an initiating event. Together, these concepts and tools form the foundations of a performance-based engineering framework that can be used for many different purposes, ranging from the revision of building code provisions to the evaluation of competing retrofit strategies.

Lastly, this report has presented several conceptual examples that illustrate application of the proposed engineering framework. The first example outlined a methodology for creating a consistent hierarchy of performance objectives for a community. Specifically, it illustrated how the event trees developed for a community can be used to establish performance objectives for a residential building from a community-level performance target. Subsequently, these performance objectives can be used to update building code provisions so that new residential buildings will perform in a manner consistent with community-level resilience goals. The second example outlined a methodology for estimating the capacity of public services disrupted by an earthquake or other natural hazard. This methodology can be used to estimate the vulnerability of a community's public services and, subsequently, to evaluate the effectiveness of different mitigation activities or strategies. It can also be used to refine the branch limits of the public

services event tree so that each outcome better delineates the scale of potential consequences (i.e., minor, moderate, significant, or catastrophic).

8.1   IMPLICATIONS

The work presented herein has the potential to change the way engineers, planners, and other stakeholders design and evaluate the built environment of a community. The growing interest in sustainable and resilient communities necessitates an updated regulatory framework, one that employs an integrated, coordinated, and comprehensive approach to account for the numerous subsystems, components, and their interactions. The framework presented in this report provides a transparent, performance-based, risk-informed methodology for planners and policymakers to set community-level performance targets and, subsequently, for engineers to calibrate their designs to meet these community-level performance targets. It provides the missing link between community-level resilience goals and component-level performance objectives. Together, the findings presented herein establish the foundations for a much-needed transformation from engineering individual components of the built environment on a component-by-component basis to engineering community resilience using an integrated and coordinated approach that begins at the community level.

For example, the framework proposed herein may provide the basis for a document that plays a role in the design and evaluation of a community's built environment similar to the role of building codes in the design and evaluation of buildings. This "community performance code" would contain provisions that explicitly spell out the performance expectations for a particular community. These explicit performance statements might take many different forms; Section 7.1 presented an example in which the community performance target took the form of an annualized probability of significant outmigration. Performance targets could also take the form of specific timetables for recovery. Regardless of their particular form, these community-level performance targets need to be established by community stakeholders in a public process so that they most effectively represent the level of risk acceptable to society.

In turn, this "community performance code" may provide the foundations for revisions to buildings codes and/or the development of new design standards for lifelines and other infrastructure. Using the framework and methodology proposed in this report, community-level performance targets specified in the "community performance code" may be used to develop a consistent set of performance objectives for each of the various components and subsystems within the built environment. In the end, these performance targets may resemble those described by Poland et al. [2009] (see Figure 2.4 and Figure 2.5); however, they will be developed using a more robust, transparent, and technically grounded engineering framework. The example in Section 7.1 demonstrated how to develop performance objectives for a residential building from a community-level resilience goal. Performance targets for other components and subsystems within the built environment (e.g., hospitals, electric power grids, etc.) can be developed in a similar fashion. These performance objectives, in turn, can be used to develop appropriate provisions for inclusion in the corresponding design standards or codes.

The "community performance code" can also be used as the basis for a community-wide resilience rating system. Communities that meet or exceed the performance objectives specified in the "community performance code" would receive higher resilience ratings than those that do not. A key element in this rating system involves having the capability to evaluate the response of an entire community relative to its specified performance targets. At the moment, an analysis like this is beyond the capabilities of most communities because they lack both the necessary inventory data about the built environment and sufficient performance evaluation tools. The framework presented herein, once refined and tested further, can function as one such tool.

8.2   FUTURE WORK

Much future work remains to be done. There are two general areas that require further attention. First, the community event trees presented in Chapter 6 require further refinement and possible expansion. Second, the methodology outlined in Section 7.1 needs to be refined and expanded. The following subsections discuss each of these tasks in more detail.

8.2.1 Refinement and Expansion of Community Event Trees

One of the most important next steps involves additional refinement of the community event trees presented in Chapter 6. In particular, the branch limits for several event trees require calibration in order to more effectively delineate the impact of each of the four outcomes in an event tree. As defined in Section 6.2 and Figure 6.1, the four outcomes of an individual event tree have varying impact, ranging from minor to catastrophic. The branch limits in an event tree establish boundaries that distinguish each outcome. Therefore, branch limits must be chosen carefully so that they effectively demarcate each of the four possible outcomes.

The branch limits for several of the event trees presented in Chapter 6 require refinement in order to more effectively differentiate the range of possible outcomes. In particular, the event trees for public services, employment, and education need most attention (see Figure 6.3, Figure 6.4, and Figure 6.5, respectively). For each of these trees, the chosen branch limits may not properly delineate the range of possible outcomes. For example, for the employment event tree (see Figure 6.3), it is unclear whether a disruption of more than 50% of businesses actually has catastrophic impact. With additional research, including analyses of previous disasters, it may be discovered that a disruption of 35% of businesses has catastrophic impact.

In order to establish more appropriate branch limits, a comprehensive analysis of previous disasters must be performed. This analysis requires development of two items. First, methodologies for estimating the initial disruption to public services, employment, and education need to be developed, verified, and validated. Section 7.2 described a methodology for estimating the disruption to public services; similar methodologies need to be developed for calculating the disruption to employment and education. Second, an extensive database of observations from a wide range of previous disasters needs to be developed. This database would contain information like the percentage of businesses without immediate access to electricity or natural gas and the percentage of schools damaged to an extent that they are not safe to occupy.

Once these two analyses have been completed, they can be used to compute the disruption to public services, employment, and education that occurred during previous disasters. Ideally, trends in the results of this analysis will emerge and, subsequently, provide the basis for more appropriate branch limits for each event tree. For example, an analysis of previous disasters may reveal that if more than 35% of businesses are disrupted, the impact on the community is likely to be catastrophic. As a result, the first branch limit in the employment event tree would be set to 35%. As a result of these efforts, a generic set of community event trees can be obtained. Individual communities can modify them if they have reason to believe that different branch limits are more appropriate.

The event trees presented in Chapter 6 capture the impact of damage on the availability of each of the four vital community functions. As such, they can be used to develop performance targets that focus on limiting the immediate damage and disruption caused by an initiating event. However, limiting initial damage is but one aspect of resilience; another important element involves containing the effects of disasters when they occur [Bruneau et al. 2003]. Therefore, in order to more adequately address the multi-faceted nature of resilience, additional sets of event trees can be developed to track recovery following an initiating event. Ultimately, these event trees can be used to develop an additional set of performance objectives for a community that focus on the restoration of vital functions.

Consider, for example, the set of performance objectives established for a residential building in Section 7.1: (1) less than 4.9% probability of being structurally unsafe to occupy in the DBE; and (2) less than 11.4% probability of being structurally unsafe to occupy in the MCE. These two objectives aim to minimize the initial damage and disruption caused by an earthquake; however, they do little to ensure that full functionality is restored to the building in a timely manner. Therefore, an additional set of performance objectives that address restoration of functionality needs to be developed using both the methodology outlined in Section 7.1 and yet-to-be-developed event trees that track community recovery. The resulting set of performance objectives for residential buildings would address not only initial damage caused by an earthquake but also restoration of functionality, thereby enhancing community resilience in a more complete fashion.

In addition to expanding the framework to include additional facets of resilience, future iterations of the framework should also aim to expand its scope beyond disaster resilience to address and incorporate broader sustainability considerations like carbon footprint, energy efficiency, resource consumption, and environmental impact of a community and its built environment.

8.2.2 Refinement and Expansion of the Methodology to Develop Consistent Performance Targets for the Built Environment

The second major task involves refining and expanding the methodology used to develop consistent performance objectives for individual components within the built environment. Section 7.1 outlined the foundations of this methodology and presented an example in which a set of performance objectives for a residential building was derived from a community-level

performance target. Many simplifications and assumptions were made throughout the course of the example. The following paragraphs discuss the future work required to address the most critical of these simplifications and assumptions.

The first step in the methodology involves establishing explicit performance targets for the community under consideration (see Section 7.1.1). For illustrative purposes, a community performance target of 1×10^{-4} mean annual frequency of significant outmigration was selected, though it was noted that this target could take other values (e.g., 1×10^{-3} or 1×10^{-2}). Additional research is required to determine how often a community is willing to tolerate a disaster with catastrophic local and regional consequences (e.g., Hurricanes Katrina and Sandy). This conversation may need to take place at the national level, as the implications of this decision can have profound impact on the economic security of the United States, mainly because the federal government typically bears a significant share of the costs associated with major disasters.

The following simple example illustrates some of the factors that need to be considered when selecting these community-level performance targets. If there are 100 major metropolitan areas in the United States, then a community-level performance target of 1×10^{-4} mean annual frequency of significant outmigration equates to approximately one catastrophic event somewhere in the United States every 100 years. In contrast, a performance target of 1×10^{-3} translates into roughly one event every 10 years. So while an individual community may be comfortable with a target of 1×10^{-3} (i.e., one catastrophic event every 1000 years), from a national perspective, this target may be insufficient. Detailed cost-benefit analyses can help illuminate which targets are most appropriate, both at local and national levels.

The second step in the methodology involves establishing performance objectives for each of the four vital community functions (see Section 7.1.2). In order to simplify this process, it was assumed that each of the vital functions was pair-wise independent, though it was noted that this assumption was not realistic because each function commonly relies on a shared network of frontline and support systems in order to operate successfully. Additional research is required to identify a multivariate distribution that can adequately capture the correlations among the four vital community functions. Once an appropriate distribution is selected, parametric studies that investigate the impact of correlation on the performance objectives required for each vital function can be performed.

The third and fourth steps in the methodology involve establishing performance objectives for frontline and support systems and individual components, respectively (see Section 7.1.3 and Section 7.1.4). The example focused on developing performance objectives for the housing stock and, subsequently, individual residential buildings. This process was relatively straightforward, largely due to simplifications and assumptions that allowed important interactions to be ignored. Future work is required to establish performance objectives for additional frontline and support systems (e.g., electric power grids, communication networks, etc.) and individual components (e.g., electrical substations, hospitals, bridges, etc.) within the built environment. For many of these systems and components, interactions cannot be ignored: for example, a hospital cannot function without power and water. At the moment, however, it is unclear how to account for these interactions in a generic fashion in order to develop a set of

design targets for these components. This is probably the most important task moving forward, as it is a major impediment to the development of the aforementioned "community performance code."

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