12th National Conference
on Earthquake Engineering
Salt Lake City, Utah
27 June - 1 July 2022
Hosted by the Earthquake Engineering Research Institute

Economic considerations for recovery-based design

J.F. Fung[1] and D.T. Cook[2] and Y. Zhang[3] and K.J. Johnson[2] and S. Sattar[2]

ABSTRACT

Current building design practice targets life safety performance for the design-level earthquake. While some buildings (e.g., schools, hospitals) may be designed for higher performance, the actual performance of most residential and commercial buildings may not align with owner and occupant expectations. In particular, the literature has documented that building users expect to be able to use their buildings after an earthquake. The National Institute of Standards and Technology is leading research efforts on recovery-based design that targets re-occupancy and restoration of function performance after an earthquake. A key aspect of this research is articulating an economic case for recovery-based design. In this paper, we discuss the importance of evaluating the economic merits of recovery-based design. We present a taxonomy for the range of benefits and costs that should be considered in an economic evaluation. Finally, we present a benefit-cost analysis case study to illustrate the approach to economic evaluation of potential recovery-based design standards. The case study suggests that nonstructural design options may provide a cost-effective solution for achieving recovery-based performance targets.

---

[1] Applied Economics Office, National Institute of Standards and Technology, Gaithersburg, MD 20899 (email: juan.fung@nist.gov)

[2] Earthquake Engineering Group, National Institute of Standards and Technology, Gaithersburg, MD 20899

[3] Applied Economics Office, National Institute of Standards and Technology, Gaithersburg, MD 20899

Fung JF, Cook DT, Zhang Y, Johnson KJ, Sattar S. Economic considerations for recovery-based design. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

Introduction

Functional recovery is defined as “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” [1], as illustrated in Fig. 1. Buildings designed or retrofitted to a higher standard than life safety could target functional recovery within acceptable limits, e.g., weeks rather than months or years, representing a paradigm shift in seismic design that “better align[s] with public expectations regarding seismic performance” [1]. However, the decision to adopt recovery-based design for individual buildings and building standards will inevitably depend on the cost-effectiveness of the design and mitigation solutions, which was identified by stakeholders as the most important attribute in assessing and implementing enhanced building performance objectives [2]. As research advances towards functional recovery design, and stakeholders weigh the necessity of recovery-based standards, questions regarding the economic arguments for recovery-based design will need to be addressed.

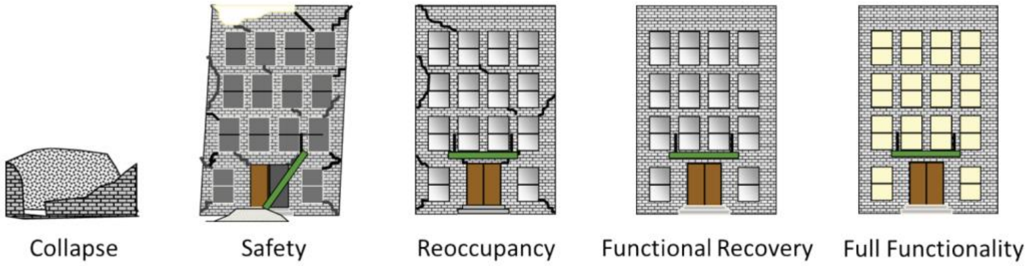

Figure 1. Theoretical range of building performance and relative placement of safety-based and recovery-based goals. Source: FEMA P-2090/NIST SP125 [1].

In this paper, we present an organizing framework for the economic evaluation of recovery-based design. In particular, we provide a roadmap for decision makers to conduct an economic analysis that considers the full range of benefits and costs relevant for functional recovery. To illustrate, we present a benefit-cost analysis case study, which highlights some important considerations for both design standards and economic evaluation. The goal of this study is to provide a generic recipe that decision makers can use when applying the economic analysis of their choice, e.g., benefit-cost analysis (BCA) or life-cycle cost analysis (LCC), whether for new construction or existing buildings, to any candidate recovery-based design standard. While economic evaluation can be used to guide performance targets, defining targets for functional recovery performance objectives is beyond the scope of this paper.

A Roadmap for Economic Evaluation

The goal of economic evaluation is to measure the economic performance of investing in recovery-based design [3]. In order to conduct an economic evaluation, the first step is to select an appropriate metric to evaluate economic performance. For a standard guide to selecting economic evaluation metrics for decisions specific to buildings and building investments, see ASTM E1185 [4].

The metric for economic performance will depend on the problem (e.g., adoption of a particular design standard vs. choosing between candidate design standards). Suppose a standards organization is presented with two candidate design standards, A and B, that both target a functional recovery performance objective for the same building. If each candidate standard is expected to achieve the same level of performance (e.g., in terms of recovery time), then the comparison of the two options essentially comes down to investment cost. In this case, an appropriate metric may be cost-effectiveness, which simply compares the total investment costs associated with each option. One caveat is that A may have lower operating and maintenance costs over the life of the building than B, in which case life-cycle costs (LCC) may be the more appropriate metric. On the other hand, suppose A and B deliver different levels of expected performance or benefits, where we define benefits as reductions in losses during disasters (avoided losses) [5]. In this case, benefit-cost analysis may be the appropriate method for economic evaluation. Other potential metrics include the internal rate of return (IRR), which is defined as the interest rate such that NPV = 0, or the payback period, which is defined as the length of time until NPV is equal to the initial investment [4].

Once a suitable metric is chosen, the next step is to conduct the economic evaluation. Given the outputs of the economic evaluation, the decision maker can calculate the metric for the decision problem and compare to the appropriate decision criterion (e.g., benefit-cost ratio (BCR) > 1 or net present value (NPV) > 0).

The Ingredients for Economic Evaluation

Once the decision problem is defined and an appropriate metric is selected, we perform the economic evaluation. Given the preceding discussion, the decision maker may be interested in either benefits, costs, or both. Quantification of benefits and costs is the most challenging step and requires care. In this section, we describe the range of potential benefits and costs specific to economic evaluation of recovery-based design.

First, recall that we define benefits as avoided losses, where losses are the consequences of building performance in an earthquake event. We define direct losses as impacts on physical infrastructure, while indirect losses include impacts to the economy, society, and other losses not directly tied to loss of physical infrastructure [5]. In particular, this implies that direct losses are those that are estimable through a building performance assessment. Table 1 presents potential direct and indirect losses avoided at three levels of building performance. Note that the avoided losses listed in the table are cumulative; e.g., a performance objective that targets functional recovery is expected to reduce repair time in addition to reducing recovery time. Moreover, each of the benefits (avoided losses) may accrue to different parties such as the building owner, developer, building occupants, or the community at large. Therefore, benefit-costs decisions, and the ingredients used in the economic evaluation, may depend on the perspective of a given stakeholder.

Table 1. Examples of potential direct and indirect losses avoided associated with three levels of building performance in an earthquake: safety, reoccupancy, and functional recovery.

	Losses to be avoided	
Performance target	**Direct**	**Indirect**
Life Safety	Repair costs and debris removal	Deaths and injuries
Reoccupancy	Repair time	Displacement Deterioration of mental health Loss of social cohesion
Functional recovery	Recovery time	Business interruption Supply chain disruption Pollution due to repairs or demolition

Recovery-based objectives are expected to reduce indirect losses from earthquake shaking. In order to conduct an economic evaluation, we need to quantify the avoided losses from reducing reoccupancy and recovery times. This requires estimating two components: time to reoccupancy or recovery of function, and the monetary damages associated with the loss over the period of downtime. The first is an active area of research and is beyond the scope of this paper; for example, see Cook and Sattar [6]. For the second, monetizing the loss (and hence the benefit) depends on whether there is a market price associated with the damages. For instance, business interruption results in loss of business income and can thus be monetized easily. On the other hand, damages to the environment from air pollution and waste or deterioration of mental health do not have market prices. For such losses, there exist methods to elicit implicit prices (willingness-to-pay) for non-market goods [5].

Note that indirect losses have broader impacts than direct losses. In addition to building owner and occupants, potential stakeholders affected by loss of function include neighbors, local government, and upstream or downstream partners in a supply chain. Finally, we note that the examples are not intended to be comprehensive but rather illustrative of the breadth of potential benefits relevant for recovery-based design. Fung et al. [7] provides a more detailed discussion of the range of potential benefits, affected stakeholders, and methods for monetizing losses.

Table 2 presents categories of costs relevant for recovery-based design. For simplicity we define "cost" in a benefit-cost analysis as investment cost (e.g., construction, inspection, permits). Reductions in operation and maintenance costs, which are those costs required to operate a building, may be considered benefits. In particular, operation and maintenance costs are included in the numerator of the benefit-cost ratio to reduce bias away from projects with relatively high maintenance costs [8].

Table 2. Categories of investment, implementation, and other costs associated with recovery-based design.

Cost	Who bears the cost	Estimation
Construction cost (new construction)	Developer	Construction cost or historical data
Retrofit cost (existing building)	Owner (title holder)	Construction cost or historical data
Plan review	Local government, design professionals	Varies locally
Quality control (testing, inspection)	Local government	Varies locally and by project
Evaluation	Owner	Varies by project
Permits	Developer/Owner	Varies locally
Financing	Developer/Owner	Varies locally and by project
Operation and maintenance costs*	Owner, tenants	Varies by project

* Note that operation and maintenance costs are incurred throughout the building's useful life and are therefore not considered investment and implementation costs.

The costs presented in Table 2 tend to be idiosyncratic and vary substantially across building construction projects [9]. Thus, for most costs there do not exist methods standard estimation methods that can be applied generally. For the purposes of economic evaluation, one might focus on pure investment costs (e.g., construction, permits) while ignoring implementation costs (e.g., plan review and quality control). However, implementation costs are expected to be non-negligible and thus must be considered when evaluating recovery-based design standards. Estimating implementation costs is thus a gap in research that requires further research.

Benefit-Cost Analysis Case Study

This section briefly presents a case study to illustrate the economic evaluation of candidate recovery-based designs for new construction. We note that our case study is illustrative and not intended as a recommendation for design. 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 [6]. The three recovery-based design options include: structural improvements only (S-4); nonstructural improvements only (NS-4); and a design that incorporates both structural and nonstructural improvements (SNS-4). For structural improvements, we redesign the sizing and reinforcement of the components of the lateral system for increased design strength and reduced lateral drifts. For nonstructural improvements, we modified 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. Note that our recovery-based designs are largely limited to increasing capacity and do not include other strategies such as base isolation or earthquake preparedness planning.

For simplicity, we consider a subset of the avoided losses presented in Table 1. In particular, 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 [6]. Indirect losses due to occupant displacement include the costs to provide temporary accommodation and the value of lost income; business income is estimated from proprietor income; rental income is estimated from the national average rental income for office buildings [7]. For the other avoided losses in Table 1, there are no generally accepted estimation methods and thus are more speculative. While their inclusion would certainly improve the analysis, determining reasonable assumptions for their estimation is beyond the scope of this paper and we leave this for future research [7]. Finally, investment costs for the four designs are based on RSMeans [10] as well as conversations with design professionals.

Table 3 presents the results of the benefit-cost analysis for the three candidate recovery-based designs. We present a low-end and a high-end estimate of the benefit-cost ratio (BCR), based on different assumptions about business income [7]. For simplicity, we define BCR = PV(benefits) / PV(costs) where PV(benefits) is the present value of expected annual net benefits and PV(costs) is 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). For BCR calculations, we choose the discount rate $\delta = 0.02$ and the planning horizon for the project $T = 75$ years. For sensitivity, we also present results assuming a higher discount rate, $\delta = 0.07$, and shorter planning horizon, $T = 50$ years.

Table 3. Case study benefit-cost analysis results (relative to baseline design).

	$\delta = 0.02, T = 75$		$\delta = 0.07, T = 50$	
Design	**BCR (Low)**	**BCR (High)**	**BCR (Low)**	**BCR (High)**
S-4	0.159	0.261	0.057	0.093
NS-4	**1.602**	**4.071**	0.556	**1.412**
SNS-4	0.469	**1.069**	0.167	0.380

Our benefit-cost analysis 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-4 (ranges from 0.552 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. On the other hand, structural improvements alone are not cost effective to achieve target objectives for recovery because of the substantial structural construction cost increases relative to marginal avoided losses at frequent hazards. Based on the decision criterion BCR > 1, which means the benefits outweigh the costs, we are most likely to choose NS-4 out of the three case-study designs. For instance, assuming a high level of business interruption losses, NS-4 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 building characteristics.

Conclusions

With the continued interest in improving community resilience through recovery-based design strategies, the economic assessment of functional recovery options will be a critical tool for stakeholders to make risk-informed, economically viable decisions. In this paper, we present a roadmap for economic evaluation of recovery-based design options and discuss essential costs and benefits to be considered. Importantly, we note that the range of potential direct and indirect benefits at various performance levels affect a wide range of stakeholders. Our case study illustrates how a decision maker may conduct an economic evaluation to selecting among several candidate recovery-based design options. However, while the case study demonstrates some of the considerations for economic evaluation, the analysis is not comprehensive and is not intended to be a recommendation for practice.

Moreover, beyond *designing* for functional recovery, there will be practical challenges with *implementing* functional recovery. In particular, designs will require review and quality control, which are associated with non-negligible costs [11]. Thus, the future of functional recovery will likely depend on a more holistic approach to design. Further research is needed on both design and economic analysis, including consideration of potential co-benefits, and we hope this paper provides a roadmap for developing both in parallel.

Acknowledgments

We would like to thank the participants of the five NIST-FEMA functional recovery workshops held between January and February 2020 [2].

References

1. NIST (2021) “NIST SP-1254: Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time" https://doi.org/10.6028/NIST.SP.1254.

2. NIST (2021) “NIST SP 1269: NIST-FEMA Post-Earthquake Functional Recovery Workshop Report” https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1269.pdf

3. ASTM International. (2020). E2506-15(2020)e1Standard Guide for Developing a Cost-Effective Risk Mitigation Plan for New and Existing Constructed Facilities. Retrieved from https://compass.astm.org/EDIT/html_annot.cgi?E2506+15(2020)e1. Accessed: 2021-09-07.

4. ASTM International. (2020). E1185-15(2020)e1 Standard Guide for Selecting Economic Methods for Evaluating Investments in Buildings and Building Systems. Retrieved from https://compass.astm.org/EDIT/html_annot.cgi?E1185+15(2020)e1. Accessed: 2021-09-07.

5. Gilbert, S, Butry, D, Helgeson, J and Chapman, R. (2015), Community Resilience Economic Decision Guide for Buildings and Infrastructure Systems, Special Publication (NIST SP), National Institute of Standards and Technology, Gaithersburg, MD, [online], https://doi.org/10.6028/NIST.SP.1197. Accessed: 2021-09-07.

6. Cook, D. and Sattar, S. (2022). The Effect of Increased Strength and Stiffness Requirements on the Functional Recovery Performance of Reinforced Concrete Special Moment Frames. 12th National Conference on Earthquake Engineering, Salt Lake City, UT.

7. Fung, JF et al. (2021). A Framework to Evaluate the Cost-effectiveness of Recovery-based Design. Unpublished.

8. ASTM International. (2020). E964-15(2020)e1 Standard Practice for Measuring Benefit-to-Cost and Savings-to-Investment Ratios for Buildings and Building Systems. Retrieved from https://compass.astm.org/EDIT/html_annot.cgi?E964+15(2020)e1. Accessed: 2021-09-07.

9. Fung JF, Sattar S, Butry DT, McCabe SL. The total costs of seismic retrofits: State of the art. Earthquake Spectra. May 2021. doi:10.1177/87552930211009522.

10. RS Means (2021). Available at https://rsmeansonline.com. Retrieved: 2021-05-01.

11. Tokas, C (2011). Nonstructural Components and Systems - Designing Hospitals for Post Earthquake Functionality. Proceedings of the ASCE & Architectural Engineering Institute Conference, Oakland, CA.