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Standard Guide for Developing Cost-Effective Community Resilience Strategies[1]

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INTRODUCTION

There is a need for best practices for resilience planning that address the increasing value-at-risk of U.S. infrastructure and communities. Communities, as a system, are particularly vulnerable to the effects of natural, technological, and human-caused disruptive events. There are best practices for community resilience assessment methodologies; however, there are gaps that remain in the characterization of robust, benefit-cost measures of community resilience, especially in the planning process. In many cases, resilience remains in a planning silo and is considered separately by communities from economic growth or disaster risk planning. Efforts to increase resilience capacities are best realized when resilience is considered as an attribute in general community planning efforts, especially in planning and implementing building and infrastructure projects. This guide develops economic decision guidance for evaluation of investment strategies designed to improve community resilience through strengthening the ability to respond, withstand, and recover from disruptive events. It is designed to support the principles and attributes of resilient communities upon which enhanced resilience may be developed, evaluated, and implemented.

1. Scope

1.1 This guide describes a generic economic methodology for evaluating investment decisions aimed to improve the ability of communities to adapt to, withstand, and quickly recover from, disruptive events. The methodology describes a framework for developing cost-effective community resilience strategies for new and existing constructed facilities—buildings, industrial facilities, and other critical infrastructure. This guide provides owners and managers of constructed facilities, architects, engineers, constructors, other providers of professional services for constructed facilities, and researchers and analysts with an approach for planning and comparing resilience strategies.

1.2 This guide frames the economic decision process by identifying and comparing the relevant present and future streams of costs and benefits to a community—the latter realized through cost savings and damage loss avoidance—associated with new capital investment into resilience to those generated by the status-quo.

1.3 This guide provides a means to increase the capacity of communities to objectively and effectively compare and contrast capital investment projects through consideration of benefits and costs while maintaining an awareness of system resilience. Topics related to non-market values and uncertainty are also explored.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E631 Terminology of Building Constructions

E833 Terminology of Building Economics

E917 Practice for Measuring Life-Cycle Costs of Buildings and Building Systems

[1] This guide is under the jurisdiction of ASTM Committee E06 on Performance of Buildings and is the direct responsibility of Subcommittee E06.81 on Building Economics.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

E964 Practice for Measuring Benefit-to-Cost and Savings-to-Investment Ratios for Buildings and Building Systems
E1057 Practice for Measuring Internal Rate of Return and Adjusted Internal Rate of Return for Investments in Buildings and Building Systems
E1074 Practice for Measuring Net Benefits and Net Savings for Investments in Buildings and Building Systems
E1121 Practice for Measuring Payback for Investments in Buildings and Building Systems
E1185 Guide for Selecting Economic Methods for Evaluating Investments in Buildings and Building Systems
E1369 Guide for Selecting Techniques for Treating Uncertainty and Risk in the Economic Evaluation of Buildings and Building Systems
E1699 Practice for Performing Value Engineering (VE)/Value Analysis (VA) of Projects, Products and Processes
E1765 Practice for Applying Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments Related to Projects, Products, and Processes
E2204 Guide for Summarizing the Economic Impacts of Building-Related Projects
E2506 Guide for Developing a Cost-Effective Risk Mitigation Plan for New and Existing Constructed Facilities

3. Terminology

3.1 *Definitions*—For definitions of general terms related to building construction used in this guide, refer to Terminology E631; and for general terms related to building economics, refer to Terminology E833.

3.1.1 *community resilience, n*—the ability of a community to anticipate, prepare for, and adapt to changing conditions, and withstand, respond to, and recover rapidly from disruptions.

3.2 *Abbreviations:*

3.2.1 *OMB*—Office of Management and Budget

3.2.2 *OMR*—operation, maintenance, and repair

3.2.3 *PVNB*—present value net benefits

4. Summary of Guide

4.1 This guide presents a generic economic methodology for evaluating investment decisions aimed to improve the ability of communities to adapt to, withstand, and quickly recover from disruptive events. The generic framework consists of seven interrelated stages. The stages are: (*1*) select candidate strategies; (*2*) define investment objectives and scope; (*3*) identify benefits and costs; (*4*) identify non-market (non-economic) considerations; (*5*) define analysis parameters; (*6*) perform economic evaluation; and (*7*) rank strategies. The generic framework builds on an approach presented in NIST Special Publications 1190 (**1**) and 1197 (**2**).

4.2 This guide identifies related ASTM standards and describes why measuring uncertainty and risk is critical in the development of cost-effective protective strategies for constructed facilities.

4.3 Appendix X1 provides an example case study to highlight the steps of the standard and demonstrate how they can be used to evaluate the cost-effectiveness of community resilience strategies.

5. Significance and Use

5.1 Investments in projects supporting community resilience are characterized by uncertainties regarding the frequency and magnitude of natural, technological, and human-caused disruptions. Accounting for these low-probability, high-consequence events challenge traditional economic evaluation methods.

5.2 The traditional approach to evaluating the benefit-cost of investment decisions routinely focus on measures directly tied to loss avoidance.

5.3 Following this guide when performing an economic evaluation assures the user that relevant economic information, including information regarding uncertainties and indirect inputs, is considered for capital project facing possible disruptions from natural, technological, and human-caused hazards.

5.4 Use this guide in the planning phases of community resilience plan development process. Consideration of risk mitigation choices early in the planning process allows both greater flexibility in addressing specific hazards and lower costs associated with their implementation.

5.5 Use this guide to integrate community resilience plans with economic development, zoning, hazard mitigation, and other community planning activities that affect buildings, public works, and infrastructure systems.

5.6 Use this guide to identify all relevant inputs—that is, costs and benefits (savings)—associated with construction, implementation, and use of the capital asset, over the lifetime of the asset. Relevant inputs include direct, indirect and externalities, and non-market values.

5.7 Use this guide for economic evaluations based on Practices E917 (life-cycle costs), E964 (benefit-to-cost and savings-to-investment ratios), E1057 (internal rate of return and adjusted internal rate of return), E1074 (net benefits and net savings), E1121 (payback), E1699 (value engineering), and E1765 (analytical hierarchy process for multi-attribute decision analysis), and Guide E1369 (treatment of uncertainty).

5.8 Use this guide in conjunction with Guide E2204 to summarize the results of economic evaluations involving natural, technological, and human-caused hazards.

5.9 This guide generalizes Guide E2506 (cost-effective risk mitigation plan for new and existing constructed facilities) by evaluating investments into capital assets for a community.

6. Procedures

6.1 The recommended steps for economically evaluating strategies for community resilience are as follows:

6.1.1 Select Candidate Strategies,

6.1.2 Define Investment Objectives and Scope,

6.1.3 Identify Benefits and Costs,

6.1.4 Identify Non-Market Considerations,

6.1.5 Define Analysis Parameters,

6.1.6 Perform Economic Evaluation, and

6.1.7 Rank Strategies.

7. Select Candidate Strategies

7.1 *Form a Collaborative Planning Team:*

7.1.1 Identify resilience leadership and team members. This should include representatives from local government; private owners and operators of buildings and infrastructure systems; developers, builders, and contractors; local business and industry leaders; representatives of social organizations and any other significant community groups.

7.2 *Understand the Situation:*

7.2.1 Characterize the existing built environment. Identify key attributes and dependencies for buildings and infrastructure systems within the community. Characteristics that will help determine the current condition of the built environment include the owner, location(s), current use, age, construction types, zoning, maintenance and upgrades, and applicable codes, standards, and regulations, both at the time of design and for current performance.

7.2.2 Characterize the social dimensions. Identify social needs and functions, including those that are supported by the built environment.

7.2.3 Identify dependencies between the built environment and the social dimensions.

7.3 *Determine Community Goals and Objectives:*

7.3.1 Establish long-term community goals and objectives for the built environment based on the input from all stakeholders, including local government offices for community development, emergency response, social needs, public works, and buildings; private owners and operators of buildings and infrastructure systems; developers, builders, and contractors; local business and industry representatives; and social and economic organizations.

7.3.2 Determine performance goals. Establish criteria for the desired performance of the built environment, and identify gaps between desired and anticipated performance levels.

7.3.3 Identify community hazards. Each community has a set of prevalent hazards that should be considered in resilience planning. Determine the likelihood and consequence of those hazards.

7.4 *Plan Development:*

7.4.1 Match performance goals for the built environment with the social needs of the community and consider the functions that buildings and infrastructure systems need to provide, as well as any dependencies between systems or cascading effects caused by failures.

7.4.2 Identify strategies, or combinations of strategies, for a comparison of desired and anticipated performance based on identifying gaps in performance that will impact community resilience and therefore need to be integrated into the alternative community resilience investment strategies. A strategy is an approach or method to enhance community resilience. A strategy may be evaluated individually or, jointly, in combinations with other strategies (as a portfolio). A candidate strategy (or a combination of strategies) can be evaluated against the status quo (do nothing), against others, or both. Note, however, rank reversals may occur when strategies are evaluated jointly (combined).

7.4.3 Consider combinations of mitigation, disaster preparedness, design and construction, emergency response, and pre-event recovery planning strategies. Inclusion of desired performance goals versus anticipated (actual) performance of the built environment to hazard events, and expected recovery sequences, time, and costs provides a complete basis for communities to understand gaps in performance, prioritize improvements through the use of economic evaluation techniques, and allocate resources.

8. Define Investment Objectives and Scope

8.1 *Define Economic Objective Function:*

8.1.1 Establish those factors that are important to consider when selecting between strategies, and take those factors into account when determining what candidate strategies to evaluate and in deciding on strategies for implementation.

8.2 *Define Planning Horizon:*

8.2.1 Select the period over which strategies are to be compared in terms of costs and benefits. The combination of the length of the planning horizon and the discount rate dictate the relative importance of future benefits and costs.

8.3 *Identify Constraints:*

8.3.1 Identify those political, legal, financial, and other considerations that might serve as important limits on what a community can implement. There are numerous factors that influence decisions that have an impact on the well-being of a community, and some may be difficult to quantify.

8.3.2 Discard from consideration alternative strategies that violate the identified constraints.

9. Identify Benefits and Costs

9.1 *Identify Costs and Losses:*

9.1.1 Identify costs of implementing a mitigation strategy that may occur one time or over the life-cycle of the project. Account for all costs, including negative effects, of implementing a resilience action. This specifically includes the initial costs, operation and maintenance costs, end-of-life costs, and replacement costs. Use Practice E1699 for guidance on how to employ value engineering concepts to help identify and estimate the costs of implementing a mitigation strategy.

9.2 *Identify Savings and Benefits:*

9.2.1 Identify benefits, including those primarily determined to improve the performance during a disruptive event compared to the status quo, that is, those obtained directly or indirectly by the implementation of the new resilience strategy. This includes benefits related to the reductions in the (*1*) magnitude of damages from a disaster and (*2*) the costs of the response and recovery phases. Other benefits to be considered include positive effects from a resilience strategy that improve non-risk related community function and value.

9.3 *Identify Externalities:*

9.3.1 Identify those costs or benefits that impact a third party that is not part of the direct decision to implement a given strategy. Externalities may be positive or negative; they also may be *non-market* in nature, meaning they are not bought or sold in the market, so their price is not observable.

9.4 *Identify Non-Market Considerations:*

9.4.1 It can be challenging to estimate economic values for some costs and benefits. For example, damages are non-economic if they exclude physical infrastructure or do not directly affect the economy. Most prominent among the non-economic losses are deaths and injuries. Others include social, cultural, and environmental impacts.

9.4.2 The value of a statistical life can be used to convert *fatalities averted* into economic value.

9.4.3 The value of a statistical injury can be used to convert *injuries averted* into economic value.

10. Define Analysis Parameters

10.1 *Select Discount Rate:*

10.1.1 The discount rate embodies a time preference of money. In general, it is commonly accepted that people tend to prefer consumption at present over future consumption. Discounting future consumption allows comparison between current and future consumption in equivalent terms. In this case, that means discounting future costs and benefits for the proposed mitigation strategies.

10.1.2 The discount rate is a key variable in the valuation process. It encapsulates the time preferences of the community. There are standard discount rates used by federal agencies, but an individual jurisdiction may choose its own discount rate, as appropriate to the project being assessed and consistent with its identified priorities. Information on the setting of the federal discount rates is contained in the OMB Circular A-94 (**3**). The selected discount rate should be appropriate to the source or sources of funding for investments in resilience. A different discount rate should apply to strategies funded through public investments versus those funded through private investments. Additional information on the selection of the discount rate for a risk analysis of engineered systems is contained in Chapter 6 of Ayyub (**4**).

10.2 *Define Probability Distributions:*

10.2.1 Link the frequency of hazard events with their potential outcomes. Distributional assumptions are required to estimate expected costs and benefits associated with competing investment scenarios. Distributional assumptions for benefits—the expected reduction in losses—are required given the uncertainties related to disaster occurrence and outcome, while the assumptions needed for costs are due to typical uncertainties related to cost estimation, and with some stemming from the dependence on the timing and severity of the disaster itself (for example, response and recovery costs).

10.2.2 Information from the probability distributions is used in two ways: (*1*) in a baseline analysis where all parameters are fixed equal to their expected value and (*2*) in a sensitivity analysis where the baseline values are allowed to vary. First, the expected value for each input variable—the annual value for each cost, loss, and benefit—is used in the baseline analysis of each alternative resilience strategy. This corresponds to the traditional approach to project investment analysis, which applies economic methods of project evaluation to best-guess estimates of project input variables as if they were certain estimates and then presents the results in single-value, deterministic terms. Second, data points from each probability distribution for each alternative resilience strategy are used as inputs in a sensitivity analysis to measure how "sensitive" the value of net benefits for the given resilience strategy is to changes in input variables (see 11.3).

10.3 *Define Risk Preference:*

10.3.1 Determine the degree of risk aversion or risk acceptance. See Guide E1369 and Chapter 7 of Ayyub (**4**).

11. Perform Economic Evaluation

11.1 *Select Appropriate Economic Method(s) for Evaluating the Candidate Community Resilience Strategies:*

11.1.1 Several economic methods are available for evaluating investment decisions aimed to improve the ability of communities to adapt to, withstand, and quickly recover from disruptive events. Use Guide E1185 to identify types of decisions that require economic evaluation and to match the technically appropriate economic methods with the decisions.

11.1.2 Four economic evaluation methods addressed in Guide E1185 apply to the development of a cost-effective community resilience plan for dealing with disruptions: (*1*) life-cycle costs (Practice E917); (*2*) present value net benefits and present value net savings (Practice E1074); (*3*) benefit-to-cost ratio and savings-to-investment ratio (Practice E964); (*4*) payback period (Practice E1121); and (*5*) adjusted internal rate of return (Practice E1057).

11.2 *Compute Measures of Economic Performance for Each Candidate Strategy:*

11.2.1 Follow the instructions given in the selected evaluation method(s) for computing the measure(s) of economic performance (see 11.1). Perform these computations with fixed parameter values. Cases where parameter values are allowed to vary are treated in 11.3.

11.2.2 Designate the strategies with the best outcome as the most cost-effective risk mitigation plan.

11.2.3 Include direct and indirect inputs using the community as the unit of observation.

11.2.4 Examine any significant effects that remain unquantified (see 9.4). Note how these effects differ across the strategies.

11.2.5 The economic evaluation can be performed on individual strategies or on combinations of strategies.

11.3 *Evaluate Impact of Uncertainty* (See Guide E1369)*:*

11.3.1 Prospective, forward-looking analyses require expectations of future costs and losses, which are often known with some level of uncertainty, in terms of timing and magnitude. The standard way of handling uncertainty is to base decisions on the "expected value" of future net benefits at the present. The expected value is essentially the average of all possible ranges of future values, each weighted for their probability of occurring.

11.3.2 Sources of uncertainty include: the timing of future disruptions; the amount of damage a future disruption will cause; future costs of mitigation strategies; the discount rate preferred by the community; the degree of risk-aversion held by the community; model uncertainty regarding the validity of the models used in estimating the present expected net benefits.

11.3.3 In addressing uncertainty, the analysis should: identify and quantify the uncertainty specific to each different source uncertainty; quantify the impact of those sources on the net benefits of a mitigation strategy; and present the level of uncertainty in the estimate in a way that is clear and understandable to the community.

11.3.4 Other sources of uncertainty may exist as well. For some of these sources of uncertainty, the level of uncertainty is likely to be relatively well-characterized. The sequence of events during disruptions likely has a relatively well-characterized probability distribution. Yet, distributions of consequences results from disruptive events are characterized by fat tails—small probability-high impact, which makes assessment of appropriate resilience strategies challenging. Ranges for discount rates and risk aversion can be found in the literature, although probability distributions over those ranges are less well known, making them ambiguous. There is little published literature characterizing the uncertainty in cost estimates for mitigation strategies, or regarding the effect of model uncertainty. A limited amount of information on these and other topics is contained in Ayyub (**4**) and Stuart and Melchers (**5**).

11.3.5 Quantifying the impact of uncertainty on present expected net benefits can be handled a number of ways. One alternative is sensitivity analysis. The objective of sensitivity analysis is to identify those variables which have a significant impact on the results. There are three approaches in common use: min-max, Monte Carlo, and the derivative approach.

11.3.5.1 In the min-max approach, the minimum and maximum values expected for each variable are used in the model while holding all other variables constant. It has the virtue of being a simple approach and easily usable, but it fails to account for joint effects of multiple variables and may not reflect the actual combinations of values from the model. Structural techniques such as factorial designs can provide limited information on joint effects.

11.3.5.2 In the Monte Carlo approach, a candidate set of variables is selected randomly from the set of possible values. This candidate set of variables is then used to determine the output of the model. This process is repeated a very large number of times. The advantage of the Monte Carlo approach is that it gives a more realistic sense of the magnitude of variation in the model, but it is more computationally intensive.

11.3.5.3 The derivative approach takes derivatives of the output in terms of each of the input variables, and uses those to estimate the degree of variability each variable contributes to the model output. It can be used to give a general idea of how the variables impact the model results, but it requires a closed-form representation of the model, and it cannot be used for models of even moderate complexity.

11.3.6 There are a number of ways to present information about the degree of uncertainty in an estimate. The most common are reporting a standard deviation of an estimate and reporting upper and lower confidence limits. In this case, where the distribution of damages is highly skewed and the present expected net benefits are also likely to be highly skewed, the reporting of upper and lower confidence limits are much more likely to be informative than the reporting of a standard deviation.

12. Select Strategies

12.1 *Rank Strategies:*

12.1.1 Rank the strategies for implementation, based on the measure(s) of economic performance, while considering any constraints and identified non-market considerations. Refer to the selected evaluation method(s) to determine the criterion for ranking strategies. Rankings can be performed across individual strategies or across combinations of strategies. Note, however, evaluating strategies either individually or jointly (in combinations) may produce a different ranking of cost-effective strategies. If applicable, note any rank reversals—that is, variation in rankings due to economic evaluation method used or changes in the composition of strategy combinations.

12.1.2 To the extent that the resilience strategies have no interacting effects and there exists no cost constraint, then the preferred set of individual strategies are those that have the largest positive net benefits. If a cost constraint exists, then the constrained-optimal set of measures are the combination of measures whose total cost is less than the cost constraint, and whose total net benefit is maximal. Note, that is a much more difficult problem.

12.1.3 Resilience strategies may have interacting effects. When these exist then the combinations of strategies should be jointly analyzed, especially when the adoption of one strategy forecloses the implementation of others, either now or in the future. In addition, when resilience strategies are mutually exclusive, they need to be explicitly considered.

12.2 *Plan Preparation, Review, and Approval* (See Guide E2204)*:*

12.2.1 Strategies are likely staged over a period of years so they can be fitted into the community's capital budgeting process. The presentation and analysis from the baseline analysis and sensitivity analysis are central to understanding and accepting the findings; they need to be carefully integrated into the community's resilience plan to promote a more complete understanding of its merits by key community decision-makers and stakeholders. If the presentation is clear and concise, and if the analysis strategy is logical, complete and carefully spelled out, then the results should stand up under close scrutiny.

12.2.2 The following are the key economic considerations that need to be integrated into the resilience plan: (*1*) recommend an alternative as the most cost-effective community resilience investment strategy; (*2*) provide a rationale for the recommendation, and include as part of the rationale findings from the baseline analysis and the sensitivity analysis; (*3*) if applicable, include a discussion of circumstances under which the recommended alternative did not have the best measure of economic performance; (*4*) describe any significant effects that remain unquantified, and explain how these effects impact the recommended alternative. Use Practice E1765 for guidance on how to present unquantified effects along with the computed values of the measures of economic performance.

12.3 *Plan Implementation and Maintenance:*

12.3.1 As the resilience plan moves into implementation, new information will become available on both costs and benefits. To insure that the resilience plan becomes an integral part of the community's economic development plan and other long-range plans that information needs to be updated and maintained. In addition, any spillover benefits not accounted for in the original plan should be documented along with any unintended consequences that detract from the merits of the plan.

13. Keywords

13.1 adjusted internal rate of return; analytical hierarchy process; building condition assessment; building economics; building systems; cost analysis; economic evaluation methods; economic impacts; engineering economics; homeland security; impact assessment; life-cycle costs; man-made hazards; measures of economic performance; Monte Carlo simulation; multi-attribute decision analysis; natural hazards; net savings; present-value analysis; project management; risk assessment; risk mitigation strategies; savings-to-investment ratio; sensitivity analysis; value engineering

APPENDIX

(Nonmandatory Information)

X1. EXAMPLE ILLUSTRATION OF EVALUATING COST-EFFECTIVENESS OF COMMUNITY RESILIENCE STRATEGIES

X1.1 Background

X1.1.1 This example demonstrates the process described in this guide. It is intended to be illustrative of the general process rather than an all-inclusive example. This example uses Practices E917 (life-cycle costs) and E1074 (net benefits and net savings) and Guides E1369 (treatment of uncertainty) and E2204 (summarize the results of economic evaluations involving natural, technological, and human-caused hazards).

X1.1.2 Riverbend is a small city with a population of approximately 50 000. It is situated in a valley along the Central River and was settled by farmers and loggers over 160 years ago because of its surrounding fertile land for agriculture and abundant timber resources. The Riverbend economy consists of agriculture, manufacturing, finance, and real estate. It is a typical middle-class city with a median household income close to the national average. Over the past few years, the logging and mining industries have experienced a downturn; however, Riverbend has been successful in transforming its economy by attracting employers to its other growing economic sectors.

X1.1.3 The four-lane interstate bridge over the Central River between Riverbend and neighboring city, Fallsborough, was a major concern for the community because it was the only crossing that carried traffic and clean water into Riverbend from Fallsborough, and the traffic volume was higher than capacity. It operated below driver expectation during peak hours. This structure was vulnerable to both flood and earthquake hazards, and it served as a main link for emergency vehicles including fire and rescue, as well as for population egress.

X1.2 Select Candidate Strategies

X1.2.1 A planning team was formed from a number of stakeholder groups in the community. They met to discuss the current concern regarding the bridge, how these affect community goals and objectives, and to identify potential solutions. The Riverbend planning team considered two alternate plans to improve community resilience. Both alternatives were designed to increase resilience from flooding and earthquakes, which would result in a reduction of economic losses and loss of life, should a disaster occur.

X1.2.1.1 *Option 1: Upgrade Central River Bridge (retrofit option/seismic rehabilitation)*—Since the existing bridge was scheduled (and budgeted) to undergo a deck replacement in 10 years, there was an opportunity to complete a seismic upgrade that would also create greater resilience against flood conditions. Deck replacement requires closing the bridge, forcing a longer route for emergency services and regular traffic during renovation. The user cost of a longer detour and the deterioration of alternate route roads are losses that should be considered.

X1.2.1.2 *Option 2: Put in Second Bridge over Central River (new construction option consistent with seismic codes)*—The new bridge could be built in an offset alignment while maintaining the traffic on the existing bridge. In case of earthquakes, the new bridge will maintain the traffic. This second crossing would relieve congestion during high traffic periods when traffic volume exceeds the capacity of the bridge, and provide additional water supply that would benefit Riverbend's long-term development plans. The new bridge would meet the seismic, redundancy and strength requirements and would be designed to last 125 years. Also, the new bridge would allow for the traffic to be shifted when replacement of the existing bridge was required. In addition, it would include a non-motorized path. It is a best practice for communities to have alternative travel modes that enhance quality of life for its residents.

TABLE X1.1 Estimated Benefits and Costs Associated with Option 1: Retrofit

Class	Item	Timing	Estimate
Costs	Direct Construction Costs	Year 0	$3 000 000
	Indirect Construction Costs	Year 0	$500 000
Benefits	Direct Loss Reduction	If Earthquake Occurs	$260 000
	Indirect Loss Reduction	If Earthquake Occurs	$2 000 000
	Repair and Replacement Loss Reduction	If Earthquake Occurs	$600 000

TABLE X1.2 Estimated Benefits and Costs Associated with Option 2: New Bridge

Class	Item	Timing	Estimate
Costs	Bridge Construction Direct Costs	Year 0	$4 250 000
	Bridge Construction Indirect Costs	Year 0	$175 000
	Bridge Construction OMR Costs	Annually	$25 000
	Additional Roadwork Direct Costs	Year 0	$2 500 000
	Additional Roadwork Indirect Costs	Year 0	$150 000
	Additional Roadwork OMR Costs	Annually	$3710
Benefits	Indirect Loss Reduction	If Earthquake Occurs	$3 500 000
	Repair and Replacement Loss Reduction	If Earthquake Occurs	$1 000 000
	Reduced Commute Time	Annually	$100 000
Externalities	Reduced Greenhouse Gas Emissions	Annually	$77 326
	Reduced Water Pollution	Annually	$39 081
	Better Linking of Communities	Annually	$39 799

X1.3 Define Investment Objectives and Scope

X1.3.1 The planning team decided they would select the option that resulted in the largest PVNB over a 50-year planning horizon. No other constraints were identified.

X1.4 Identify Benefits and Costs

X1.4.1 A consultant was obtained to estimate the costs and benefits associated with each option. Tables X1.1 and X1.2 summarize the size and timing of the benefits and costs associated with each option. Option 2 was deemed to result in a number of positive externalities (for example, reduced water pollution) that the planning team wanted to include in the analysis. Note benefits that result from improvements in resilience are calculated using the expected value of the loss avoided, which are based on the hazard recurrence annualized over the study period, while the non-disaster-related benefits (that is, reduction in commute times) and externalities are calculated based on traditional cash flows.

X1.5 Identify Non-market Considerations

X1.5.1 Both options were determined to improve life-safety in the event of an earthquake. Option 1 was estimated to avert 0.1 fatalities. Option 2 was estimated to avert 0.2 fatalities. (Because the improvements are represented as reductions in risk, non-integer estimates of fatalities averted are possible.) Based on an assumed $7.5 million value of a statistical life, Option 1 yields an additional $750 000 in benefits, while Option 2 yields $1 500 000 in benefits. No sociocultural nor other environmental impacts were identified.

X1.6 Define Analysis Parameters

X1.6.1 The planning team used a real discount rate of 3 %. Funding for the project will come from the state; thereby, the economic analysis of the project must use the discount rate specified by state's department of transportation, which in this case is set at 3 %.[3] Follow Practice E917 for discounting. (All discounting was performed using continuous compounding.) Tables X1.3 and X1.4 provide definitions of the probability distributions assumed for the sensitivity analysis related to input of each option. In addition, the annual probability of a significant seismic event was determined to be 4 % or once every 25 years. The planners assumed risk-neutrality, making the expected value approach the appropriate choice.

X1.7 Perform Economic Evaluation

X1.7.1 Practice E1074 covers the recommended procedure to calculate net benefits. For this example, the PVNB are defined in Eq X1.1:

$$PVNB_{j,t} = \sum_{t=0}^{N} \frac{(B_{j,t} - C_{j,t})}{(1+i)^t} \qquad (X1.1)$$

where:

B = dollar value of benefits,
C = dollar value of costs,
i = discount rate,
j = indexes community resilience strategies,
t = indexes time periods, and
N = length of study period (here 50 years).

X1.7.2 The results of the baseline economic evaluation are shown in Table X1.5. While Option 2 costs more than twice of that for Option 1, it yields far greater benefits and positive externalities. The PVNB for Option 2 was estimated at $5 066 090, compared to $295 704 for Option 1, making the

[3] While the example presented in Appendix X1 is fictitious, the discount rate used is consistent with Jiang et al. (6) for projects funded by state's department of transportation.