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Juan F. Fung
Yating Zhang
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Juan F. Fung
Yating Zhang
Applied Economics Office
Engineering Laboratory

Katherine J. Johnson
Dustin Cook
Siamak Sattar
Earthquake Engineering Group
Engineering Laboratory

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Abstract

Modern building codes and standards are generally focused on safeguarding public health and safety by ensuring buildings meet life safety performance objectives following an earthquake event. Certain classes of buildings, such as hospitals and schools, may be designed to a higher standard to minimize disruption. As communities target resilience of their built environment, it is becoming evident that life safety performance can nevertheless result in massive disruptions for large classes of residential and commercial buildings. It is possible to design buildings to provide more rapid restoration of reoccupancy and functionality than life safety standards. Recovery-based design is intended to support a community's post-earthquake resilience and represents an advancement in design practice. This report presents a framework to provide guidance on the economic benefits and costs of adopting functional recovery in design practice. A unique aspect of the framework is the acknowledgement that benefits from recovery-based design are distributed across various community stakeholders (e.g., residents, customers, local government), in addition to stakeholders at the building level (e.g., owners and tenants). Thus, the framework carefully details the attribution of impacts to the range of stakeholders potentially affected by improved building-design criteria. A key objective of the framework is to identify the set of potential benefits and costs, impacted stakeholders, and available data and tools for quantification. In the process, we identify gaps in measurement science for conducting a complete benefit-cost analysis. In addition, we provide a brief case study example that illustrates an application of the framework.

Key words

Buildings, Community resilience, Earthquake, Economics, Functionality, Functional recovery, Recovery-based design, Reoccupancy

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Glossary

ABM: Agent-Based Model

BCA: Benefit-cost analysis

BCR: Benefit-cost ratio

CEA: Cost-effectiveness analysis

EAL: Expected Annualized Losses

FEMA: Federal Emergency Management Agency

FR: Functional recovery

FR-BCA: Functional recovery Benefit-cost analysis

IBC: International Building Code

ICC: International Code Council

I-O: Input-Output

IO: Immediate occupancy

IRR: Internal rate of return

LS: Life safety

NPV: Net present value

PBD: Performance-Based Design

PBEE: Performance-Based Earthquake Engineering

ROI: Return on investment

WTP: Willingness-to-pay

PTSD: Post-Traumatic Stress Disorder

QoL: Quality of Life

GDP: Gross Domestic Product

US&R: Urban Search and Rescue

VSL: Value of a Statistical Life

1. Introduction and Motivation

Recovery-based design has attracted attention from policy makers to the public, from the local to the national level, and represents the future of earthquake engineering (ICC 2019). Functional recovery is a "a post-earthquake performance state in which a building is maintained, or restored, to safely and adequately support the basic intended functions associated with the pre-earthquake use or occupancy of the building" (NIST 2021). Designing for functional recovery would be a notable shift in design philosophy from current safety-based objectives to recovery-based objectives. Identifying and defining recovery-based objectives would require the combined efforts of agencies, stakeholders, and communities (NIST 2021).

In practice, the decision to design a building to meet recovery-based objectives will depend on cost-effectiveness, which has been identified by stakeholders as the most important attribute in assessing and implementing functional recovery options (Abrahams et al. 2021). FEMA's Benefit-Cost Analysis Guide (FEMA 2021) and ASTM-E1074 Standard Practice (ASTM International 2020a-f) all provide guidelines for benefit and cost evaluation on conventional building improvements. However, there is no standard approach for the economic evaluation of functional recovery design, which is a new concept itself. Therefore, a new framework is needed to assist decision makers to evaluate the cost-effectiveness of adopting recovery-based design criteria.

The goal of this report is to provide actionable information and best-practice guidance tailored to decision makers at various scales (individuals, community, and government). The present framework includes the methods to assess the benefits and costs of building design beyond code requirements, and the approaches to quantify the value of enhanced recovery of building functions after a natural hazard event. In particular, ten loss categories and twenty-seven benefit categories are presented to support decision making of different stakeholder groups. Three recovery states (i.e., reoccupancy, functional recovery, and full recovery) that prioritize building functions and repair sequences are incorporated into the framework for economic evaluation on business interruption loss.

Two main challenges associated with benefit-cost analysis of recovery-based design are addressed in this report: (1) Functional recovery may affect various stakeholders with conflicting goals (e.g., those who can pay for functional recovery are not necessarily the same as those who benefit from it). We therefore identify impacts at three distinct tiers: individuals (building owner, developer, occupants); community (non-occupants who benefit from a building's services); and government (local, state, and federal). At each tier, the framework identifies direct and indirect benefits and costs, as well as positive and negative externalities, potential co-benefits, and sources of uncertainty. (2) Additionally, functional recovery is a new and evolving concept, and design criteria do not yet exist (ICC 2019). Thus, what it means, and what it costs, for a building to be designed to provide functional recovery is not well-defined. To circumvent this gap, we illustrate the estimation of construction costs for a range of building designs that achieve comparable post-earthquake performance.

The key takeaways of this report are as follows:

- Compared to traditional code-conforming design, recovery-based design provides additional benefits to building owners, occupants, and the community by reducing repair costs, displacement costs, business interruption losses, and rental losses after a seismic event.

- Improving seismic performance of nonstructural components can significantly enhance building overall performance and can produce greater net benefits compared to structural improvements only.
- It is important to understand how benefits and costs are disturbed among various stakeholders because the amount paid are often not proportional to the amount of benefit enjoyed.
- While direct benefits from mitigation actions are well studied (e.g., avoided building damage and human injuries), indirect benefits are often ignored in benefit-cost analysis. However, these indirect benefits can be highly relevant to community resilience, social equity, and environmental sustainability. In addition, the data required to evaluate indirect benefits is scarce even though the methods are readily available.

While this report is focused on seismic hazards, the concept of functional recovery is applicable to other natural and human-made hazards, and many of the contributions of the proposed BCA framework can be extended to additional hazards.

This report does not provide technical guidance on design standards, specifically on how to define and design functional recovery performance targets. Rather, the goal of this report is to provide a risk-based economic framework for selecting among candidate design options, as well as how building owners, occupants, and communities can evaluate the decision of whether to adopt a new functional recovery design standard. On the other hand, the framework can be used in conjunction with development of design standards if there is a desire to ensure economic feasibility of a candidate design standard. The goal of the report is to build on existing economic analysis tools by providing a catalog of inputs (and methods for estimating them) for such tools. Our contribution is providing the roadmap for the inputs specific to an economic analysis of functional recovery design, as well as available tools and measurement needs.

The report is organized as follows:

- Section 2 provides background information on functional recovery
- Section 3 reviews options for the economic evaluation of building design standards
- Section 4 reviews the literature on conducting benefit-cost analysis for building design standards
- Section 5 presents the framework for Functional Recovery Benefit-Cost Analysis (FR-BCA), including a brief case study example to illustrate the FR-BCA framework
- Section 6 reviews remaining gaps and highlights directions for future research

2. Background on Functional Recovery

2.1. Development of seismic building codes and standards

The extent of seismic impacts within the United States have been well-demonstrated through the New Madrid (1811), Charleston (1886), San Francisco (1905), Long Beach (1933), Alaska (1946 and 1964), San Fernando (1971), Loma Prieta (1989), and Northridge (1994) earthquakes. Each produced lessons on risks from buildings and infrastructure, fires, liquefaction, and tsunami. Even with some of the earliest of these earthquakes, communities have often modified building codes, standards, and practices after an event to help reduce destruction for the purposes of preserving lives.[1] Historically, building codes and standards have been agreed upon and enforced because they are viewed as minimum safety standards (Zhang et al. 2021).

The International Building Code (IBC), first published in 2000, is a model code widely adopted by states and local jurisdictions for building design, construction, maintenance, repair, and demolition (ICC 2021). The code provides minimum requirements to safeguard public health, safety, and welfare, which ensures buildings meet the life-safety performance objective.[2] The ASCE 7-16 standards for *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* form the basis of the structural provisions of the IBC (ASCE 2017a). Other standards referenced by IBC include ACI 318 *Building Code Requirements for Structural Concrete* (ACI 2021), TMS 402/602 *Building Code Requirements and Specification for Structural Masonry* (TMS 2021), AISC 360 *Specification for Structural Steel Buildings*, and the *National Design Specification (NDS) for Wood Construction* (AISC 2021).

In ASCE 7-16, critical buildings such as hospitals and schools are designed to a higher level of performance compared to ordinary buildings. The ASCE 7-16 standards classify buildings into four categories based on the risk posed by the building in the event of failure (See Appendix A). The four risk categories are reflected by the importance factor, a modifier for design lateral force, in seismic design. Commercial and residential buildings (Risk Category II) use an importance factor of 1, while schools (Risk Category III) and hospitals (Risk Category IV) use a higher importance factor of 1.25 and 1.5 respectively, enabling them to sustain 25 % and 50 % larger seismic forces. Moreover, schools and hospitals are subject to tighter drift limits, which helps to minimize damage to some structural and non-structural components (Ghosh 2019).

While current building codes are intended to prevent building collapse and ensure people can evacuate safely, buildings that meet these minimum safety requirements may still sustain severe damage and be unrepairable or unusable after an earthquake. Interruptions to the operation of critical facilities can cause widespread social and economic loss as demonstrated by the earthquakes at the end of the 20th century (e.g., the 1994 Northridge and 1995 Kobe Earthquakes). As a result, some states like California adopted legislation to address the need for adequate protection of hospitals and other critical facilities. For instance, California Senate Bill 1953, signed into law on September 21, 1994, requires all hospitals to be capable of operating following a large earthquake by 2030 (Meade and Kulick 2006).

[1] An example is the increased earthquake design for California schools instituted after the 1933 Long Beach earthquake (Turner 2004).
[2] The IBC applies to nearly all types of new buildings. The International Residential Code (IRC) applies to new one- and two-family dwellings and townhouses of not more than three stories in height. The International Existing Building Code (IEBC) applies to the alteration, repair, addition, or change in occupancy of existing structures. See https://www.fema.gov/emergency-managers/risk-management/earthquake/seismic-building-codes for more details.

2.2. Performance-Based Earthquake Engineering

Alternative to traditional code-based design, performance-based design (PBD) offers a building design philosophy in which the performance of a particular design is analytically quantified and compared with target performance metrics, set by building owners or other stakeholders, to determine the acceptability of the design. Target performance metrics can be tailored to the needs of a specific project or be adopted from a performance-based standard; however, minimum requirements specified by building codes should be fulfilled. Common performance metrics include repair costs, downtime, casualties, as well as a discrete performance state classification (e.g., Immediate occupancy, Collapse Prevention). The most widely adopted PBD standards and methods in the U.S. include ASCE 41 (ASCE 2017b), the PEER Tall Building Initiative (PEER 2017), and FEMA P-58 (FEMA 2018). While PBD offers advantages in terms of the explicit quantification and communication of expected building performance, it is often more engineering intensive and computationally expensive compared to code-based design. In the United States, most buildings are designed based on locally adopted building codes, while PBD methods are used in seismic retrofits and design of tall buildings in high seismic hazard zones.

2.3. What is functional recovery?

As modern building performance has improved, recent earthquakes have pointed out additional needs for quicker recovery for buildings and key lifeline infrastructure systems. Enhanced performance is needed to lessen economic impacts (Kroll et al. 1991), prevent catastrophic disruption to transportation systems (EERI 2019, Yashinsky 1998), ensure water and fuel availability (Taylor 2014), and reduce vulnerability of critical buildings (Jaret 2019). The 2010-2011 Canterbury earthquake sequence in New Zealand, in particular, demonstrated the potential for extensive and long-term effects across all facets of an urban society (Potter et al. 2015). In addition, advances in science, engineering, and cross-disciplinary collaboration have improved the robustness and applicability of regional earthquake damage simulations to illustrate potential community impacts to residents, planners, and politicians (USGS 2021).

While improving aspects of recovery from earthquakes is not new (Beck et al. 1997, Comerio 2014, REDi 2013) attempts to support those goals via the alteration of building codes, standards, and practices has increased in the past few years. This shift towards improving post-earthquake outcomes changes the emphasis from minimal life safety objectives to a higher state of performance linked to specific recovery needs. In California, recent bills attempted to promote higher performance levels and to identify particularly vulnerable buildings (EERI 2021). The National Institute of Standards and Technology (NIST), as well as the Federal Emergency Management Agency (FEMA), two federal agency members of the National Earthquake Hazards Reduction Program (NEHRP), recently received charges from Congress to lead efforts in the area of improved recovery.

NIST SP1224 (NIST 2018) details findings for research needs and implementation actions to produce an immediate occupancy performance objective across natural hazards. More recently, NIST and FEMA published FEMA P-2090/NIST SP1254 (NIST 2021), a report containing options for improving the built environment and critical infrastructure to reflect performance goals stated in terms of post-earthquake re-occupancy and functional recovery time.

FEMA P-2090/NIST SP1254 recommends developing codes and standards to consider functional recovery design objectives for new buildings, existing buildings, and lifeline infrastructure, in addition to pre-disaster planning, education and outreach, and access to financial resources.

As NEHRP's advisory committee points out: *"Designing new buildings and retrofitting existing buildings to a functional recovery design objective will better align with public expectations regarding seismic performance of the infrastructure, enable our communities to recover more quickly following an earthquake, and ultimately achieve the resilience desired.*" (ACEHR 2019). Figure 1 illustrates the theoretical range of building performance attainable for recovery-based design objectives.

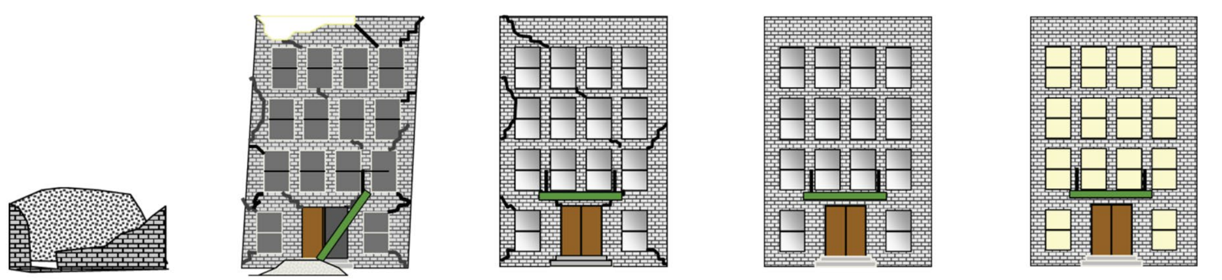

Figure 1. Theoretical range of building performance and relative placement of safety-based and recovery-based goals. Source: FEMA P-2090/NIST SP1254.

In the figure, recovery-based goals are placed relative to safety-based goals. Of the recovery-based goals, reoccupancy represents a building performance state that is safe and habitable and can be used as basic shelter, whereas Full Functionality occurs when the building is at, or restored to, its pre-earthquake condition. Functional recovery is a performance state higher than reoccupancy, but lower than full functionality, targeting reasonable recovery times for basic re-occupancy and service provisioning in order to reduce displacement, downtime, and significant long-term social and economic impacts.

NIST and FEMA's publications are the result of state-of-the-art thinking by many individuals and organizations across various fields of expertise, including: structural engineering, civil engineering, architecture, urban planning, emergency management, code development, disaster science, economics, and public policy. While the general goals for functional recovery are quite clear, the mechanisms to put those goals into practice within buildings and lifelines infrastructure needs further work (ICC 2020, NIST 2021). Translating ideas for improvements to resilience and performance into the technical and practical approaches necessary will require long-term commitment, collaboration and consensus-building.

The framework presented in this report for assessing costs and benefits related to improved performance represents one key component for further development. While critical lifelines are fundamental for the reoccupancy and recovery of a building, economic assessment is more challenging due to the spatial distribution of lifeline networks. Thus, in this report we focus on functional recovery of buildings and adopt the FEMA P-2090/NIST SP1254 definition of functional recovery specific to earthquakes:

> **Definition:** *Functional recovery is a post-earthquake performance state in which a building is maintained, or restored, to safely and adequately support the basic intended functions associated with the pre-earthquake use or occupancy of the building.*

The economic evaluation of recovery-based design standards for critical infrastructure is left for future work.

3. Options for the Economic Evaluation of Recovery-Based Design

In this section, we review methodological options for the economic evaluation of improved seismic design standards. The options vary in their scope and data requirements. It is worth noting that the options presented are not mutually exclusive, and in some cases may be complementary. Moreover, the methods covered in this section are not exhaustive, but meant to be representative of the range of options available.

Note that in principle, while the focus of this report is on providing the tools to evaluate alternative candidates for recovery-based design standards ("adoption"), that decision will be driven by evaluating the economic benefits and costs associated with actually designing or retrofitting a building to a new standard ("implementation"). Thus, the economic evaluation is from the perspective of those who implement the design (typically developers and building owners), as well as those who are affected by the design (occupants, neighbors, the community), rather than those that set design codes and standards (state and local governments, independent entities, federal agencies).

3.1. Benefit-cost analysis

The idea behind benefit-cost analysis (BCA) is simple: do the outcomes of an action outweigh the costs of investing in that action? The outcomes of interest include all of the possible direct, indirect, and intangible benefits of an action (Boardman et al. 2017). The key to BCA is that benefits and costs are measured in the same units so that they are comparable. In particular, benefits that may be nonmonetary in nature are typically converted to monetary values (Zerbe and Bellas 2006).

The goal of BCA is to capture a comprehensive accounting of potential benefits and costs over time, regardless of when they occur (Boardman et al. 2017). Depending on the action, benefits may continue accruing beyond the length of the investment (e.g., public health interventions). For actions that affect the built infrastructure, including new construction, demolition, and renovation, economic evaluation is restricted to the lifetime of the project (e.g., a building's useful life). In any case, a discount rate, δ, is used to normalize the stream of future benefits to present value terms.

The most familiar evaluation criterion consists of a straightforward ratio of all the possible benefits of the action to the costs of undertaking the action, the benefit-cost ratio (BCR):

$$BCR = \frac{benefits}{costs} \tag{1}$$

If the BCR > 1, the action may be recommended on the basis that the benefits outweigh the costs. When evaluating or ranking a *set* of alternative actions, a decision may be justified on the basis of choosing the action that maximizes the BCR. However, when choosing between alternative design standards for a given building, it is recommended practice to consider the incremental benefits gained relative to the additional cost of each design, otherwise relative BCRs may not reflect the relative benefits of the alternatives (ASTM E964). For instance, there may be different operating and maintenance costs ("operational costs") associated with each design, which are distinct from the costs of implementing the design ("investment costs") and complicate the comparison of the numerator to the denominator:

$$BCR = \frac{(benefits - operational\ costs)}{investment\ costs} \tag{2}$$

A major caveat to the BCR > 1 criterion is that there may be other, perhaps unquantifiable or non-economic factors that can affect a decision to adopt an action, such as fairness, public opinion, and political factors (Arrow et al. 1996; Tulchinksky and Varavikova 2014). It is worth noting that a benefit-cost analysis is only one component of a risk mitigation strategy, which includes performing a risk assessment, specifying combinations of engineering, management, and financial risk mitigation strategies, and performing an economic evaluation for the portfolio of strategies (ASTM E2506).

Note that because the BCR is a ratio of dollars to dollars, the metric has no units. In practice, the BCR is often interpreted as saying: "Every dollar we spend on X will save Y dollars," where X is the action and Y is the BCR (e.g., Miller and Hendrie 2008; NIBS 2019).

On the other hand, once benefits and costs are quantified, a decision maker can consider alternative metrics than the BCR.[3] For example, the net present value (NPV) of an investment is simply the (discounted) benefits net of (investment) costs:

$$NPV = benefits - costs \tag{3}$$

In this case, the criterion for investment is NPV > 0.[4] Note that NPV is measured in dollars, in contrast to the BCR. Thus, the metric is naturally suited to comparing or ranking a set of alternatives and is not subject to ambiguities due to different operational costs.

Typically, BCA is prospective (conducted ex ante), in order to evaluate the expected value of a potential intervention; e.g., environmental protection (Pearce et al. 2006); management of health care (Tulchinsky and Varavikova 2014); and the evaluation of education policies (Fletcher 2010). However, BCA can also be retrospective (conducted ex post) to analyze the impact of an actual policy action, such as the impact of enhanced building codes in Moore, OK in response to destructive tornadoes (Simmons et al. 2015). There is also potential to conduct BCA both ex ante and ex post when evaluating the value of improving an existing policy, such as expanding investments in COVID-19 vaccine capacity (Castillo et al. 2021).

The simplicity of BCA belies the potential complexity of estimating the benefits. The challenge lies in not only enumerating the set of potential benefits, but also in monetizing those benefits; for example, monetizing the value of improving public health through upgrades to water and wastewater infrastructure systems (Zerbe and Bellas 2006). On the other hand, where possible, the ability to monetize benefits and compare all benefits and costs measured in the same units is also a strength of BCA. For the evaluation of design standards whose objectives are to improve building performance relative to some hazard, the direct benefits are the avoided losses from the action (e.g., reduced damage from a hazard due to higher design standards). Estimating avoided losses thus requires evaluating building performance under stress. For hazards such as earthquakes, this is typically estimated using software tools such as Hazus (e.g., NIBS 2019) and OpenSees (e.g., Goulet et al. 2007). Once avoided losses are estimated, they can be entered into benefit-cost analysis software, such as FEMA's BCA tool (FEMA 2021) or NIST EDGe$ (Helgeson et al.

[3] It should be noted that the calculated BCR may result in ambiguities (e.g., if BCR < 0, is it because the numerator is negative or the denominator?). The validity of the BCR may be questioned, in particular as regards to the manipulability of the numerator, so it is important to be as clear as possible about all of the underlying assumptions. As with any other metric, it is meant as a guide rather than an absolute rule.
[4] This criterion is also known as the net benefits (NB) criterion (ASTM E1074).

2020).[5] Section 4 discusses methods and software tools used in BCA studies of design standards. The application of BCA to recovery-based design is described in more detail in Sec. 5.

Alternative criteria include the Savings to Investment Ratio (SIR),[6] the Internal Rate of Return (IRR),[7] and payback (PB) or break-even analysis.[8] In addition, there are related metrics such as life-cycle costs (LCC, discussed in Sec. 3.3) and the Return on Investment (roughly, ROI = NPV/costs) that may be more appropriate depending on the action. More details on discounting and alternative metrics for actions specific to buildings and building investments are provided in ASTM E1185. Table 3.1 provides a summary of benefit-cost related metrics and their use for building investment decisions. As the table illustrates, BCA using BCR or NPV can be applied across a broad range of building investment decisions, which include:

- Accept/Reject: a single choice (e.g., design to higher standard or not)
- Design: choosing one out of several competing design options (e.g., choosing between several candidates for a recovery-based design standard)
- Size: the choice of scale or level of investment (e.g., how much bracing)
- Priority or ranking: choice of one or more options from a group (e.g., what parts of building to renovate)

Table 3.1. Alternative metrics for building investment decisions and their use for different types of decisions. Adapted from ASTM E1185.

Decision	**BCR (or SIR)**	**NPV (or NS)**	**IRR (or AIRR)**	**PB**	**LCC**
Accept/Reject	X	X	X	X**	X
Design	X*	X	X*		X
Size	X*	X	X*		X
Priority or ranking	X	X	X		

Note: X = Acceptable; X* = Acceptable if using incremental benefits and costs; X** = Acceptable with caveats.

3.1.1. Extensions of "traditional" BCA methods

Traditional BCA attempts a holistic approach to evaluating outcomes for all relevant stakeholders (e.g., building owners and tenants). For these reasons, BCA is sometimes referred to as *social* benefit-cost analysis (Boardman et al. 2017). However, in certain applications it might make more sense to focus on BCA from the perspective of specific stakeholders. For example, mitigation decisions such as seismic

[5] It is worth noting that the methodology used in the EDGe$ software is based on a guidance document (Gilbert et al. 2015) that is the basis for a standard for the economic evaluation of resilience strategies (ASTM E3130).
[6] The SIR differs from the BCR in that it prioritizes cost savings of an action, where cost savings are defined as benefits net of operation and maintenance costs (not investment costs). For building projects, it is assumed that total operation and maintenance costs over the life of the project are less than zero (i.e., the project saves costs) and moreover that total cost reductions exceed total benefits (ASTM E964).
[7] The IRR is defined as the discount rate such that NPV = 0 (ASTM E1057; ASCE 2021).
[8] The payback period is defined as the length of time, typically in years, until the NPV is equal to the initial investment (ASTM E1121).

retrofits are typically made by the building owner. Thus, Cutfield and Ma (2015) present a building-owner focused BCA that shifts the perspective to the owner to assess key drivers in the decision to retrofit, demolish, or do nothing. The analysis places emphasis on all of the owner's potential cash flows and includes the option to sell the building, while ignoring social benefits that would not persuade the building owner to take action.

A different perspective builds on the observation that investing in an action has diminishing returns: an additional dollar invested does not necessarily result in a proportionate level of benefits. A core concept in economics is that net benefits are maximized when the *marginal benefit* is equal to the *marginal cost*, MB = MC (Arrow et al. 1996). Marginal BCA can thus be used to choose from a set of options by optimizing the marginal benefit relative to the marginal cost. For example, Li et al. (2009) adopt an expected utility framework to conduct a marginal BCA over four seismic retrofit options in Turkey. While the application in Li et al. (2009) ranks alternative options, marginal BCA is best suited to problems where a decision maker such as a regulator must optimize the *level* of risk reduction across a set of options (size decisions). Thus, a key challenge with this approach is in measuring the level of risk reduction relative to monetary benefits and costs.

Finally, a very different extension is to expand the scope of the BCR from a single number to a range that captures some of the uncertainty inherent in estimating benefits. Probabilistic BCA models the distribution of the BCR in order to derive exceedance curves for the probability that BCR > 1. Cardona et al. (2008) model the net present value of losses as a random variable and thus derive analytical formulas for the probability distribution of the BCR. In addition, Mora et al. (2012) demonstrate a Monte Carlo computation of the distribution based on the loss exceedance curve produced by standard probabilistic risk analysis that closely approximates the analytical form. Similarly, Ghesquiere et al. (2006) model annual losses as a random variable and derive BCR exceedance curves using outputs from an earthquake risk assessment of buildings in Bogota, Colombia.

3.2. Cost-effectiveness analysis

An alternative approach to benefit-cost analysis is cost-effectiveness analysis (CEA). In contrast to BCA, the objective of CEA is to choose the option that minimizes the cost of an action relative to a *single outcome* of interest; e.g., reduced casualties from seismic codes (Peterson and Small 2012) or curriculum changes to improve student achievement (Levin et al. 2003). It is therefore used to determine the least expensive way of achieving a particular, well-defined goal (Tulchinsky and Varavikova 2014). The advantage of CEA is that the analysis does not require quantifying the full range of benefits. Indeed, a decision maker may simply optimize a single measure without consideration of benefits at all. For example, Nuti and Vanzi (2003) develop a parametric criterion to evaluate the decision to retrofit a building, based on the ratio of retrofit cost to the repair cost and the change in mean failure rate due to retrofit. The criterion is derived by minimizing the annual equivalent cost, an alternative to net present value.[9]

A disadvantage of CEA is that it implicitly assumes some action to be undertaken to achieve a desired outcome. On the other hand, BCA typically considers the value of an action relative to the status quo (or "do nothing") option (Zerbe and Bellas 2006). One potential advantage of conducting a BCA is that by enumerating the range of potential costs and benefits from an action, one can also conduct a CEA by

[9] Annual Equivalent Cost, more commonly known as Equivalent Annual Cost (EAC), is a method that converts cash flows from an asset to uniform, annual amounts (Jones and Smith 1982). In contrast, Net Present Value (NPV) discounts cash flows to present value terms.

focusing on a single outcome (e.g., reduced downtime) and comparing cost across a set of options for achieving that outcome. However, the outcome must be equivalent across options. In the case of recovery-based design, for instance, a CEA would compare costs of alternative design options that each achieve re-occupancy within three weeks (with 90 % probability under a design-level earthquake). In addition, tools like NIST's EDGe$ can conduct both BCA and CEA at the same time (Helgeson et al. 2020).[10]

3.3. Life-cycle cost analysis

Life-cycle cost (LCC) analysis, like CEA, focuses on a project's cost-effectiveness. However, the key difference is that LCCs cover all relevant (discounted) project costs, including operation and maintenance costs as well as any other costs incurred for the assessment period (e.g., acquisition, ownership, operational costs, and disposal) (ASCE 2021). It is analogous to BCA, but the focus is on costs and the only benefits considered are those that are realized as lower costs (or savings).

As shown in Table 3.1, life-cycle cost analysis is applicable to accept/reject, design, and size decisions that are driven by cost (ASTM E1185). However, it is important to note that comparing alternatives requires the alternatives to satisfy the same functional requirements across the same study period (ASTM E917). The LCC method is especially suited to potential actions for which higher initial costs may be justified by lower future costs (ASCE 2021). For instance, LCC is routinely used for the evaluation of investments in building energy efficiency, as the potential cost savings from such investments are key to investment decisions (Kneifel 2010).

Life-cycle costs may be useful for quantifying the expected damage from earthquake events across the life of the building (Ramirez et al. 2012). For earthquake risk reduction, LCC analysis has been applied to the evaluation of the optimal design of buildings (Wen and Kang 2001; Liu et al. 2003); the optimal level of strengthening, conditional on undertaking a retrofit (Kappos and Dimitrakopoulos 2008); and the management of highway bridge systems (Frangopol et al. 2001). In all cases, the primary consideration is a design or size decision in which the stream of costs over the life of a structure is important. In addition, LCC analysis has potential applications for the evaluation of programs that pair energy efficiency with earthquake risk reduction as documented in Zhang et al. (2022). For recovery-based design, LCC may be useful for comparing alternative design options that all deliver the same performance (in terms of re-occupancy and recovery of function targets) and initial upfront costs may not tell the whole story (for example, if one has higher initial costs but lower maintenance costs).

3.4. Willingness-to-pay

In economics, willingness-to-pay (WTP) is a measure of how much an individual would pay for a good or service—typically one that is not traded in a market and therefore does not have a market price, such as clean air or a potential new product (Breidert et al. 2006).[11] For earthquake risk reduction, for example, it may be used to directly estimate the value homeowners place on seismic strengthening (Manganelli et al. 2018). Willingness-to-pay is sometimes used in policy or legal arguments as a proxy measure for the welfare an individual derives from a good or service (Bar-Gill 2020). However, the relationship between

[10] An alternative that does consider the status quo is the incremental cost-effectiveness ratio (ICER), which is the ratio of the cost difference of an action relative to the status quo to the differential effectiveness between the action and the status quo, where effectiveness is with respect to a single measurable outcome (Bilger 2017). The ICER is commonly used in the medical literature to evaluate health interventions.

[11] An alternative measure, willingness-to-accept (WTA), represents how much an individual would have to be compensated for a good or service.

WTP and welfare is tenuous; for instance, people are often willing to pay for goods or services that do not improve their welfare (Sunstein 2007).

Most often, WTP is used to monetize benefits from an action that are difficult to price. For example, the value of a statistical life (VSL), which is used to monetize the value of reduced mortality risk from a policy, is based on an aggregate measure of individual estimates of WTP (Sunstein 2013). In this way, WTP may be used as a complement to BCA and has become a standard method for valuing ecosystem services and other environmental amenities (Stevens et al. 2000). For earthquake risk reduction, WTP may be used to approximate how much an individual values enhanced building codes by focusing explicitly on the WTP for the benefits derived from improved performance, such as an increase in the building's useful life or a reduction in environmental impacts (Di Bari et al. 2020; Belleri and Marini 2016).

There are two main approaches to measuring WTP (Breidart et al. 2006):

- Stated preference methods (e.g., contingent valuation, conjoint analysis) are based on surveys or interviews that require respondents to evaluate hypothetical scenarios, or "choice experiments" (Kanya et al. 2019). Willingness-to-pay is estimated by either explicitly asking people for their WTP for a good or service or implicitly having them value related goods or services. However, stated preference estimates of WTP are often criticized as suffering from hypothetical bias (differing from actual WTP), strategic bias (respondents want to please the researcher), and for high variation in WTP estimates across methods (Stevens et al. 2000). Thus, stated preference methods may be best used as an approximate lower bound for WTP.[12] Finally, it should be noted that, as with survey methods in general, stated preference methods for estimating WTP may be time consuming and costly, reducing their practical value.

- Revealed preference methods (e.g., hedonic analysis, travel cost method) infer WTP from pricing decisions, either from actual markets for goods or experimental designs to simulate market trade. Thus, to the extent that revealed preferences align more closely with a consumer's actual willingness to pay for a good or service, the method requires data on market transactions. This requirement constrains the scope for the use of revealed preference methods. It should be noted, however, that a strength of revealed preference methods is that the good or service need not be itself tradeable in a market; e.g., hedonic methods are routinely used to estimate willingness-to-pay for urban and environmental amenities such as school quality (Black 1999), clean air (Chay and Greenstone 2005), and the remediation of hazardous waste sites (Greenstone and Gallagher 2008). Of course, the major caveat to revealed preference methods is the requirement of (backwards-looking) data or the careful simulation of a market setting.

Most methods focus on measuring *use value*, which is the value derived from actual use of or interaction with the good or service. A few methods, such as contingent valuation, can also measure *non-use value*, which is not tied to direct use of the good or service, but is rather value derived from the existence of a good or service; e.g., an individual may place a positive value on an aquatic ecosystem even if the individual derives no direct benefit from it (Kanya et al. 2019). While non-use value may be relevant for recovery-based design, it is unlikely that it is a significant enough fraction of the benefits.

[12] WTP is also criticized for being sensitive to wealth effects; that is, individuals face different budget constraints and value goods accordingly. In some cases, WTA may be a more reliable measure to the extent that it is less sensitive than WTP to wealth effects (Bar-Gill 2020).

3.5. Economic impact analysis

A very different approach to economic evaluation is economic impact analysis (EIA). As the name suggests, the main purpose of EIA is to determine how an action affects economic activity (e.g., employment, income). A distinguishing feature of EIA is the focus on a well-defined region of economic activity (Weisbrod et al. 2016). In contrast, BCA focuses on determining whether an action makes "society" better off, typically without a well-defined geographic boundary.[13] In addition to the spatial dimension, BCA and EIA differ on the following dimensions:

- The temporal dimension: BCA focuses on the present value of impacts within a well-defined study period, while EIA focuses on undiscounted future impacts within a less well-defined medium and long-term.

- The impact dimension: EIA focuses on impacts on money flows (such as expenditures); in principle, BCA considers all benefits and costs to society, but as the discussion in Sec. 3.1 illustrates, in practice this is often reduced to those that can be monetized.[14]

- The output: while BCA summarizes each of the impacts into a single metric (BCR or NPV), the impacts in an EIA (e.g., employment, income) remain disaggregated as the objective of EIA is to determine how impacts are distributed in the economy.

Thus, BCA and EIA may be seen as complementary approaches with different perspectives. For instance, EIA could be used to measure impacts on productivity or employment, which could then be used as inputs into a BCA.

Economic impact analysis has been used to explore changes in transportation policy (Weisbrod et al. 2016), regional impacts of large events such as sporting events (Dwyer et al. 2006), and to quantify the direct and indirect impacts of natural disasters (Okuyama 2007). The standard approach to economic impact analysis relies on input-output (I-O) models, which rely on accounting tables that trace inter-industry purchases and sales in a region (Weisbrod and Weisbrod 1997). An I-O models economic multipliers that determine how a dollar spent on a good or service leads to direct and indirect impacts on employment, income, and output.

One criticism of this approach is that it focused solely on positive impacts and ignores negative impacts (Taks et al. 2011). Simulation models, such as computable general equilibrium (CGE) or agent-based models, build on I-O models by considering additional aspects of the economy such as household purchases from industry, shifts in population, and productivity (Weisbrod and Weisbrod 1997; Hallegatte 2008; Inoue and Todo 2019). Such models therefore provide a more comprehensive picture of economic impacts. Of course, the added level of sophistication comes with greater modeling and data costs, making model assessment by non-experts is difficult.

At the margin, designing or retrofitting a single building for recovery likely has a negligible impact on the local economy and thus BCA is the more appropriate method for economic evaluation. On the other hand,

[13] It should be noted that while the intent is for BCA to take a holistic perspective, in practice it is challenging to fully account for the complexities of society, including who bears the benefits and costs and associated equity concerns.
[14] Moreover, BCA implicitly assumes (a) independent valuations for each impact that reflect trade-offs among the different types of benefits and costs, and are additive for calculating total impacts over time (Weisbrod et al. 2016). In general, EIA does not depend on these assumptions.

economic impact analysis may be useful for quantifying the direct and indirect benefits[15] of community-level adoption of enhanced building design.[16] Moreover, such analyses might provide reasonable bounds on the indirect impacts of recovery-based design, such as reduced supply chain disruptions, that could be used as inputs into BCA.

Due to the nature of EIA models, it may be difficult to distinguish spending flows as benefits or costs. In cases where this distinction is important, BCA may be the preferred approach. Finally, it is important to note that by design EIA is not intended to provide outputs or other information that can inform a decision support tool, while BCA does so.

3.6. Summary

For the purposes of recovery-based design, the preceding discussion suggests BCA as the most appropriate method because it is comprehensive and is particularly well-suited to decision support for investments in single buildings. However, other methods such as CEA and LCC may be appropriate if the primary concern is the cost side.

[15] In principle, EIA can also be used to estimate co-benefits, which are benefits that occur even if there is no hazard (Fung et al. 2021a).
[16] For instance, suppose enhanced building designs are more attractive; they may increase property values, which attracts wealthier businesses/tenants, which increases the tax base, which increases public services, which increases quality of life, which attracts even more people.

4. Benefit-Cost Analysis for Building Design: A Review

Economic evaluation of enhanced building design, such as benefit-cost analysis, does not typically consider above code design, but rather is conducted contemporaneously with newly proposed or implemented code changes. Much of the focus is therefore on designing new buildings or bringing existing buildings up to code. This section presents a review of the literature, with a particular focus on methodologies and tools used. The review is by no means comprehensive, but is meant to be illustrative of the literature. For an extensive review of the state-of-the-art, see Zhang et al. (2022). The main takeaway is that functional recovery represents a new design paradigm and these earlier studies do not provide an adequate precedent for the economic evaluation of recovery-based design.

4.1. Benefits and costs of adopting higher standards for new construction

For new buildings, studies are typically conducted to analyze the economic impact of code changes; in particular, the impact of complying with modern building codes. Not all studies conduct a full benefit-cost analysis. Some focus on the benefits (reduction avoided losses) associated with compliance, while others focus on the additional construction cost associated with compliance. A few exceptions (Goulet et al. 2007; NIBS 2019) consider exceeding code requirement, as discussed at the end of this subsection.

Ryu et al. (2010) compare annual expected losses for commercial buildings constructed to a life-safety performance objective using 2003 IBC, 2006 IBC, and 1999 Standard Building Code (SBC) in Memphis, TN. Using Hazus, they find that losses can be reduced by approximately 1 % when either 2003 or 2006 IBC is implemented, relative to 1999 SBC. FEMA (2020) conducts a study of the value of meeting I-codes for new construction for 2000-2018, relative to 1994 UBC. Using damage functions from Hazus with parcel and building footprint data for six western states,[17] as well as input from experts in building performance and building code history, FEMA (2020) estimates roughly $60 million in avoided losses associated with complying with I-codes.

The National Association of Home Builders (NAHB) assesses the costs for single and multi-family homes conforming to 2018 IBC, using a combination of RSMeans Cost data, Census data, Bureau of Labor Statistics data, and data from distributors' or retailers' websites (NAHB 2018). For multi-family homes, the construction cost is expected to increase by around $16 000 for a two-story apartment and by around $44 000 for a three-story apartment when subject to the code change of 2018 IBC, relative to 2015 IBC.

NEHRP Consultants Joint Venture (2013) employs the PEER Performance-Based Earthquake Engineering (PBEE) design framework, implemented in FEMA's PACT software (FEMA 2012b), to analyze the impacts of compliance with 2012 IBC, relative to 1999 SBC. Cost estimates are developed by a consulting firm. Results indicate that the structural cost of a two-story reinforced concrete office building (total floor area of 100 000 square feet) may increase by 4.6 % when designing for 2012 IBC, due to increased requirements for braced frames, collectors, and foundations. The total building cost may grow by 0.7 % when adding required bracing and anchorage of nonstructural components and systems to the building. These measures together can reduce annualized losses by 40 %.

[17] FEMA (2020) focuses on the six states with the highest seismicity (Alaska, California, Hawaii, Oregon, Utah, and Washington), which together account 78.5 % of the national Average Annualized Losses per FEMA (2017).

The National Institute of Building Sciences (NIBS) analyzes the benefits and costs of implementing 2018 IBC seismic design requirements for the minimum performance objective of life safety (NIBS 2019). Using Hazus, they estimate annualized losses due to earthquakes for one percent of the building inventory across the 48 contiguous United States. Compared to 1990's seismic codes, NIBS (2019) finds that 2018 IBC can help prevent property losses of $1500 per building, reduce deaths, injuries, and trauma-related losses by $800 per building, and decrease business interruption losses by $2000 per building. The total benefit is expected to be $4.3 billion per year, three times greater than the total cost (i.e., BCR of 3). The construction cost is assumed to increase by 1 % for a 50 % increase in strength and stiffness (based on Porter 2016). Since the strength requirement of the 1990's code is approximately 67 % of that of 2018 I-code, the increased compliance cost for 2018 I-code is 0.7 % (NIBS 2019).[18]

NIBS (2019) also creates a benefit-transfer matrix, shown in Table 4.1, to allocate the estimated benefit to five closely involved stakeholder groups: developers, title holders, lenders, tenants, and communities. Among the five groups, tenants benefit most from the code with a net benefit up to $2 billion, followed by title holders, communities, and lenders. The assumptions underlying the benefit-transfer matrix represented in Table 2 are derived based on a process for eliciting expert judgment (NIBS 2019).

Table 4.1. Benefit-transfer matrix (NIBS council 2019).

Stakeholder group	**Construction cost**	**Property loss**	**Direct business interruption**	**Indirect business interruption**	**Insurance**	**Death and injury**
Developer		2 %			4 %	
Title holder	50 %	58 %			86 %	
Lender		7 %			10 %	
Tenant	50 %	33 %	100 %			99 %
Community				100 %		1 %

On the other hand, the literature on evaluating benefits and costs of above-code seismic design is more limited. Goulet et al. (2007) evaluate the benefits of designing reinforced concrete buildings to exceed 2003 IBC seismic design requirements. The results show that above-code design can reduce expected annual losses from fatalities by up to 66 % compared to code-minimum design. Particularly, using uniform beams and columns throughout the building can lower expected annual losses by 22 % compared to the original design.

[18] The construction cost for buildings complying with the 1990's code is estimated using the RSMeans CostWorks 2018 data.

NIBS (2019) assesses the cost-effectiveness of designing buildings to exceed 2015 IBC strength and stiffness requirements. The study assumes that 1 % of the existing building inventory is replaced by new buildings that are designed for a higher importance factor of 1, 1.25, 1.5, 2, or 3, varying by county.[19] The tabulated vulnerability functions are used to estimate annualized losses of structures and nonstructural contents due to earthquakes. For construction cost, the same assumptions are made as for compliance with 2018 IBC; that is, the increased construction cost is 1% due to a 50% increase in strength (NIBS 2019). The results indicate that the BCR tends to be higher in counties with a higher seismicity, and the national average BCR is approximately four considering a discount rate of 2.2 %. In addition, tenants obtained the greatest benefit, followed by title holders, communities, and lenders.

4.2. Benefits and costs of seismically retrofitting existing buildings

There are relatively many more studies that evaluate the economic value of mitigation strategies for existing buildings. However, as with new construction, the focus tends to be on bringing existing buildings “up to code” rather than exceeding current codes for enhanced performance. An exception is ATC (2009), which considers retrofit of wood-frame residential buildings for Immediate Occupancy, as discussed below.

Reinforced concrete buildings. Carofilis et al. (2020) investigate the retrofit strategies for school buildings constructed with reinforced concrete, precast concrete, and URM in Italy. The benefits of retrofit strategies are estimated using a combination of OpenSees, TreMuri, and PACT. The results indicate that adding steel braces or carbon fiber reinforced polymer (CFRP) strips to beam-column joints is not cost-effective for the reinforced concrete building but cost-efficient for the precast concrete building, with a payback period ranging from 56 to 83 years. The payback period for the URM school building is 32-39 years when CFRP strips are attached to both sides of masonry piers and spandrels. However, using CFRP strips and viscous dampers together is not economically feasible due to the high cost of dampers. Similarly, Haghpanah et al. (2017) evaluate three retrofit techniques for a concrete school building: base isolation, concrete jacketing, and steel jacketing. The results show that base isolation not only enables the building to meet the immediate occupancy performance criteria but also significantly reduces economic and casualty losses in the event of a large earthquake. On the other hand, the building with concrete or steel jacketing may be unoccupiable following a large earthquake. Smyth et al. (2004) analyze three retrofit methods for reinforced concrete apartment buildings. A five-story building in Caddebostan, Turkey, is selected to represent concrete buildings constructed under the 1967 code, which prescribes much smaller seismic loads than the current code. The benefit-cost analysis results suggest that the three retrofit methods are cost effective when the useful life of the building is longer than 10 years. Partial retrofit produces greater net benefits compared to full retrofit and bracing.

Wood-frame buildings. ATC (2009) compares three retrofit schemes for wood-frame buildings that contain soft stories, which are more flexible and weaker than the stories above due to lack of walls or frames (e.g., due to large openings for parking space).[20] Four representative residential buildings in San Francisco, CA, are selected to compute and compare the benefits (in terms of avoided loss to structures and contents) and costs of the retrofit schemes. The results show that the financial benefit of retrofitting

[19] An importance factor of 1.5 is required for essential facilities by 2015 IBC, and lower values of 1.25 and 1 are used for designing buildings falling into Risk Category III and Risk Categories I and II, respectively (ASCE 7-16).
[20] One scheme uses steel cantilevered columns and greater shear walls to strengthen the soft story, which would allow residents to remain in their units after a major earthquake and strong aftershocks, analogous to retrofitting for an immediate occupancy (IO) performance objective (ATC 2009).

decreases as the size of an earthquake increases, as retrofitted buildings may be just as damaged as non-retrofitted buildings in an extreme earthquake. The direct construction costs for the four buildings, accounting for labor, equipment, and materials costs, range from $9000 to $19 000 per unit, while avoided losses range from $24 000 to $52 000 per unit. Similarly, Porter et al. (2006) evaluates retrofit strategies for wood-frame residential (single and multi-family) buildings in California, and finds that retrofit is only cost-effective in regions near fault or on soft soil.

URM buildings. Paxton et al. (2017), Goettel (2016), and Gibson et al. (2014) estimate the benefits and costs of retrofitting URM buildings at the city scale. Modifications are made to Hazus models to reflect local conditions and code requirements. Gibson et al. (2014) perform a benefit-cost analysis for URM buildings in Seattle, WA, and find that retrofit is not cost-effective because of high intial cost. However, some benefits that are not included in the analysis may weaken the conclusion, such as the increase in building's market value, reduction in building's insurance costs, greater historic preservation, and maintaining community visual character (Gibson et al. 2014). Similarly, Goettel (2016) conducts a benefit-cost analysis for URM buildings in Portland, OR, but finds that retrofitting URM buildings is cost-effective considering a 2 % discount rate and a 50-year useful life of the buildings. However, the results are subject to large uncertainty because the benefit-cost ratio is highly sensitive to discount rate and useful life. In addition, some benefits are not evaluated in this study, such as avoided damage in buildings adjacent to URM buildings, prevented fire following earthquake damage, prevented water damage from failed water pipes, decreased insurance costs, avoided injuries of visitors outside the buildings, and extended useful life of URM buildings (Goettel 2016). Paxton et al. (2017) analyze URM buildings in downtown Victoria, British Columbia, Canada. The benefit-cost results show that partial retrofit (adding tension anchorage to all floor-to-wall interfaces and adding out-out plan bracing to all slender walls) is cost-effective in enhancing the seismic performance of URM buildings, whereas full retrofit that complies with 2012 International Existing Building Code is not economically feasible even though it allows the least economic and casualty loss during earthquakes.

4.3. Benefits and costs of enhanced building designs in other domains

There is an extensive literature that analyzes the benefits and costs of meeting or exceeding building codes for other hazards, such as hurricane (Simmons et al. 2017) and tornado winds (Simmons et al. 2015). Unlike seismic events that cause damages to nearly all components of a building, wind damage is mainly focused on the envelope and roof-covering components, but hurricane winds followed by floods can result in water damage to building contents.[21] Finally, Berry and Davidson (2016) present a review of methodologies for economic evaluation of energy-efficiency upgrades in more stringent codes, including benefits and costs not typically considered, with a case study in Australia.

[21] At the intersection of earthquake and wind, Joyner and Sasani (2020) assess the performance of two seven-story concrete buildings that were built in compliance with ASCE/SEI 7-10 seismic and wind design requirements for Risk Category II.

5. The FR-BCA Framework

Based on a thorough review of the literature, we present the following three-step process to standardize benefit-cost analysis (BCA) for the evaluation of seismic risk reduction of buildings. This process is generic and can apply to both building codes for new construction as well as the retrofit of existing buildings. Where applicable, we point out differences in the process for each case. At each step of the process, we highlight the key components with respect to functional recovery, where there exist standard values for monetizing recovery-associated losses, and where gaps remain.

The objective of the functional recovery benefit-cost analysis framework (FR-BCA) is to tailor the process specifically for enhanced seismic design standards, rather than to reinvent the wheel with respect to conducting benefit-cost analysis. We outline a broad range of potential benefits and costs relevant to recovery-based design, with particular attention to impacted stakeholders and methods and tools for estimation. For many benefits, methods and tools may not be available and we highlight this gap as a research need.

The greatest challenge to conducting BCA for functional recovery is obtaining cost data. There is no current design standard for functional recovery on which to base construction costs.

Steps for conducting FR-BCA

Step 0: Set analysis parameters (r: real discount rate, T: planning horizon, m: mitigation option).

The choice of discount rate has been discussed thoroughly in the literature (e.g., Gibson et al. 2014). A typical discount rate is between 2 % and 10 %. The Office of Management and Budget (OMB) recommends 7 % (FEMA 2009). This may be critical if a project is federally funded or managed. In all other cases, the choice of discount rate is left to the discretion of the decision maker.

A typical planning horizon for built infrastructure such as buildings is the building's expected useful life. This tends to be somewhere between 50 and 75 years for new buildings (NIBS 2019), with $T = 30$ a reasonably accepted planning horizon for existing buildings after seismic retrofits (FEMA 2009).

Step 1: Estimate benefits, B_i, of action *i.*

In many benefit-cost analyses, this may be the most challenging step. For FR-BCA, this step requires first identifying any assets that are sensitive to earthquakes and then estimating the relationship between the severity of expected losses (damages) and the ground shaking hazard. The benefits of recovery-based design may then be estimated from the avoided losses under design option *i* relative to the status quo, as discussed in more detail in Sec. 5.1.

Step 2: Estimate costs, C_i, of action *i.*

In principle, estimating the cost associated with a particular design option is more straightforward than estimating the benefits. In practice, obtaining relevant cost information can also be challenging, especially for new design or retrofit standards for which there are no actual construction costs available. This is discussed in more detail in Sec. 5.2.

Step 3: Compare benefits and costs.

Once benefits and costs are estimated, the analyst can compare benefits to costs using two metrics:

Benefit-cost ratio (BCR): B / C

Net present value (NPV): B - C

where a BCR > 1 or NPV > 0 imply that the benefits of the design option outweigh the costs. Of course, these criteria may be sufficient but not necessary. That is, while a BCR > 1 should encourage adoption of the design option, a BCR < 1 need not discourage it. The BCA is limited to how well it can quantify the losses and, thus, the benefits. If key benefits are excluded (e.g., externalities or non-market values) or if loss estimation is flawed, then the BCR is likely to underestimate the relative benefits of the design option.[22] Moreover, there may be other, intangible reasons (e.g., political will) for recommending adoption of a design option.

Step 4: Okay, we lied. There's a fourth step, but this step is optional.

Given estimates from steps 1 and 2, one can distribute benefits and costs across stakeholders (to obtain tiers of impacts). If we then compute the BCR for each stakeholder (or impact tier), we obtain a *distributed* BCR for each tier. Alternatively, once the BCR is computed, one can distribute the total BCR to obtain fractional BCRs for each tier to obtain BCR *shares per tier*. This step is rarely adopted, but there are exceptions (e.g., Cutfield and Ma 2015; NIBS 2019).

Moreover, sensitivity analysis can be used to examine whether the BCR shifts dramatically when inputs vary due to uncertainties in building's useful life, inflation rate, benefit and cost assumptions, hazard level, and model simulations. It is often helpful to determine the sensitivity range for each input and identify the inputs most important in estimating the baseline BCR (Gibson et al. 2014; Porter et al. 2006).

5.1. Estimating benefits associated with enhanced building design

As discussed above, the benefits from recovery-based design will come largely from avoided losses, which requires quantifying expected losses from an earthquake event. Of course, as we discuss below, there may also be other benefits that accrue independently of the occurrence of an earthquake (e.g., extending the useful life of a building).

Expected losses are quantified in annual terms (Expected Annualized Losses, or EAL), with (EAL_i) and without (EAL_0) the action. A general formula for EAL is:

$$EAL = \int_0^{\infty} L|dP(L)| \tag{4}$$

where $P(L)$ is the PEER mean annual rate of exceedance for the loss L (Porter 2003; Krawinkler et al. 2006; Mitrani-Reiser 2007):

[22] Note that one can also subtract the "salvage value" of the building from the cost (e.g., Kappos and Dimitrakopoulos 2008).

$$P(L) = \int_{dm} \int_{edp} \int_{im} G(L|dm)|dG(dm|edp)||dG(edp|im)||dP(im)| \tag{5}$$

where $G(x|y) = 1 - F(x|y) = P(X \geq x|Y = y)$ denotes the "exceedance" probability (i.e., the complementary CDF, or survival function); *dm* denotes the *damage measure* (e.g., damage state); *edp* denotes the *engineering demand parameters* (e.g., max drift); and *im* is the *intensity measure* (e.g., pga). $P(im)$ is expected rate of return of the ground shaking hazard derived using a Poisson model for the annual rate of exceedance for the intensity measure *im*. Colloquially, $P(im)$ is the "hazard curve."

In the literature on performance-based earthquake engineering (PBEE), $P(L|dm)$ is also written as $P(dv|dm)$ where *dv* is a *decision variable*, such as damage, downtime, and casualties (Mitrani-Reiser 2007).[23]

If we use a discrete damage measure such as damage state (*DS)* then EAL may be computed as:

$$EAL = \int_{edp} \int_{im} \sum_{DS} L_{DS} \times G(L|DS)d(DS|edp)dG(edp|im)dP(im) \tag{6}$$

The $G(L|dm)$ is typically calculated using consequence functions that link damage to losses (typically the loss ratio, which is the ratio of repair costs to replacement costs). Consequence functions may be defined at the global-level (e.g., building level), for a coarse level of detail, or at the component-level, for finer level of detail. Consequence functions are typically derived from data on actual losses or from expert judgement (Odabasi et al. 2020). Hazus, for instance, provides detailed global-level consequence functions for various occupancy types and damage states. On the other hand, FEMA P-58 provides component-level consequence functions for both repair *costs* and repair *time*. To leverage the accuracy of component-level consequences for global assessment, component-level performance must be aggregated into global-level consequences considering the interdependencies in the repair of multiple components within a given asset (FEMA 2018, Cook et al. 2022).

The benefit of risk reduction (new construction or existing building) is the present value of the avoided losses due to action *i*:

$$B = [EAL_0 - EAL_i] \sum_{t=1}^{T} (1 + r)^{-t} \tag{7}$$

Equivalently, by sum of geometric sequences

$$B = [EAL_0 - EAL_i] \times \left[\frac{1 - (1 + r)^{-T}}{r}\right] \tag{8}$$

[23] There is also a literature that explores simplified methods for computing EAL (e.g., Porter et al. 2004; Solberg et al. 2008; Ramirez et al. 2012; Welch et al. 2014; Cardone et al. 2017; Cardone et al. 2019a, 2019b).

Thus, the key to benefit calculation is to identify and quantify the relevant potential losses, since avoided losses constitute the major portion of benefits.

Remark: Note that the preceding discussion focuses on quantifying a point estimate of the benefit. In principle, one can also compute the variance of benefits by calculating the variance of avoided losses: $Var(B) = V[Avoided\ Losses] \sum_{t=1}^{T} \ (1+r)^{-2t}$ where

$$V[Avoided\ Losses] = V[EAL_0] + V[EAL_i] - 2Cov[EAL_0, EAL_i] \quad (9)$$

Recall that $V[X] = E[X^2] - E[X]^2$and $Cov[X,Y] = E[XY] - E[X]E[Y]$. Thus, to calculate variance of avoided losses, we need to calculate $E[EAL_i^2]$ for i = 0, 1 and $E[EAL_0 EAL_i]$, which can be computed using the same formula; e.g., $EAL^2 = \int_0^\infty \ L^2|dP(L)|$. This may be valuable for uncertainty quantification.

Table 5.1 summarizes the potential benefits relevant to recovery-based design, including the affected stakeholders and typical methods for monetizing those benefits, where available.[24] As the preceding discussion illustrates, benefits are obtained by estimating avoided losses with respect to a recovery-based design option. Thus, the benefits in Table 5.1 are presented in terms of the relevant losses that should be estimated to obtain avoided losses. The key to estimating benefits for functional recovery is to estimate downtime (time to re-occupancy or recovery of function), as discussed in more detail in Sec. 5.3. Given estimates of downtime, one can estimate monetary losses associated with downtime using Table 5.1. In addition, there may be co-benefits that accrue even in the absence of an earthquake during the planning horizon, including reduced environmental impacts (Belleri and Marini 2016; Dong and Frangopol 2016), extended lifespan of the asset (Di Bari et al. 2020; Belleri and Marini 2016), and increased economic resilience (Fung et al. 2021a). Since such co-benefits are not dependent on enhanced performance, and moreover established methods for estimating them are not available, we do not cover them in detail but note that they may be critical to making a business case for recovery-based design.

Note that in practice, it may not be feasible to calculate the full range of benefits. Some benefits, such as impacts on quality of life and property value, tend to be highly idiosyncratic and are difficult to monetize, especially if there is no readily available data on the values of such benefits. Other benefits, such as avoided damages to and from neighboring buildings, require more sophisticated models for loss assessment that incorporate multiple assets and their spatial dependence. As a result, Table 5.1 also identifies additional needs for tools and data required to monetize these benefits. Each category of losses and the associated potential benefits are discussed in the subsections that follow.

[24] For a review of methods and tools available, see the review of Zhang et al. (2022).

Table 5.1. Potential direct and indirect loss categories and the associated benefits from enhanced design, as well as the potential beneficiaries and methods for monetizing.

	Loss	Benefit	Beneficiaries	How to monetize
Direct	Building damage	Avoided repairs to structural and nonstructural components	Owner, Taxpayers (government assistance)	(Repair cost × Prob[Repair]) + (Demolition cost × Prob[Demolition]) OR *x* % of Replacement cost (*x* = Damage ratio)
	Contents damage	Avoided loss of contents (e.g., equipment, furniture)	Owner[+], occupants	*x* % of Replacement cost (*x* = Damage ratio)
	Casualties (deaths and injuries)	Avoided deaths and injuries	Owner[+], occupants, visitors	(VSL) × (number of deaths/injuries)
Indirect	Economic losses	*Business interruption*		
		Avoided loss of business income	Occupants, community (local, national) due to direct and indirect impacts	(Average daily revenue) × (days of business interruption)
		Avoided loss of rental income	Owner	(Average rental rate/sq m) × (Fraction of area rented) × (Days of business interruption)

		Avoided loss of productivity	Occupants, community	See literature on section 5.1.2.*
		Avoided reduction in customers	Occupants, community	See literature on section 5.1.2.**
		Avoided reduction in employment	Occupants, community	See literature on section 5.1.2.**
		Insurance-related losses		
		Avoided increase in insurance premium costs	Owner, occupants	(Premium after earthquake event) - (Premium before earthquake event)*
		Avoided delays in settling insurance claims	Owner, occupants	See literature on section 5.1.3.**
		Improved equity through reduction in regressive hazard insurance	Owner, occupants	See literature on section 5.1.3.**
		Indirect property losses		
		Avoided property value decrease (due to physical damages, capitalized risk)	Owner, owners of similar properties	See literature on section 5.1.4.*
		Avoided reduction in tax base	Community	See literature on section 5.1.4.*
		Avoided delays in recouping return on	Owner, Developer	See literature on section 5.1.4.***

		investment due to delays		
		Supply chain disruption		
		Avoided supply chain delays (upstream and downstream)	Owner+, occupants+, upstream/ downstream partners	See literature on section 5.1.5.*
	Social losses	Avoided displacement costs	Owner+, occupants, taxpayer+	See literature on section 5.1.6.
		Avoided loss of life quality due to deterioration in physical or mental health	Owner+, occupants, neighbors	See literature on section 5.1.6.
		Preserve culture/history/character and help attract tourism investments	Community (local, national)	See literature on section 5.1.6.
		Avoided loss of sense/connectedness/community	Local community	See literature on section 5.1.6.**
		Reduction in perception of risk due to improved performance	Owner, occupants, owners of similar properties, local community	See literature on section 5.1.6.***
		Reduced burden on emergency response	First responders	(Number of first responders at risk) × (QoL × WTP) OR

				(Number of injuries) × (Medical expense)
		Reduced crime rate	Community	See literature on section 5.1.6.**
		Impacts on underserved communities/reduction in affordable housing	Community	See literature on section 5.1.6.**
		Government assistance	Taxpayer	See literature on section 5.1.6.**
	Physical losses	Avoided clean-up costs and closures due to on-site/off-site debris	Owner, occupants, visitors	(Clean-up costs) × (Amount of debris) *NB: Do not double count. This is used to attribute the fraction of losses due to debris.*
		Avoided energy consumption, greenhouse gases emissions, environmental pollution due to repairs/demolition	Owner, community (local and at large)	See literature on section 5.1.7.

Notes: Building owner = Title holder. VSL = Value of a Statistical Life. WTP = Willingness-to-pay. Prob = Probability. QoL = Quality of Life.
[+] Potential impact.
* Research is needed with precedent in related literature.
** Research is needed without precedent.
*** Highly speculative.

5.1.1. Direct benefits

Building and contents damage are standard outputs of a performance-based earthquake risk assessment (e.g., FEMA P-58). Note that these losses are typically calculated based on the replacement value of the building (the damage ratio). Casualties (deaths and injuries) may not be standard outputs, but methods exist for estimating casualties based on building performance (e.g., using the PEER framework in Eq. (2)); see for example Mitrani-Reiser 2007. Note that for recovery-based design, avoided casualties may be low relative to code-conforming design, but are expected to be higher relative to older buildings (that is, the benefits from reduced casualties are expected to be much higher for retrofits than for new construction).

5.1.2. Indirect economic benefits

The next category of losses in Table 5.1 covers indirect losses due to business interruption. A reasonable approximation to the number of days of business interruption is days to recovery of function (though it may be shorter conditional on the ability to rent temporary space and resume operations). Assuming this can be estimated (for instance, using the methods discussed in Sec. 5.2), indirect economic losses are calculated as:[25]

$$Business\ loss\ =\ (loss\ per\ day)\ \times\ (days\ of\ business\ interruption) \tag{10}$$

The loss per day may be relatively easier to estimate for some benefits than for others. For instance, business income is typically calculated based on average daily revenue. Absent data on actual revenue, daily revenue may be estimated from economic measures such as proprietor income or value added.[26] Similarly, rental income may be based on market rental rates, which vary by building occupancy.[27]

On the other hand, loss of productivity may be more challenging. To estimate loss of productivity, we need to estimate both productivity and the impact of business interruption on productivity:

$$Productivity\ loss\ =\ (Productivity\ per\ day)\ \times\ (Productivity\ decrease)\ \times\ (days) \tag{11}$$

Productivity is typically measured as wages or gross value added (Seppanen et al. 2004). The more challenging step is estimating the impact of business interruption on productivity, which can be measured directly through surveys or indirectly through observational studies. For example, the literature that studies the impact of building environment (such as temperature and indoor air quality) on worker productivity relies on a combination of thermal comfort models, questionnaires or surveys to elicit subjective impacts, and indirect assessment of occupant performance through measures such as absenteeism, turnover, and grievances (Horr et al. 2016). Using models from the literature, Kershaw and Lash (2013) estimate potential productivity losses from climate change for office workers in England between \$23 and \$31 per sq ft (\$248 and \$334 per sq m) annually. For enhanced seismic codes, we are

[25] For more accuracy, it is typical to use income per square foot per day, then multiply that by the building in the study's square footage.
[26] The Bureau of Economic Analysis (BEA) defines proprietor income as the "current-production income of sole proprietorships, partnerships, and tax-exempt cooperatives" that excludes dividends, rental income, and interest payments (BEA 2018a). Value added is defined as the "gross output of an industry or a sector" net of intermediate purchases (BEA 2018b).
[27] Market rental rates, as well as estimates of the fraction of a building that is rented, can be obtained from Hazus (FEMA 2012a) or BOMA (2018).

not aware of literature that estimates impacts on productivity.[28] Thus, this is an identified research gap.[29,30]

Finally, reductions in customers and employees are more difficult to quantify. The data available in the literature is anecdotal at best (Potter et al. 2015). We caution that while estimating such impacts may be valuable depending on the application, there is a danger of double counting benefits.[31] The potential losses in Table 5.1 assume the building has restored some level of functionality, but nevertheless suffers a reduction in customers or employees. This could be due to cascading effects from the event that result in dislocation, emotional well-being, or increased risk perception due to observable damage *even if the building is functional*. Losses due to reduction in customers could be estimated as

$$Customer\ loss = (Revenue\ per\ customer) \times (Number\ of\ lost\ customers) \tag{12}$$

Similarly, losses due to a reduction in employees could be estimated as

$$Employee\ loss = (Revenue\ per\ customer) \times (Number\ of\ lost\ customers) \tag{13}$$

Note that neither of these losses are directly tied to loss of functionality. However, restoration of function may reduce these impacts relative to code-conforming or existing buildings. Estimating the numbers of lost workers or customers may require building this into performance assessments, surveys, or potentially economic impact assessment models for which impacts can be downscaled (Sarmiento 2007; Belasen and Polachek 2009). We leave this as an open area for research.

5.1.3. Insurance-related losses

The insurance-related losses in Table 5.1 are distinct from indirect economic losses as they are intended to capture impacts on insurance markets, which may be difficult to quantify. In principle, estimating the (avoided) increase in insurance premiums following an earthquake should be straightforward. In practice, it requires access to proprietary information from insurance companies. If a building owner, manager, or developer, or a community, has experienced an increase in insurance premiums following an event, they may use their knowledge as an approximation.

Delays in settling insurance claims result in delayed repairs. Potter et al. (2015) note delays of two years or more following the Canterbury earthquake sequence. Such delays, as well as delays due to processing loans, post-earthquake inspection, and contractor mobilization are called impeding factors in the literature on downtime (Almfuti and Wilford 2013). REDi (2013) characterizes financing delays as the most uncertain impeding factor, with the caveat that insurance deductibles often exceed the expected losses. The recommended approach to mitigate such losses is to limit expected losses so that repairs can be financed with available funds. Thus, while the avoided losses may be substantial, the expected impact of

[28] The California Governor's Office of Emergency Services (Cal OES) suggests using $8,736 per worker for benefit-cost analyses of seismic retrofits for residential buildings. However, there are no details on how this figure was obtained. https://www.caloes.ca.gov/RecoverySite/Documents/2019%20BCA%20Presentation.pptx (Accessed: 2021-08-20).
[29] Another example uses cognitive performance scores to assess the impact of optimizing window views and daylight on productivity (MacNaugthon et al. 2021).
[30] The literature on productivity losses due to the COVID-19 pandemic may be able to provide insight on measurement approaches.
[31] For example, loss of business income will be directly tied to loss of customers and employees. One could think of these losses as ways to disaggregate loss of business income, if that is of interest and the data is available.

impeding factors on delays will vary case by case.[32] As noted in Sec. 5.2, this is an active area of research as it is critical for estimating downtime. In principle, if a performance assessment can estimate downtime due to repairs ("rational downtime") as well as downtime due to impeding factors ("irrational downtime"), we can apply similar logic as in Sec. 5.1.2 to disaggregate business losses (Comerio 2006).

On the other hand, losses due to reduced equity are more speculative but a potential research need. Owen and Noy (2017) examine half a million claims for the New Zealand earthquake insurance program and find that the system is regressive; that is, lower income households pay proportionately more than higher income households. This is largely due to the nature of the premium, which is risk-based and thus tied to socioeconomic status. Thus, in principle a reduction in insurance premiums or coverage could improve equity by reducing the disproportionate burden on lower income households. However, as Owen and Noy (2017) note, there has been little research to date on natural hazard insurance programs and their impact on equity. Moreover, to go one step further and monetize the benefit would require estimating the burden of such regressive insurance schemes on different kinds of households. In part, this would require data on insurance premiums, but it would also require socio-economic data such as household income. Thus, this is left as an open area for research.

5.1.4. Indirect property losses

In addition to the direct losses from building and contents damage, there may be indirect losses associated with property damage. For instance, a damaged building that survives an earthquake event may suffer from a reduction in property value due to increased salience of perceived risk (Timar et al. 2018a).[33] In addition, buildings that provide enhanced performance may experience a property price premium (Filippova et al. 2017).

Such benefits for property value are typically estimated using willingness-to-pay (WTP) methods that attempt to capture the capitalization of risk into property prices. D'Alpaos and Bragolusi (2020) use stated preference methods (contingent valuation) to estimate a positive price premium for earthquake risk reduction in the Italian housing market. Filippova et al. (2018) use revealed preference methods (hedonic regression) to estimate the impact of earthquake risk after the Canterbury Earthquake Sequence on commercial buildings in Auckland, New Zealand and find a 12.5% price reduction for office buildings (and no effect on retail). Using fault map changes in California over the period 1970-2010, Singh (2016) finds that, on average, home prices increase by 1.8 % for every one-mile increase from the fault zone.

Moreover, property value losses may have cascading impacts for the community by reducing the tax base. Estimating the benefit to the community, at least from the perspective of a single asset, is not straightforward. First, the marginal impact of a single building on the tax base may not be substantial enough to include in an economic analysis (and is likely to vary highly across buildings). Moreover, meaningful reductions in the tax base are more accurately captured as general equilibrium impacts due to other factors such as displacement of businesses and households. Thus, the most appropriate method for estimating impacts on the tax base is likely economic impact analysis. However, since economic impact analysis measures regional impacts, the use of such methods would require assumptions for downscaling

[32] Relying on private or federally-backed loans may result in much higher delays. Table 8 in REDi (2013) provides median and dispersion estimates for different kinds of impeding factors.
[33] Several papers find that risk disclosure alone does not affect property values, but that earthquake events make such disclosures more salient. See for instance Timar et al. (2018b), Huang (2021). Moreover, salience in one region may increase in response to earthquakes in other regions, even if unaffected (Fekrazad 2019).

impacts with respect to a single building. While this is possible, we are not aware of applications in the literature and thus leave this as a research need.

Finally, owners and developers may experience deferred recouping of investment costs if repairs and impeding factors cause massive delays. However, this loss is speculative, and we are not aware of any methods in the literature for monetizing this benefit.

5.1.5. Supply-chain disruption

The position of businesses in modern supply chains means that local disruptions can have global impacts. Recent research suggests that disruptions due to local hazards can propagate through the supply chain to create losses that exceed local impacts (Thomas and Helgeson 2021). A building's business interruption may have indirect effects on its supply chain, both in terms of reduced purchases or delayed payments upstream (to sellers) or delayed delivery downstream (to buyers). For instance, in a survey of Japanese firms affected by the 2011 floods of Thailand, Ye and Abe (2012) find that while only 19 % of respondents experienced direct damage, 78 % experienced indirect losses due to supply chain disruption. Thus, from the perspective of a building that has been designed for functional recovery, the relevant avoided losses are to its upstream and downstream supply chain partners. If a building is functional but cannot obtain products due to upstream disruptions, there is nothing enhanced design can do for that building's occupants.[34]

Despite the abundance of research on both supply chain disruptions and business interruption, there is relatively little literature that estimates firm-level losses due to upstream or downstream propagation of a disruption (Katsaliaki et al. 2021). Dormady et al. (2022) conduct a survey of businesses impacted by Hurricanes Sandy and Harvey and find that supply chain disruptions account for 23 % of business interruption losses, on average. In a review of the empirical literature on supply chain disruptions, Katsaliaki et al. (2021) find that supply chain disruptions lead to an average drop in profitability of 107 %, a drop of 7 % in sales growth, and an increase of 11 % in costs. Dolgui et al. (2018) review the literature on modeling and quantifying the propagation of supply chain disruptions and present a few case studies of large-scale disruptions that do not generalize to typical buildings. Nevertheless, we observe a research need in estimating willingness-to-pay to avoid supply chain disruptions.

Due to the complexity of modern supply chains, economic impact analysis methods are well suited to capturing upstream and downstream losses due to local disruptions, and the cascading impacts of those losses locally (the feedback loop).[35] Both Input-Output (I-O) and agent-based models (ABM) can be used to estimate upstream or downstream impacts of business interruption on its supply chain. For instance, Henriet et al. (2012) disaggregate I-O tables to represent a regional economy as a network of individual production units. However, while this approach captures more complex relationships among a production network, it is not intended to capture firm-level impacts of supply chain disruptions. Inoue and Todo (2019) use an ABM to model the propagation of impacts of the 2011 Great East Japan earthquake through the supply chain and find that the indirect effects due to propagation are 10.6 % of GDP, while the direct

[34] Wagner and Bode (2006) survey German executives and identify global sourcing as a key driver of catastrophic supply chain risk (e.g., due natural hazards, terrorism, political instability). Surprisingly, dependence on a few suppliers is correlated with reduced catastrophic risk.
[35] Dolgui et al. (2018) and Katsialiaki et al. (2021) review methods for modeling supply chain disruption, including numerical optimization and simulation methods. In principle, these can be combined with economic impact models to estimate losses from supply chain disruptions.

effects are only 0.5 % of GDP.[36]

In principle, it should be possible (with additional assumptions) to downscale estimates from those models to a single building. However, while there is plenty of research using I-O or ABM methods to estimate the regional impacts of a supply chain disruption, we are not aware of any research that downscales results to a single building. Thus, this is left as speculative and a potential area for further research.[37]

5.1.6. Indirect social losses

In addition to the economic impacts discussed above, loss of occupancy and building functionality impacts people in other less tangible ways. We call such impacts indirect social losses. In this subsection, we discuss some key categories of indirect social impacts as well as methods for monetizing social losses (predominantly willingness-to-pay methods).

Displacement. Loss of occupancy and function can result in displacement of building occupants. Displacement of occupants is associated with a range of measurable costs, including moving and travel costs (e.g., rental costs, transportation costs, transportation time) to households and businesses. Some displacement costs, such as the cost of travel to a new location, can be considered fixed or one-time costs, while other displacement costs, such as rental costs for temporary space, can be considered recurring costs. Thus, fixed costs are a function of *whether* a building loses occupancy/functionality, while recurring costs are a function of *how long* a building loses occupancy/functionality. Thus, losses associated with displacement may be estimated as

$$\begin{aligned} &Displacement\ loss \\ &\quad = [DC_{fixed} + (DC_{recurring} \times days)] \times (Number\ of\ displaced\ persons) \end{aligned} \tag{14}$$

where DC_k are displacement costs for *k = {fixed, recurring}* and *days* is the number of days until restoration of occupancy/functionality. Estimates of DC_k may be obtained using stated or revealed preference methods. Whitehead (2003) uses a combination of stated and revealed preference methods to estimate the opportunity costs associated with hurricane evacuation costs. Average total recurring costs during displacement (including lodging, food, and entertainment) are estimated between $20 and $275, while average total fixed costs (including travel and the value of time) are estimated between $58 and $195.[38]

In addition, population displacement, either temporary or permanent, can have a significant effect on a city or regional economy after a hazard event. Oftentimes, these numbers are difficult to calculate because official sources of information typically come from census data, which are collected infrequently. For example, using 2013 data New Zealand reported a 2 % decrease in Christchurch's city population after the 2011 earthquake sequence, but a 3.4 % regional population increase over the same time period. However, the calculations are dependent on 2006 census data to provide a baseline (Bayer 2013). Newer

[36] Okuyama (2007) presents a review of I-O and related models for economic disaster impact assessment. Modern approaches tend to combine I-O tables and ABMs (e.g., Hallegate 2019).
[37] Recently, there has been a lot of research into the supply chain impacts of COVID-19 non-pharmaceutical interventions such as lockdowns (e.g., Guan et al. 2020). This literature could be useful as well.
[38] Note that recurring costs are estimated over the total time displaced. The estimation of expected costs is conditioned on storm severity and evacuation model (no order, voluntary, mandatory) rather than length of evacuation (Whitehead 2003). Nevertheless, the same methods could be applied to the estimation of daily displacement costs. Reported costs are in 2003 dollars.

methods, utilizing social media tracing or cellular phone location data, may prove to provide more accurate and timely estimates for population displacement and outmigration (Acosta et al. 2020; Yabe et al. 2020). It is also important to note that minority and disadvantaged populations are oftentimes disproportionately burdened via displacement and recovery (Phillip 2015).

Government assistance. Following a disaster, local building and safety departments organize teams of inspectors to identify damaged buildings. Inspectors will conduct a safety assessment and issue a colored tag on the inspected structure, with "green" indicating no hazards, "yellow" indicating the building is moderately damaged and its habitability is limited, and "red" indicating the building is unsafe and should not be entered under any circumstances (Eguchi et al. 1998). Inspectors may also provide rough estimates for the repair costs of inspected buildings. Eguchi et al. (1998) report that more than 105 000 inspections were carried out by local governments following the Northridge Earthquake.

Government funds are important to post-disaster building repairs and displacement of affected residents. Following the 1994 Northridge Earthquake, a total $13 billion federal fund was allocated to aid earthquake victims (Petak and Elahi 2001). About $1.424 billion was used to provide temporary housing, emergency home repairs, and mortgage assistance, and $0.167 billion was used to assist in personal property replacement, permanent repairs, and transportation, medical, and funeral expenses (Petak and Elahi 2001). In addition, $4.6 billion was designated to repair and replacement of damaged infrastructure, emergency service, and debris removal (Petak and Elahi 2001).

Burden on taxpayers. There are indirect losses to taxpayers via direct disaster assistance and other forms of financial support. Stein and Van Dam (2019) report that, since 1990 in the United States, federal spending for disaster relief appropriations has increased eight-fold. They also highlight a Pew Charitable Trust report that states that only about 44 % of total disaster spending comes from this disaster relief fund, with other amounts coming from other public and private entities. The Congressional Research Service (CRS 2021) identifies $12 billion in total gross disaster relief fund appropriations for fiscal year 2019. The Internal Revenue Service (IRS 2021) data implies that 154 million individual taxpayers each pay at least $80 per year for disaster relief. Moreover, Deryugina (2017) argues that natural hazard events also lead to non-disaster government funding, such as unemployment insurance and public medical payments, which actually exceeds the value of direct disaster aid. Therefore, taxpayer burden for disaster and disaster adjacent costs is underestimated, particularly as reflected only by federal disaster relief fund expenditures. In recent years, hazard mitigation has also become an important component of disaster spending. In 2018, Congress incentivized local mitigation measures by increasing the federal share available for disaster recovery in states that have invested in mitigation (Pew 2018). Functional recovery design would enable cost reductions in all areas of taxpayer burden including disaster response, mitigation, and other related costs.

Deterioration of physical or mental health. Loss of occupancy/functionality and the resulting displacement may have compounding negative impacts for both individual physical and mental health. Hogg et al. (2016) study the impact of different modes of displacement on mood and anxiety following the Canterbury earthquakes. They find that temporary relocation is a short-term risk factor. Moving within the city mitigates impacts on mood/anxiety but returning is a significant risk factor. Out-of-city movers are especially vulnerable. Fussell and Lowe (2014) analyze pre- and post-Katrina survey data on black single mothers and find that displacement increases general psychological distress and perceived stress. However, physical and mental health impacts of post-disaster displacement are less studied.

Uscher-Pines (2008) finds only four of 24 articles that assess displacement impacts focus on physical health. Moreover, the article reveals "weak study designs, inconsistent results, and inattention to physical health impacts and the challenges facing vulnerable populations." In addition, definitions of relocation/displacement are not consistent (NB this article is from 2008).

Disasters also affect the mental health of a broad population. Bromet et al. (2016) estimate that the incidence of post-traumatic stress disorder (PTSD) following natural and human-made disasters is anywhere from 3-5 % to 20-40 %. Morris and Deterding (2016) suggest that post-Katrina dispersion of social networks is associated with PTSD. There is "a lack of deep belonging and a lack of mattering as they are unable to fulfill obligations to important distant ties" due to increased physical distance from social network members.

Physical and mental health are non-market goods, meaning there is no objective market price to value negative impacts on health (Sidney et al. 2017). In the public health literature, the standard approach for estimating impacts on health rely on monetizing quality-of-life (QoL) adjustments due to a change in health outcomes (Lachaine et al. 2012). This requires both (1) a way to measure changes in QoL and (2) a way to monetize the value of changes in QoL.

$$Loss\ of\ QoL\ = (Change\ in\ QoL)\ x\ (Value\ of\ QoL) \tag{15}$$

Two approaches can be employed to measure the *change in QoL*. One approach is to estimate reductions in health care costs due to an intervention (Sidney et al. 2017). Another approach relies on questionnaires that are developed for specific health interventions to assess impacts on QoL or quality- and *quantity*-of-life, known as quality-adjusted life-years, or QALYs (Whitehead and Ali 2010). As an example, the European Organisation for Research and Treatment of Cancer (EORTC) has developed a widely used questionnaire to assess QoL for cancer patients: the EORTC QLQ-C30 (Fayers et al. 2002). Similar questionnaires exist for mental health interventions (Connell et al. 2014).

Given a measure of QoL, the next step is to estimate willingness-to-pay (e.g., Huang et al. 2018) or potential savings (e.g., Sidney et al. 2017) from a particular QoL change. For instance, Sidney et al. (2017) study the impact of employer well-being programs on employee health. Using a combination of medical and pharmaceutical claims, the authors estimate a total of $3060 saved in annual costs per reduction in disease occurrence.[39] Moreover, employees with disease occurrence save $62 annually on average, while employees without disease occurrence save $26 annually on average.[40]

Burden on first responders. The ability of a building to recover function quickly after an earthquake should reduce the need for an extended emergency response presence. The standard approach to estimating the burden of disasters on first responders[41] is to measure the impacts on their physical and

[39] It is worth noting that Sidney et al. (2017) is a notable example of a study that uses a combination of micro-level employer data with input-output data to estimate both direct and indirect benefits of an action. The study's methods could be adapted to preceding discussions such as supply chain disruption.
[40] Similar methods could be applied to estimate the value of QoL improvements due to improved building functionality; however, in the absence of retrospective data as in Sidney et al. (2017), such research would rely on stated preference methods.
[41] Wanner and Loyd (2021) describe the command structure of response: the Incident command system (ICS). The first level is local response, including Emergency Medical Service (EMS), Medical Reserve Corps (MRC), and Community Emergency Response Teams (CERT), which are the immediate responders. If local capabilities are overwhelmed, state and regional response is available, including National Guard, EMS districts, and Nongovernmental Organizations (NGOs). Large-scale disasters may require federal response via presidential disaster declaration (PDD), which makes additional medical resources available.

mental health (Benedek et al. 2007). Thus, the methods discussed above can be applied specifically for measuring the value of QoL impacts from disaster response. To estimate the losses associated with loss of function, we also need to determine how many first responders would be impacted. For instance, if we are interested in mental health impacts,[42] we might consider incidence of PTSD among first responders:

$$Mental\ health\ impacts = (Rate\ of\ PTSD) \times (Number\ of\ first\ responders) \times (days) \tag{16}$$

In a review of the literature on wildland-interface fire, Thomas et al. (2017) report incidence rates of PTSD for firefighters between 13 % and 20 %. However, mental health impacts may increase over time. Berninger et al. (2007) find that one year and four years after the World Trade Center (WTC) 9/11 attack, the prevalence of PTSD among 10 074 firefighters increased from 9.6 % to 10.8 %. Wisnivesky et al. (2011) also note that one year and nine years after the WTC attack, the prevalence of PTSD increased from 12.8 % to 31.9 % for 27 449 rescue and recovery workers, including firefighters.

The number of first responders may vary by the level of emergency, particularly the number of people threatened, the type and size of the building, and the stage of the fire when firefighters arrive. Fire departments will designate an alarm (the 1st, 2nd, 3rd, etc. alarm) for major incidents, and the type of alarm determines how many firefighters are sent to the emergency (IFD 2021). As for the post-disaster emergency response, the National Urban Search and Rescue (US&R) Response System, established by FEMA in 1989, has 28 US&R task forces. Each task force is composed of 70 members specializing in search, rescue, medicine, hazardous materials, and logistics and planning (FEMA 2022). In addition, there were 1150 local US&R response teams by 2006, varying from one team per state to 79 teams in California (Denver et al. 2007). Thus, it is difficult to estimate the average number of first responders for an earthquake. However, it may be possible to estimate the number for specific scenarios.

Estimated mental health impacts can then be combined with monetized QoL measurements for reductions in occurrence in PTSD to measure the burden on first responders:

$$Burden\ on\ first\ responders = (Mental\ health\ impacts) \times (Value\ of\ QoL) \tag{17}$$

As an example, Butry et al. (2019) use national databases of fire incident reporting to estimate the economic burden of firefighter deaths and injuries and find the annual cost per firefighter to be between $1468 and $5412. Thomas et al. (2017) report an average of $4075 in costs to treat PTSD among military personnel. We are not aware of any literature that explicitly considers the burden of earthquakes on first responders, but there is sufficient precedence in related literature that this is a promising topic for research.

Loss of cultural heritage. In addition to building damage and property value impacts, property losses can also result in losses of a community's cultural heritage. We use the term heritage building to denote a building that has historic or cultural value. Heritage buildings, which are typically protected by local building regulations, may have intangible value to the community that can be irreversibly lost after an

[42] We use PTSD to illustrate potential impacts. Other potential mental health risks to first responders include suicide, substance abuse, and depression or anxiety (Fitzpatrick 2020). In addition, first responders face physical risk of injury and death.

earthquake.[43] While it is costly to retrofit heritage buildings that require preservation of character, the potential value of cultural losses may be much larger and potentially extend beyond the building itself. Of course, it should be noted that this benefit is only relevant for existing buildings.

Willingness-to-pay methods are best suited to estimate the value of preserving a heritage building's character. Lazrak et al. (2014) use spatial hedonic methods to estimate the value of cultural heritage in Dutch real estate markets. They find that buyers are willing to pay 27 % more for a building with a historic designation. Similarly, Andersson et al. (2019) estimate a price premium between 36 % and 60 % for historic buildings in Sweden using hedonic methods. Moreover, hedonic methods can be used to estimate the cultural externality from being located near a historic building. For instance, Lazrak et al. (2014) estimate a 0.28 % price premium for buildings within a 50-m radius of a historic building. Andersson et al. (2019) estimate the cultural externality value to be around 1 %. On the other hand, while Ahlfeldt and Maennig (2010) do not find a statistically significant premium for heritage designation in Berlin, they do find a cultural externality of up to 2.8 % for properties within a 600-m radius of a heritage building.[44]

In addition to revealed preference methods, stated preference methods may also be useful for estimating WTP. Powell et al. (2015) survey building owners in Wellington, New Zealand following the Canterbury earthquake sequence as well as legal changes requiring seismic strengthening for earthquake-prone buildings. Respondents report an average increase in property value of 282 % for heritage buildings, in comparison to a 23 % increase for modern buildings. Moreover, stated preference methods may be used to supplement revealed preference methods. Alberini and Longo (2006) combine the travel cost method with contingent valuation to estimate a use value of between $28 and $44 per person for cultural monuments in Armenia, which imply that preservation policies can improve social welfare from $ 2.8 million to $4.2 million.[45]

Loss of social cohesion. The relationship between a disaster and social cohesion can go in two directions. Social cohesion can improve community resilience to natural disasters. Ludin et al. (2018) find strong associations between community resilience and social cohesion among six flood-prone communities in Malaysia. Townshend et al. (2015) also find a "consistent significant positive correlation between cohesion and resilience" among rural Canadian communities experiencing disasters and evacuations. In addition, Thornley et al. (2015) indicates that social cohesion improved recovery after Canterbury earthquakes, though the existing hardships were exacerbated by the earthquakes. Hikichi et al. (2016) suggests that pre-disaster social cohesion is associated with lower rates of PTSD among survivors of 2011 Tohoku earthquake. Greene et al. (2015) notes that social cohesion increases resilience and reduces poor mental health outcomes in flood-affected areas of England.

On the other hand, natural disasters may enhance social cohesion. Calo-Blanco et al. (2017) suggests that social cohesion increases after earthquakes, though the effect erodes over time, especially for less severe events. Shigemoto and Kawachi (2020) find that there was no significant association between social cohesion and QoL in the short run following the 2008 Hurricane Ike, but a significant *positive* correlation

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[43] Forte et al. (2021) provide a characterization of the characteristics that give cultural assets their value, as well as a review of methods for estimating lost value due to damage from an earthquake.
[44] Historic preservation can also have negative impacts due to constraints on development. For instance, Bade et al. (2020) study the price effects of being located within an area with a heritage designation in Auckland, New Zealand. They find that there is a 9.6 % penalty for being located within such an area, though they still find a positive cultural externality of 1.7 % on average for homes within 50-m of a heritage area building.
[45] All values in 2006 U.S. Dollars.

appeared in the long run (i.e., 15 months after the event).

In addition, the impacts on social cohesion have indirect effects on social behavior. Disasters may reduce crime due to prosocial behavior (based on the theory of the therapeutic community) or increase crime due to loss of social cohesion (based on the theory of social disorganization or the theory of routine activities).[46] Prelog (2016) finds a positive correlation between disaster magnitude and crime rates across continental counties in the United States. Zahran et al. (2009) find that index, property, and violent crimes *decrease* while domestic crime *increases* in Florida after natural disasters. Breetzke et al. (2018) report that *overall* crime in Christchurch decreased after the Canterbury earthquake sequence (CES), but about 85 % of its neighborhoods experienced an increase in overall crimes. This paradoxical finding can be explained by closure of the Central Business District (CBD), which accounted for a large share (12 %) of *all* crime pre-CES and thus drove a large part of the reduction. After the CES, crime was *displaced* from usual hot spots to the rest of the city, as well as the neighborhoods. There was no pattern for neighborhoods that experienced increased crimes, but lower median income was found associated with one or more categories of crime increase (Breetzke et al. 2018), in contrast to predictions from social disorganization theory. However, domestic violence increased from 2 % to 4 % in Christchurch (unlike the other crimes). The actual number could be higher since domestic violence is often underreported.

The standard way to estimate social loss due to crime[47] is using the willingness-to-pay (WTP) approach.

$$\begin{aligned} &Loss\ due\ to\ crime \\ &\quad = (WTP\ to\ reduce\ crime) \times\ (Incidence\ of\ crime\ due\ to\ a\ disaster) \end{aligned} \tag{18}$$

The first component, *WTP*, has been extensively discussed in the literature. The *WTP* can be quantified by either revealed preference (e.g., Bishop and Murphy 2011; Pope and Pope 2012) or stated preference (e.g., Cohen 2004), as previously discussed. Cohen (2004) finds that investing \$100-\$150/year on crime control programs can reduce crime by 10 %. The Institute for Women's Policy Research (IWPR 2017) reports that the mean cost of medical care for those who sought treatment after a physical assault by an intimate partner was \$4,273 per incident in 2017 dollars. Of those seeking mental health services, there was an additional cost of \$1,631 per incident. Interested readers may refer to Doyle and Aizer (2018) for a comprehensive review of the state of the art in economics of domestic violence.

5.1.7. Indirect physical losses

Finally, there are other indirect costs that can be saved by adopting enhanced design, such as debris removal and management expenses, greenhouse gas emissions and energy use for building repairs, and environmental pollution associated with material production and waste disposal.

Debris removal. Debris after a disaster may include waste soils and sediments, vegetation (e.g., trees,

[46] In the context of a natural disaster, social disorganization theory would posit that crime increases in the ensuing chaos of response and recovery after an event. In contrast, routine activity theory would posit that increases in crime arise from disruptions to the routine activities of potential offenders, such as displacement or evacuation, which align to provide a motivated offender, a suitable target, and the absence of a capable guardian for the target (Zahran et al. 2014).

[47] The cost of crime to society is significant. OJP (1996) reported that victimizations generated \$105 billion annually in property and productivity losses and medical expenses in the United States, which means an annual “crime tax” of roughly \$425 per person. When adding in pain, long-term trauma, and risk of death, annual costs of crime could reach \$450 billion, or annual “crime tax” could be \$1,800 per person. A more recent study suggests that the annual cost of crime could be between \$690 billion and \$3.41 trillion in 2016 dollars (GAO 2017).

limbs, shrubs), municipal solid waste (e.g., common household garbage, personal belongings), construction and demolition debris (e.g., building materials, roads, bridges), vehicles (e.g., cars, trucks, boats), food waste, large home appliances (e.g., refrigerators, freezers, air conditioners), and household hazardous waste (e.g., cleaning agents, pesticides, pool chemicals). Each type of waste may contain or be contaminated with certain toxic or hazardous constituents (CRS 2011; EPA 2019). Common options to manage debris include landfilling, recycling, and burning. During the 1992 Hurricane Andrew, about 43 million cubic yards of debris were generated over a 500-square-mile area (CRS 2011). The 1994 Northridge Earthquake left about 7 million cubic yards of debris (CRS 2011). During the 2005 Hurricane Katrina, more than 99 million cubic yards of debris were generated, and debris removal alone cost more than $3.7 billion (EPA 2019).

The costs for debris removal depend on the amount of debris and unit price for cleanup:

$$Debris\ removal\ costs\ = (Cleanup\ costs)\ \times\ (Amount\ of\ debris) \tag{19}$$

Following Hurricane Katrina, FEMA developed a Reasonable Cost Matrix for estimating debris removal costs and determining eligible reimbursement levels for contractors. The matrix provides unit prices for nine categories of debris in line with the FEMA 322 Public Assistance Guide (FEMA 2020). Note that debris removal is largely funded by FEMA and partially funded by state and local governments (CRS 2011; FEMA 2020).

Greenhouse gas emissions. The construction sector accounted for more than 11 % of annual global CO_2 emissions in 2018 (IEA 2019). Building repairs and demolition after a natural hazard event can result additional CO_2 emissions (Gonzalez et al. 2022). Comber et al. (2012) estimate that a 5-story concrete moment frame office building (75 000 sf/ 6 968 m^2, designed under current codes) could suffer damage resulting in an environmental impact of 2 820 tCO2e, or 19 % of the building's total embodied carbon footprint after a MCE (maximum considered earthquake) event in Seattle, WA. A 5-story concrete shear wall office building (75 000 sf/ 6 968 m^2, designed under current codes) could suffer damage resulting in an environmental impact of 2 260 tCO2e, or 15 % of the building's total embodied carbon footprint after a MCE event in Seattle, WA. In addition, a tilt-up concrete research laboratory (49 000 sf/ 4 552 m^2, constructed in 1963) could suffer damage resulting in an environmental impact of 7 320 tCO2e, or 31 % of the building's total embodied carbon footprint after a MCE event in San Francisco Bay Area.

The social cost of carbon (SCC) due to building damage and repairs depends on damage level and embodied carbon footprint of the building:

$$SCC =\ (Damage\ ratio)\ \times (Embodied\ carbon\ footprint)\ \times (Carbon\ price) \tag{20}$$

Embodied carbon footprint refers to CO_2 emissions arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials. In most cases, only emissions associated with materials are considered because data for other items are scarce (Comber et al. 2012).

Under the Executive Order 12866, the federal government's Interagency Working Group (IWG) developed an estimate for SCC, considering climate change impacts on agriculture, forestry, water, energy use, sea level rise, ecosystems, human health, and extreme weather (IWG 2016). The purpose of such estimate is to assist agencies to incorporate the social benefits of reducing CO_2 emissions into BCA of regulatory actions. Table 5.2 presents the estimated SCC at different discount rates from 2010 to 2050.

Table 5.2. Social cost of carbon from 2010 to 2050, in 2007 dollars per metric ton of CO_2. Adapted from IWG (2016).

Year of emission	**Average estimate at 5 % discount rate**	**Average estimate at 3 % discount rate**	**Average estimate at 2.5 % discount rate**	**High impact estimate (95th percentile estimate at 3 % discount rate)**
2010	10	31	50	86
2015	11	36	56	105
2020	12	42	62	23
2025	14	46	68	138
2030	16	50	73	152
2035	18	55	78	168
2040	21	60	84	183
2045	23	64	89	197
2050	26	69	95	212

However, market-based carbon prices are much lower than the SCC estimates. So far, twelve U.S. states have enrolled into carbon pricing programs. The Regional Greenhouse Gas Initiative (RGGI) is a cooperative effort among eleven Eastern states to cap and reduce CO_2 emissions from the power sector. The minimum allowance price is $2.38 per metric ton of CO_2 in 2021 (RGGI 2021). In California, the carbon pricing program involves power, building, transportation, and industry sectors. The minimum allowance price is $17.71 per metric ton of CO_2 in 2021 (ICAP 2021).

Energy consumption. Building repairs may involve demolition and replacement of damaged components, temporal protection for affected areas, and relocation and reinstallation of equipment. Feese and Bulleit (2015) estimate that in Los Angeles, steel buildings built to high code standards (high code of Hazus) may sustain damage that incurs a total repair cost of $38 226 and energy consumption of 33 565 MJ under a seismic event equivalent to the 1994 Northridge Earthquake. The annualized energy consumption for repairing a high-code steel building could be 1663 MJ. For a moderately designed (moderate code of Hazus) steel building, annualized energy consumption for repairs could be 4103 MJ. On the other hand, high-code concrete buildings may sustain damage that incurs a total repair cost of $56 189 and energy consumption of 91 778 MJ under a seismic event equivalent to the Northridge

Earthquake. The annualized repair energy could be 606 MJ for a high-code concrete structure and 1968 MJ for a moderate-code concrete structure.

The energy cost due to building damage and repairs depends on damage level and embodied energy of the building:

$$Energy\ costs = (Damage\ ratio) \times (Embodied\ energy) \times (Energy\ price) \qquad (21)$$

Many databases are available for life-cycle assessment with respect to CO_2 emissions and energy consumption (e.g., Athena database, U.S. life cycle inventory database). A comprehensive review and comparison for those databases can be found at Martinez-Rocamora et al. (2016).

Environmental pollution. Material production and transportation, building construction, repair and demolition, as well as waste disposal (e.g., landfills, combustion), can discharge various pollutants into the environment. The most concerning environmental impacts include ozone depletion due to chlorofluorocarbons (CFC), photochemical oxidation due to ethylene (C_2H_4), eutrophication due to phosphorus concentration (PO_1^-), and acidification due to sulfur dioxide (SO_2), as specified by the ISO 14025 Standard.

5.2. Estimating costs associated with enhanced building design

Table 5.3 provides a list of the potential costs associated with implementing recovery-based design, while accounting for the parties who bear the costs. The table also depicts common methods for cost estimation.

Table 5.3. Potential adoption/implementation costs, who bears cost, and how to estimate cost.

Cost	**Who bears**	**Estimation methods**
New construction	Developer	▪ Construction cost data (e.g., RSMeans, Craftsman) ▪ Historical data ▪ Statistical models
Retrofit (hard and soft)	Owner (title holder)	▪ Construction cost data (e.g., RSMeans, Craftsman) ▪ Historical data ▪ Statistical models
Maintenance	Owner	▪ Life-cycle cost data (e.g., RSMeans) ▪ Historical data (e.g., ASHRAE Service Life and Maintenance Cost database) ▪ Statistical models
Code implementation	State and local governments	Historical data (e.g., code book purchase, education and training expenses, technical support, financial incentives)
Plan evaluation	Owner	Covered by permit fees
Site inspection	Owner	Covered by permit fees
Construction permit application	Owner	% of construction or improvement costs
Financing	Owner	(Interest rate) × Principal
Additional cost to preserve historical or cultural characteristics	Government	Historical data (e.g., cost estimates, dedicated funds, financial incentives)

Initial construction cost. The construction cost of a building comprises material, labor, and equipment costs, as well as contractor overhead and profits. Construction costs are influenced by the location of the project because the availability and costs of materials and labors, as well as regulatory requirements, vary from region to region. Construction costs also change over time due to inflation and other factors. While consulting firms, contractors, and agencies tend to develop their own codes for cost estimation, construction cost books, such as RSMeans and Craftsman, offer an alternative way to estimate costs based on a national database. Regional indices are provided by these books for quick adjustment from the national average to any cities.

Yet, there are two main constraints with use of construction cost books. First, cost data is collected on residential and commercial buildings nationwide, whereas public buildings (e.g., schools) and critical facilities (e.g., hospitals) are not included. In recovery-based design, the methods that critical facilities take to attain high performance objectives can be extended to designing residential and commercial buildings for higher performance. Lack of data for critical facilities may restrict the use of construction cost books for enhanced building design. Second, the data does not distinguish local difference in code requirements (e.g., design hazard levels, design loads), which can affect building design and construction costs. Understanding the impacts of local code requirements on construction costs is important to accurately estimate cost. Other methods for cost estimation are elaborated in Appendix B.

Structural improvement costs. The increased structural cost reflects increased material and labor costs for a building constructed with enhanced structural systems relative to the status quo. Structural costs are computed as unit prices of structural components multiplied by quantities. Improvement costs are estimated as the difference in structural costs before and after upgrades.

$$Structural\ costs\ = \sum\ [(Unit\ price\ of\ a\ structural\ component)\ \times Quantity] \tag{22}$$

Figure 2 illustrates the procedure to estimate structural costs using RSMeans data. Step 1 inventories the type and quantity of structural components in the building. Step 2 looks up the RSMeans assembly database for each type of structural component. If there is a matched assembly in the database with respect to materials, size, and maximum capacity, the total cost of this component type can be estimated by multiplying assembly cost and quantity. Otherwise step 3 is taken to assemble the costs for the component using the RSMeans unit cost database, or alternatively interpolate the costs from two similar assemblies. Once the unit cost is determined, the total cost is estimated by multiplying unit cost and quantity.

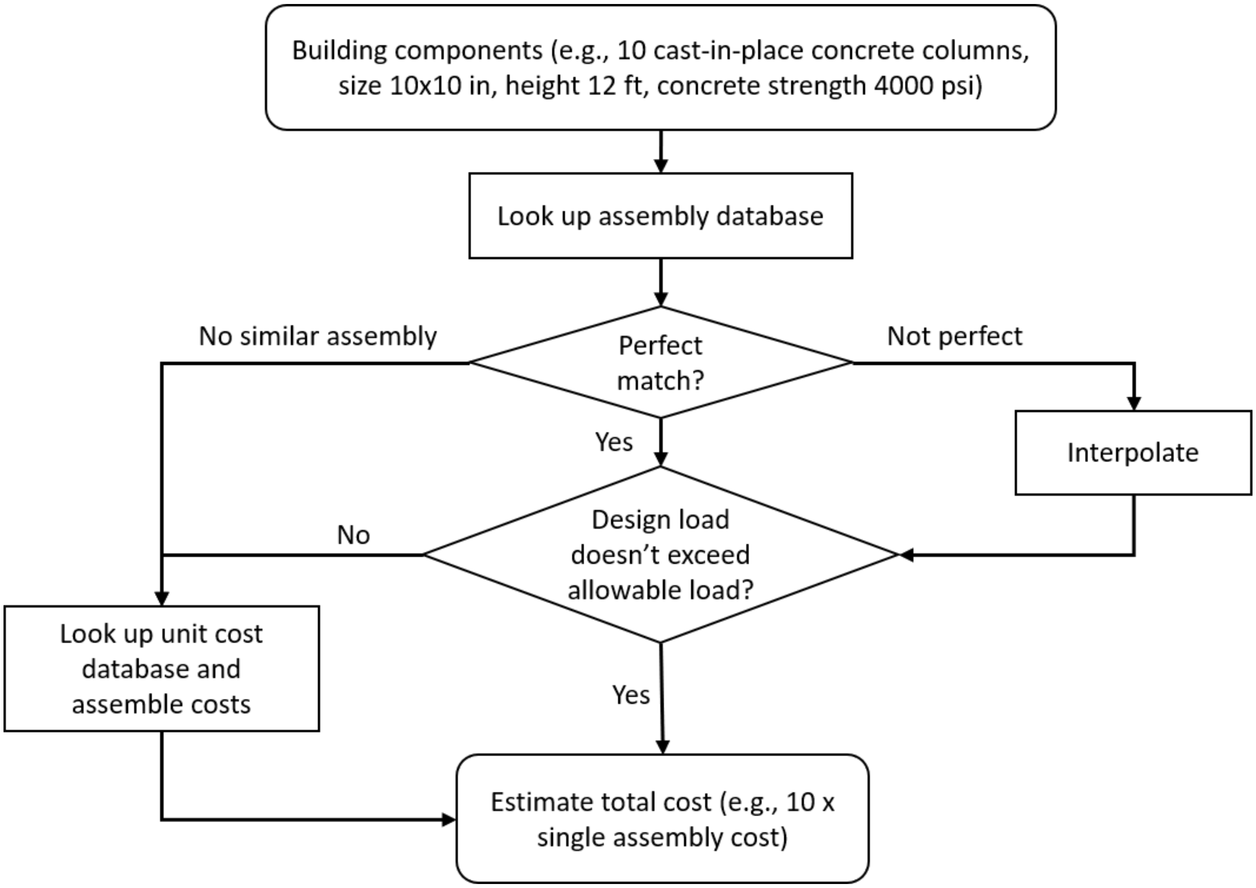

Figure 2. Structural cost estimating procedure.

Nonstructural improvement costs. There are three common approaches to estimating increased nonstructural costs.

Approach 1. Nonstructural improvement costs are estimated as a percentage of structural improvement costs.

$$Nonstructural\ improvement\ costs\ = Percent\ \times (Structural\ improvement\ costs) \quad (23)$$

The percentage is somewhere between 50 % and 100 %. Preston et al. (2019) report that on average, the cost of nonstructural upgrades (from NPC-2 to NPC-5) is 50 % of that of structural upgrades (from SPC-2 to SPC-4D) based on data from 45 hospitals in California. The ratio of nonstructural to structural costs ranges from 0.051 to 1.08. Fung et al. (2021b) suggests that nonstructural retrofit costs can be comparable to structural retrofit costs for residential buildings. Approach 1 is used when nonstructural improvements are not clearly defined but a coarse and handy estimate for nonstructural costs or total improvement cost is needed.

Approach 2. Nonstructural improvement costs are estimated as cost per square footage of upgrades times floor area.

$$Nonstructural\ improvement\ costs\ = (Cost\ per\ sqft\ of\ upgrades)\ \times (Floor\ area) \tag{24}$$

This approach is used when nonstructural improvements are defined but lack design details. Thus, cost data for similar buildings (e.g., use category, location, improvements) are utilized to evaluate upgrade costs for the building.

Approach 3. Nonstructural costs are computed as unit prices of nonstructural components times quantities. Improvement costs are estimated as the difference in nonstructural costs before and after upgrades.

$$Nonstructural\ costs = \sum [(Unit\ price\ of\ a\ nonstructural\ component)\ \times Quantity] \tag{25}$$

Nonstructural components include stairs, elevators, cladding and glazing, distribution panels, ceilings, heating, ventilation, and air conditioning (HVAC) systems, which are important to the functions of a building. Notably, the Department of Health Care Access and Information (HCAI), formerly the Office of Statewide Health Planning and Development (OSHPD), has established a seismic certification program for nonstructural equipment (Special Seismic Certification Preapproval, OSP) and anchorages (Preapproval of Anchorage, OPA) used in health facilities in California. The pre-approved equipment and anchorages can bear higher seismic loads and ensure continuing operation of hospitals after a major earthquake. Detailed reports for those components are provided on HCAI's website, as well as contact information for manufactures, providers, and suppliers (HCAI 2022). However, the cost premiums for those components are not available in construction cost books. Moreover, emergency systems may be revamped to achieve functional recovery goals. This may involve emergency equipment, alarms, messaging, and emergency communication plans or strategies in support of organizational resilience (Almfuti and Wilford 2013).

Approach 3 can provide the most accurate cost estimates, but it also takes the greatest effort to collect cost data, including but not limited to conversations with engineering professionals, consultants, and manufacturers, as some of those data are not publicly accessible. Moreover, detailed information for nonstructural design is needed when this approach is employed.

Life-cycle cost. The life-cycle cost (LCC) is the total cost associated with building design and construction, building operation and maintenance, and building disposal at the end of the life cycle. FEMA's BCA guide recommends considering at least a replacement for nonstructural components in the middle of the life cycle when both nonstructural and structural improvements are analyzed (FEMA 2009). This is reasonable because the useful life of nonstructural components is between 15 and 30 years, less than that of structural components. The cost for replacing nonstructural components is an important portion of maintenance costs. Yet, maintenance costs also include the costs for scheduled maintenance to keep mechanical systems in working order, preventative maintenance to reduce the likelihood of system failure, and actual repairs of building's mechanical, electrical, and plumbing systems. Overall, maintenance costs are flexible and dependent on many factors other than the building itself (e.g., budget).

There might be questions on how recovery-based design affects maintenance costs over the life of the building. For example, are nonstructural components more robust to maintenance, reducing maintenance costs? Does building in redundancy add to maintenance costs? To answer these questions, more data is needed to determine whether the divergence in costs is large enough to affect decision making. Moreover, such maintenance cost impacts are not benefits in and of themselves, as discussed in Sec. 3, should be subtracted from benefits.

5.3. Estimating building downtime

A key step of the FR-BCA process is quantifying the benefits of functional recovery design in terms of avoided losses for mitigated and unmitigated alternatives, as discussed above. To do so requires an analytical method capable of quantifying expected building performance into important direct and indirect losses such as building repair costs and downtimes. Additionally, the method should be detailed enough to capture differences in performance between selected mitigation alternatives.

This section reviews available methods and software that can be used to estimate building repair costs and downtime and key advantages and disadvantages of each approach, as well as gaps in the state-of-the-art. Four of the most commonly used methods are discussed in the preceding sections and summarized below in Table 5.4. Among the four methods discussed, the specific definition of building functional recovery can vary. While additional recovery-based performance states and definitions can be found in other literature (e.g., Comerio 2006; Burton et al. 2015; Mieler and Mitrani-Reiser 2018), most of the methods discussed here quantify recovery time in terms of re-occupancy, functional recovery, and full recovery, where re-occupancy means the building is safe to enter and able to provide shelter and functional recovery means the building may not be fully repaired but has enough capacity to serve its basic intended function. The downtime assessment methods presented here quantify losses and repair times at the building level, focusing on the performance of the building itself, rather than influences from surrounding infrastructure, regional recovery policy, or individual household or business capacities to function outside the building.

Table 5.4. Assessment methods for downtime/functional recovery time estimation.

Method	FEMA P-58	REDi	Hazus	ATC 138*
Level of Modeling	Component	Component	Building	Component and Building Systems
Scope of recovery assessment	Recovery time due to building damage alone	Recovery time includes time to repair building damage, post-earthquake inspection, engineering mobilization, financing, contractor mobilization, permitting, and utility downtime.	Recovery time includes time for decision making, building construction and clean-up, and time to obtain financing, permits and complete design.	Recovery time includes time to repair building damage, post-earthquake inspection, engineering mobilization, engineering design, financing, contractor mobilization, and permitting.
Repair time model	Building repair time is estimated from simulated component repair times using simplified serial and parallel worker allocation assumptions.	Building repair time is estimated from simulated component repair times using a repair scheduling algorithm which considers workers allocations limits and repair sequence constraints	Based on heuristic and empirical estimates of building repair time.	Building repair time is estimated from simulated component repair times using a repair scheduling algorithm which considers workers allocations limits and repair sequence constraints
Building Function Assessment	No explicit assessment of building function.	Building regains function when the repair schedule for all RC2 and RC3 components is complete.	Judgment-based multipliers to determine whether building repair interrupts business operation (e.g., relocation).	Each tenant unit within the building regains function when the building is safe, accessible, and the required systems become acceptably operational for basic function.

Basis of recovery and repair time data	*Fragility database* provides empirical recovery time for more than 700 structural and nonstructural components at various damage states.	*Fragility database* provides empirical recovery time for more than 700 structural and nonstructural components at various damage states.	*Consequence tables* provide median recovery time estimates for 33 occupancy classes at five building damage states (none, slight, moderate, extensive, complete). A set of *multipliers* are used to adjust recovery time to account for different building size and financing difficulty.	*Fragility database* provides empirical recovery time for more than 700 structural and nonstructural components at various damage states.
Key Limitations	Does not explicitly consider building function.	Recovery time tends to be overestimated because too many impediments are considered in the recovery model (Terzic and Kolozvari 2020). Building function model is not occupancy specific and does not consider the operations of building systems.	Only median recovery time is used, without upper and lower bounds that account for uncertainties. Outcomes limited to the building class level and are not capable of capturing certain building-specific response characteristics.	When building-specific data is not available, assumptions regarding tenant requirements for basic intended function and system operations are based on engineering judgment.
Key Advantages	Building specific and probabilistically robust.	Incorporates consideration of impeding factors and more advanced repair scheduling.	Computationally inexpensive.	Explicitly models system operation to quantify building function

Note: RC = Recovery class. See Sec. 5.2.3 for details.
*ATC-138 is an ongoing project led by FEMA and Applied Technical Council (ATC), which will establish recovery-based objectives for high-performance buildings.

There are several publicly available and proprietary software packages that facilitate the estimation of functional recovery times for buildings and building portfolios according to these four methodologies as shown in Table 5.5. For additional review of the state-of-the-art in this rapidly evolving field, see Meiler and Mitrani-Reiser (2018) and Cook et al. (2022).

Table 5.5. Software programs for downtime/functional recovery time estimation.

Software	PACT	SP3	Hazus	PELICUN
Assessment Method(s)	FEMA P-58	FEMA P-58 REDi ATC-138	Hazus	FEMA P-58
Platform	Publicly available local software package	Proprietary web-based analysis platform	Publicly available local GIS-based software package	Open-source python software package hosted on web-based analysis platform
Publisher	FEMA	Haselton Baker Risk Group	FEMA	SimCenter

5.3.1. Hazus

To date, the most common method of assessing building recovery time in the literature, especially when evaluating the recovery of a community or region, has been through the use of recovery functions such as those from Hazus (FEMA 2012). Hazus was developed as part of the FEMA Multi-hazard Loss Estimation Methodology for estimating seismic risk to U.S. infrastructure. Hazus includes prediction models for direct physical damage and loss, induced physical damage, direct economic and social losses, and indirect economic losses.

To develop loss predictions, the Hazus methodology combines site hazards with predefined fragility and consequence functions for a given building class. Building classifications in Hazus consist of four building attributes: building type (e.g., wood light frame or concrete moment frame), height classification (low-rise, mid-rise, and high-rise), level of code (based on the building's location and age), and occupancy (e.g., commercial office or single-family dwelling). Hazus uses the capacity spectrum method to estimate the building's spectral accelerations and spectral displacements for a given level of shaking, which are in turn used to quantify the building's damage state (none, slight, moderate, extensive, or complete) and damage consequences (e.g., repair cost or recovery time) from the predefined fragility and consequence functions, respectively. While building-specific inputs can be used to adjust the building's capacity spectrum, such as building period and base shear strength, typical values are provided for each building class to facilitate the estimation of building response and damage.

To estimate building recovery and service interruption time, Hazus defines building-level repair and recovery times as a function of occupancy class and damage state. Note that building recovery times consider construction and clean up time as well as time to obtain financing, permits and complete design, whereas building repair times only consider construction and clean up time. In addition, Hazus uses a set of multipliers to adjust recovery time to account for different building size and financing difficulty.

The fragility and consequence functions developed in Hazus are based on a mix of historical data, previous research, and engineering judgment. In particular, the method heavily relies on the MMI damage and loss functions and building classifications developed as part of the ATC-13 project (ATC 1985), which were primarily based on expert judgment. While the repair costs functions were calibrated to empirical data from the Long Beach (1993), San Fernando (1971), Coalinga (1983), Morgan Hill (1984), Loma Prieta (1989), and Northridge (1994) earthquakes (Kircher 2006), all repair and recovery time and loss of function modifiers provided in Hazus are based solely on engineering judgement.

While empirical and judgment-based building-class-level recovery functions are useful to aggregate risk information from large building stocks, they typically are unable to capture building-specific attributes of performance necessary to compare the performance of two buildings with unique design characteristics. For example, since Hazus classifies buildings into one of three building age categories, pre-1941, 1941 to 1973, and post-1973, any building designed after 1973, including those designed after the Hazus release of 1997, are estimated to have the same performance as any post-1973 buildings of the same class, regardless of building design features.

5.3.2. FEMA P-58

Performance-based earthquake engineering (PBEE) is a statistically robust means of quantifying and communicating building performance into resilience metrics, such as repair costs or functional recovery. The approach integrates a probabilistic hazard analysis, with a structural response assessment and a component-level damage assessment to quantify the damage to each structural and nonstructural component within the building for a given shaking intensity (Porter 2003; Moehle and Deierlein 2004). The performance outcomes from a performance-based assessment depend on the building's specific design and configuration characteristics and can be used to facilitate the comparison of design alternatives and mitigation strategies for new resilience-based performance objectives.

FEMA P-58 (FEMA 2018) is one of the most commonly used implementations of the PBEE methodology and probabilistically quantifies building performance based on its structural and nonstructural characteristics in terms of repair costs, repair time, casualties, and unsafe placards. To facilitate the component-level damage simulations, FEMA P-58 collects a database of over 700 component fragility and consequence functions for various structural and nonstructural building components based on empirical earthquake data, experimental testing, analytical analysis, and engineering judgment. Building repair times are quantified as an aggregation of the estimated time a worker will take to repair damage to each component within the building; component-level repair times are aggregated based on a repair schedule that assumes all workers will either repair all stories at once (parallel) or one story at a time (series).

Compared to the building-class recovery times estimated by Hazus, FEMA P-58 provides detailed repair time estimates based on building-specific response and component characteristics, but requires significantly more detailed assessment inputs to define the building-specific characteristics and is computationally more expensive to run (depending on the structural analysis method used to define building response). In its current form, FEMA P-58 only quantifies building repair times due to direct building damage and does not explicitly consider the recovery of building function (which differs from the repair time of all components in the building) or external factors that may impede the start of construction, however, previous studies have used the story-based repair time estimates from FEMA P-58 as an upper bound of building functional recovery time (Cimellaro and Piqué 2016). Building repair times from FEMA P-58 are also based on a simplified repair schedule algorithm, which does not consider critical constraints when estimating building-level repair times.

5.3.3. REDi and REDi-based methods

The Resilience-based Earthquake Design Initiative for the Next Generation of Buildings (REDi), expands on the FEMA P-58 methodology to quantify, probabilistically, building re-occupancy and functional recovery times (Almufti and Willford 2013). Additionally, the REDi methodology improves on some of the key limitations of the FEMA P-58 framework by incorporating estimates of pre-repair impeding factors, such as time time required to gather finances or obtain building permits; the REDi method replaces the simplified FEMA P-58 repair schedule algorithm with a more sophisticated repair sequence, which borrows key concepts form the critical path method (Kelley and Walker 1959) to schedule repairs of damaged components based on worker limitations and component repair sequence constraints.

To facilitate the quantification of building re-occupancy and functional recovery times, REDi assigns a Repair Class (RC) to each damage state of every component within the FEMA P-58 fragility database. The Repair Classes define the impact the component's damage has on the building performance, where RC1 represents minor or cosmetic damage that hinders full recovery; RC2 represents more significant damage which hinders building function; and RC3 represents heavily damaged components that pose a life-safety risk and hinder building reoccupancy. The total building functional recovery time is estimated using a repair schedule to repair damage to all components with RC2 or RC3 level damage.

The REDi method has been used in the performance-based design of new buildings, such as the 181 Fremont Tower in San Francisco (Almufti et al. 2016), and as part of the U.S. Resiliency Council's seismic rating system (USRC 2015). However, the REDi method oversimplifies the quantification of functional recovery; instead of explicitly modeling the effect component damage on the operation of building systems, REDi bases the building's functional recovery time on the performance of the "worst-case-component" (e.g., damage to a single component flagged as affecting function will cause a loss of function of the entire building). Additionally, previous studies have noted that REDi tends to provide overly conservative estimates of recovery time for cases with low levels of damage, due to a low threshold for triggering high consequence impeding factors and other impediments considered in the recovery model (Paul et al. 2018; Terzic and Kolozvari 2020).

Several studies have proposed modified frameworks to address key limitations for assessing functional recovery in the REDi methodology. Notably, Paul et al. (2018) proposes updates to the repair class and impeding factor logic to improve the sensitivity to triggering large consequences for low damage states and a more holistic consideration of assessment uncertainties. Additionally, Molina-Hutt et al. (2022) proposes a new framework built upon the REDi methodology. The framework defines two new building performance states for building stability and building shelter, incorporates functions to estimate delays due to temporary repairs and demolition time, and includes a new repair schedule algorithm to estimate the recovery of function of each story in the building.

5.3.4. ATC-138 and fault tree-based methods

Key to quantifying a building's functional performance is the capability of an analytical method to model the operations of a building's various structural and nonstructural systems and their subsequent effect on tenant function. Porter and Ramer (2012) introduce the idea of applying fault trees (Fussell et al. 1974) to model the reliability of a building system to assess post-earthquake downtime of a California data center, representing a robust framework to model the various dependencies among building systems and explicitly quantify overall building function. Recently, Cook et al. (2022) and Terzic and Villanueva (2021) propose new assessment methodologies for the quantification of building functional recovery, which introduce fault tree models to explicitly model the operation of various structural and nonstructural buildings within the FEMA P-58 assessment framework. Both studies utilize the FEMA P-58 fragility and consequences database to facilitate the simulation of building damage, and contribute to improved repair scheduling algorithms to estimate recovery times.

The ATC 138 project is an ongoing FEMA-funded project which adopts the functional recovery assessment framework proposed by Cook et al. (2022), as part of a NIST-Funded effort, into the FEMA P-58 methodology to establish recovery-based design tools and guidelines. The adopted methodology provides the various default system-level fault trees, component-level attributes, and tenant-specific requirements to model the re-occupancy and functional recovery times for modern U.S. buildings. In most cases, these default attributes are based on engineering judgment, given the lack of empirical and experimental data. The repair schedule algorithm includes the consideration of temporary repairs that mitigate near-term impact of component and system failures on building function and quantifies external factors that delay the start of repair such as inspection, permitting, gathering financing, and engineering and contractor mobilization (similar to REDi). A computational implementation of the method is currently accessible from the proprietary software SP3 (HB-Risk 2022) and a MATLAB source code (Cook 2022).

5.4. Case study

To illustrate the application of FR-BCA, we present a case study example of recovery-based design options for new construction. The case study is not intended to be exhaustive or suggestive of a design recommendation for practice. More details can be found in Fung et al. (2022) and upcoming follow-up publications.

Step 0. Since the case study is illustrative, we consider a conservative discount rate, $\delta = 0.07$, and planning horizon, $T = 50$ years, as well as a more lenient discount rate, $\delta = 0.02$, and planning horizon, $T = 75$ years. In addition, our baseline design is an archetype 4-story reinforced concrete moment frame (RCMF) commercial office building designed per ASCE 7-16 (B-4), for a generic site with Seismic Design Category D (S_{ds} = 1.0g and S_{d1} = 0.6g) and Site Class C (Cook and Sattar 2022). The three recovery-based design options include:

- structural improvements only (S);
- nonstructural improvements only (NS); and
- a design that incorporates both structural and nonstructural improvements (S-NS).

Structural improvements include redesigning the sizing and reinforcement of the components of the lateral system to increase design strength and reduce lateral drifts. Nonstructural improvements include modifications of the building model to include the effects of increased anchorage and bracing, the use of seismically rated equipment, and several other design modifications to reduce the vulnerability of certain nonstructural systems. It should be noted that these designs are largely limited to increasing capacity and do not consider other strategies (e.g., base isolation, resilience planning).

Step 1. We consider a subset of the avoided losses presented in Table 5.1. Specifically, we consider repair costs, repair time, time to reoccupancy, and time to functional recovery (all results of performance assessment), as well as costs associated with occupant displacement and loss of business and rental incomes (due to business interruption). Direct losses are calculated using the probabilistic performance-based assessment method described in Cook and Sattar (2022). Indirect losses due to occupant displacement include the costs to provide temporary accommodation and the value of lost income (IMDC 2020); business income is estimated from proprietor income (BEA 2020); rental income is estimated from the national average rental income for office buildings (BOMA 2018).

Given the research needs required for some of the other categories of losses in Table 5.1, we include those that are the least controversial. While the inclusion of a broader set of avoided losses would certainly improve the analysis, determining reasonable assumptions for their estimation is beyond the scope of this case study example.

Step 2. Finally, we estimate investment costs for the four archetype designs. Investment costs are based on RSMeans (2021) as well as conversations with design professionals. It should be noted that these costs are not intended to reflect construction costs in practice. However, based on conversations with design professionals, as well as trends in the construction industry, the cost *differences* between the baseline and recovery-based designs are plausible (that is, within bounds of average expected costs). For a BCA, this difference in investment costs represents the cost of a recovery-based design option.

Step 3. Given avoided losses and investment costs, we compute PV(benefits), the present value of expected annual net benefits, and PV(costs), the present value of additional investment costs relative to the baseline design. Note that while the definition of PV(costs) is specific to new construction, the formula for BCR is generic (for existing buildings, PV(costs) would be the retrofit costs as the baseline option is to do nothing). We then compute the benefit-cost ratio (BCR), defined as BCR = PV(benefits) / PV(costs), and the net present value (NPV), defined as NPV = PV(benefits) - PV(costs). Table 5.6 presents the results of the benefit-cost analysis for the three candidate recovery-based designs.

Table 5.6. Case study benefit-cost analysis results (relative to baseline design). Low: $\delta = 0.07, T = 50$. High: $\delta = 0.02, T = 75$.

Design	BCR (Low)	BCR (High)	NPV (Low)	NPV (High)
S	0.093	0.261	-$571 096	-$465 492
NS	**1.412**	**4.071**	$56 684	$410 584
S-NS	0.380	**1.069**	-$475 948	$52 888

The case study suggests that nonstructural improvements alone may provide cost-effective design options for achieving recovery-based performance objectives. The relatively large BCRs for NS (ranges from 1.412 to 4.045) are due to the relatively low costs of implementing nonstructural improvements compared to the reductions in avoided loss associated with the improved robustness of the nonstructural systems. Structural improvements alone, on the other hand, do not appear to be cost effective for recovery-based objectives due to the substantial structural construction cost increases relative to marginal avoided losses at frequent hazard levels. Using the decision criterion BCR > 1 (i.e., the benefits outweigh the costs) or NPV > 0 (i.e., the value of the investment exceeds its cost), we are most likely to choose NS out of the three case-study designs, which saves between $1.41 and $ 4.07 per dollar invested. Note, however, that benefit-cost analysis outcomes and recovery-based design solutions may vary significantly from this case study for different levels of seismicity and varied building characteristics. In forthcoming companion publications, we provide the details of benefit and cost estimation for several archetypes and structural systems.

Step 4. We now apply the benefit-transfer matrix presented in Table 4.1 to distribute benefits and costs. Given the results of Step 3, we focus on the NS archetype. Note that we only consider the first four columns of Table 4.1, which represent construction cost, property loss, and direct business interruption, and indirect business interruption. In addition, we distribute rental income losses to the title holder and displacement costs to the tenant. The remaining columns (i.e., insurance and deaths/injuries) are not covered by our case study. The results are shown in Table 5.7.

Table 5.7. Distributed benefit-cost analysis for archetype NS, based on the benefit-transfer matrix in Table 4.1 (NIBS 2019). Weights for benefits are unnormalized.

Stakeholder	**Weights (benefits)**	**Weights (costs)**	**Distributed benefits**	**Distributed costs**	**Distributed BCR**	**Distributed NPV**
Developer	0.02 / 5		776.86		-	776.86
Title holder	(0.58 + 1) / 5	0.5	61 372.14	68 765.77	0.89	-7393.63
Lender	0.07 / 5		2719.02		-	2719.02
Tenant	(0.33 + 1 + 1) / 5	0.5	90 504.49	68 765.77	1.32	21 738.72
Community	1 / 5		38 843.13		-	38 843.13

Since we apply the benefit-transfer matrix *ex post*, we sum the weights for benefits across columns and normalize so that weights sum to one. Note that we apply the table as given, assuming that the title holder bears the cost for new construction and passes 50 % of that cost to the tenant. It might be more reasonable to distribute costs between the developer and title holder instead. Moreover, based on the review of the literature on indirect economic losses due to supply chain disruptions, we assume a conservative multiplier factor of 5 to scale direct business interruption losses to the community.[48]

Note that the BCR is not defined for developers, lenders, and the community since their cost is zero. On the other hand, the title holder and tenant face a BCR of 0.89 and 1.32, respectively. This example illustrates the concern that recovery-based design disproportionately benefits the stakeholders that bear less (or none) of the cost. The NPV, which is well-defined for all stakeholders, emphasizes this point more clearly.

[48] While there is not a lot of data on these factors, Inoue and Todo (2019) suggest a multiplier factor of about 20.

6. Conclusion

6.1. Summary/practical guidance

Economic evaluation is a key step toward developing standards and policies. Building codes define the minimum requirements for new construction, with the objective to safeguard the health and safety of occupants through affordable means. Retrofit policies target the most vulnerable portions of the building, in order to improve building performance while limiting retrofit costs. For recovery-based design, economic evaluation is especially important since no design criteria currently exist and functional recovery may have large-scale impacts, from building owners and occupants to the region and nation through supply chains. For individual decision makers, economic evaluation is a useful tool for comparing alternative strategies and assessing the feasibility of an investment.

This report provides a roadmap for how to evaluate benefits and costs for recovery-based design. The roadmap consists of four steps: set analysis parameters – estimate benefits – estimate costs – allocate benefits and costs to stakeholders. In each step, we provide a review of the methods and tools for performing the analysis.

- **Estimate benefits**. Twenty-seven benefit categories relevant to recovery-based design are described in Sec 5.1. Methods and data sources that can be utilized to quantify these benefits are elaborated with one or more examples, while highlighting opportunities for further research.

- **Estimate costs.** The approaches to estimating initial construction costs, structural improvement costs, nonstructural improvement costs, and life-cycle costs are reviewed in Sec 5.1. Appendix B provides additional methods for cost estimation.

- **Allocate benefits and costs to stakeholders.** The potential beneficiaries of each benefit category are enumerated in Table 5.1. Section 4 explains how to distribute benefits and costs to various stakeholder groups using a benefit transfer matrix (NIBS 2019).

While this roadmap is specific to recovery-based design, the principles may apply more broadly to other new design paradigms.

This report also elaborates the advantages and limitations of five economic evaluation methods in Section 3: benefit-cost analysis, cost-effectiveness analysis, life-cycle cost analysis, willingness-to-pay (WTP) methods, and economic impact analysis. Readers may refer to this guidance to determine the proper method to use.

6.2. Major findings

Based on an extensive literature review, we find that many indirect benefit categories are not well investigated in previous studies, even though these indirect benefits are highly relevant to community resilience, social equity, and environmental sustainability. In addition, the data required to quantify these benefits is scarce even though the methods (e.g., WTP) are readily available.

- Among the 27 benefit categories, three direct benefits are extensively assessed in the literature and considered as primary metrics for BCA: building damage, content damage, and casualties.

- Six indirect benefits are well studied and frequently included in BCA: avoiding displacement and debris removal, avoiding loss of business or rental incomes, avoiding loss of life quality, preserving culture/history/character, and avoiding energy consumption and greenhouse gasses emissions incurred by building repairs or demolition.

- Five benefit categories are investigated less within the literature but may have great influence on property owners and business owners: avoided loss of productivity, avoided reduction in customers, decrease of property value, increase in insurance premium, and supply chain delays.

- Seven benefit categories are rarely studied but may have profound influence on a broader community: avoided reduction in employment, tax base, and affordable housing, improved equity through reduction in regressive hazard insurance, reduced crime rate, and avoided government assistance in building repairs, inspection, and displacement of residents.

- Five benefit categories are rarely assessed in the literature due to high complexity and uncertainty: avoided delays in recouping return on investment due to delays, delays in settling insurance claims, litigation costs,[49] loss of sense of connectedness or community, and reduction in perceived risk due to building's high performance.

The case study for reinforced concrete moment frame (RCMF) buildings is part of our ongoing effort to measure the cost-effectiveness of recovery-based design. Other building types, such as buckling-restrained braced frame (BRBF) and steel moment frame (SMF), will be analyzed subsequently to provide a more holistic perspective of cost effectiveness. The preliminary results suggest that nonstructural improvements can contribute to a large proportion of annual avoided loss and can be more cost-effective than structural improvements alone. This implies a promising way to achieve functional recovery goals through nonstructural enhancement.

The case study also contributes to improved methods for benefit-cost analysis by taking nonstructural improvements and building-specific attributes into account. Previous studies often focus on enhancing structural systems while ignoring or underestimating the role of nonstructural enhancement. In less intensive earthquake events, nonstructural damage may cost more than that of structural damage when buildings are designed under the current code. This study takes the first step to compare the cost-effectiveness of three design strategies: structural improvements only, nonstructural improvements only, and combined structural and nonstructural improvements. As noted before, enhancing nonstructural components could improve building overall performance and produce greater net benefits compared to structural enhancement.

Furthermore, the case study utilizes a state-of-the-art performance-based assessment method to predict downtime for commercial office buildings (Cook et al. 2022). Building characteristics, occupancy categories, and performance objectives are addressed in the modeling stage and reflected in benefit estimates. The improved estimates could enhance decision making for a specific building given that

[49] Assuming a building is code-conforming, the owner/title holder has limited liability in case of damaging event. However, that does not preclude litigation, hence it is difficult to predict (avoided) litigation costs; moreover, litigation could result in additional delays in resuming operations, which would result in additional business interruption losses. Given the speculative and understudied nature of this category, we do not cover it in Table 5.1.

conventional estimation methods rely heavily on empirical and expert judgements, which are helpful to study a large building stock but are not accurate enough for a single building.

6.3. Future directions

Benefit-cost analysis framework. We provide a first step toward enumerating the range of potential benefits, as well as stakeholders and beneficiaries, associated with building functional recovery; however, this framework is not comprehensive. Future studies could explore co-benefits (i.e., benefits accrued even if no event occurs) and externalities (e.g., damage to other buildings) that may influence decision making for enhanced building design. Such co-benefits are understudied and present an opportunity for future research to enhance the business case for functional recovery. Another limitation of the framework is that the enumerated benefits may overlap or strongly correlate with other types of benefits. Thus, an ontology of benefits (classes of benefits, stakeholders, quantification) could be useful to unify this framework across various domains, which could be investigated in future work.

Case study for recovery-based design. We assess five benefit categories in the case study: reduced structural and nonstructural repair costs, avoided displacement costs, and avoided business and rental interruption costs. More benefit items that involve a broader range of stakeholders could be included in future analyses. In addition, there is a need for validated methods for distributing benefits and costs that build on Table 4.1 (NIBS 2019). Future studies may also aggregate results from the asset level to community level to provide a holistic view of the cost-effectiveness of alternative design strategies. In addition, we analyze three design strategies without controlling performance levels (e.g., repair time), improvement costs, or total benefits. While optimizing design strategies is not a priority at this stage, future studies could control one or two of the three variables and optimize the rest of variables, such as minimizing improvement costs for a target performance level or maximizing total benefits for a fixed improvement budget. Finally, beyond *designing* for functional recovery, there will be practical challenges with implementing functional recovery (including review and quality control) that are associated with non-negligible costs (Tokas 2011). Thus, practical recovery-based design will require a more holistic approach.

Existing buildings, critical infrastructure, and community impacts. While our case study is focused on new construction, future work could examine existing buildings and critical infrastructure. Economic evaluations of these systems may produce different results because existing building conditions could limit the capacity of improvements, and critical infrastructure may have greater impacts on the community. Moreover, the recovery of building functions depends on external conditions such as lifelines, which adds complexity to downtime estimation. Finally, it is important to understand and evaluate the impacts of recovery-based design standards for underserved communities. Improved building standards could enhance community resilience but at the same time increase housing and rental prices. Underserved communities are more likely to be affected because owners often pass increased construction costs to tenants through rents (ATC 2009).

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Appendix A. Risk category and seismic design category

Table A-1. Risk category of buildings and other structures for earthquake loads (ASCE 7-16).

Occupancy group	Definition	Examples
I	Buildings and structures that represent low risk to human life in the event of failure	Barns and storage shelters
II	All buildings and structures except those listed in Risk Categories I, III and IV	Residential, commercial and industrial buildings
III	● Buildings and other structures, the failure of which could pose a substantial risk to human life ● Buildings and other structures, not included in Risk 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 ● Building and other structures not included in Risk Category IV, containing toxic or explosive substances where the quantity of material exceeds a threshold quantity established by the authority having jurisdiction and is sufficient to pose a threat to the public if released	● Theaters, lecture halls, and dining halls ● Grade schools, prisons, and small healthcare facilities ● Power-generating stations, water treatment, and sewage treatment plants

IV	• Building and other structures designed as essential facilities • Building and other structures, the failure of which could pose a substantial hazard to the community • Building and other structures containing sufficient quantities of highly toxic substances where the quantity of material exceeds a threshold quantity established by the authority having jurisdiction and is sufficient to pose a threat to the public if released • Building and other structures required to maintain the functionality of other Risk Category IV structures	Hospitals, police stations, emergency control centers

Table A-2. Seismic design category (ASCE 7-16).

Design category	Definition
A	Buildings in areas where expected ground shaking is minor
B	Buildings of Occupancy Groups I, II and III where expected ground shaking is moderate
C	Buildings of Occupancy Groups IV where expected ground shaking is moderate and buildings of Occupancy Groups I, II, and III where more severe ground shaking will occur
D	Buildings in areas expected to experience severe and destructive ground shaking but not located close to a major fault
E	Buildings of Occupancy Groups I, II and III in areas near major active faults
F	Buildings of Occupancy Groups IV in areas near major active faults

Appendix B. Methods/Tools for estimating costs

There are many tools designed to assist in cost estimating. Below lists the tools that are readily available to any users.

- Craftsman National Cost Estimator, http://www.craftsmansitelicense.com
- Standard Estimating Practice edited by American Society of Professional Estimators (ASPE), https://www.aspenational.org/page/SEP
- Autodesk Construction Cloud, https://go.construction.autodesk.com/demo-request/
- Corecon Technologies Cost Database, https://www.corecon.com/estimating-cost-databases
- EG Sigma Software, https://sigmaestimates.com/products/cost-database-construction/
- Design Cost Data (DCD), https://www.dcd.com/articles/category/estimating
- HomeAdvisor seismic retrofit costs by zip codes, https://www.homeadvisor.com/cost/environmental-safety/earthquake-retrofit-a-home/

Yet novel methods are needed for estimating construction costs and retrofit costs, such as using machine learning methods trained on cost data (Fung et al. 2017, 2018a, 2018b, 2019, 2020). Note that a database of retrofit costs for functional recovery is not available, except maybe for Risk Category IV, but this is not generalizable to other buildings. One potential direction for future research is to collect engineering consulting estimates for different building prototypes, but this faces the same problem as to how to generalize. Another potential direction for future research is to develop an analytical model that minimizes "annual equivalent cost," as discussed in Nuti and Vanzi (2003).