DEVELOPMENT AND APPLICATION OF PROBABILISTIC DECISION SUPPORT FRAMEWORK FOR SEISMIC REHABILITATION OF STRUCTURAL SYSTEMS

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DEVELOPMENT AND APPLICATION OF PROBABILISTIC DECISION SUPPORT FRAMEWORK FOR SEISMIC REHABILITATION OF STRUCTURAL SYSTEMS

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SUMMARY

Seismic rehabilitation of structural systems is an effective approach for reducing potential seismic losses such as social and economic losses. However, little or no effort has been made to develop a framework for making decisions on seismic rehabilitation of structural systems that systematically incorporates conflicting multiple criteria and uncertainties inherent in the seismic hazard and in the systems themselves.

This study develops a decision support framework for seismic rehabilitation of structural systems incorporating uncertainties inherent in both the system and the seismic hazard, and demonstrates its application with detailed examples. The decision support framework developed utilizes the HAZUS method for a quick and extensive estimation of seismic losses associated with structural systems. The decision support framework allows consideration of multiple decision attributes associated with seismic losses, and multiple alternative seismic rehabilitation schemes represented by the objective performance level. Three multi-criteria decision models (MCDM) that are known to be effective for decision problems under uncertainty are employed and their applicability for decision analyses in seismic rehabilitation is investigated. These models are Equivalent Cost Analysis (ECA), Multi-Attribute Utility Theory (MAUT), and Joint Probability Decision Making (JPDM). Guidelines for selection of a MCDM that is appropriate for a given decision problem are provided to establish a flexible decision support system. The resulting decision support framework is applied to a test bed system that consists of six hospitals located in the Memphis, Tennessee, area to demonstrate its capabilities.

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Our decisions shape our lives (Hammond et al., 1999). It is fair to say that anyone's life is formed by countless decisions. People make decisions on either easy or difficult matters in numerous ways. Among them, engineering decisions can be important to society and more difficult to make because of their considerable social and economic impacts on large numbers of people. This statement applies even more so to the field of earthquake engineering because the consequences of an earthquake can involve significant loss of life along with substantial economic loss.

An earthquake is a catastrophic event that can result in substantial losses of various kinds, including economic and social losses. However, because of the low probability of large earthquakes, structural systems are often constructed without extensive consideration of seismic consequences. This tendency is even greater in Mid-America (Central and Southeastern United States) than on the West Coast because of the lower probability of major earthquakes in the region. Therefore, the vulnerability of many structural systems in this region is even higher because of the lack of consideration of the lateral seismic force.

The possible consequences due to earthquakes, however, can be reduced with appropriate intervention actions. Decisions about intervention schemes to be applied to structural systems to reduce earthquake risk are complex and difficult to make because they may not solely depend on structural performance and/or direct structural cost. In fact, they usually involve a large number of other factors, such as life losses and secondary economic losses.

Numerous researchers have studied the problem of making appropriate decisions about seismic intervention for various structural systems. For example, Ang and De Leon (1997) performed a decision analysis for identification of the optimal target reliability level for rehabilitation of a building structure against seismic hazard. Various seismic losses (e.g., building repair cost and loss of life) are estimated from probabilistically assessed damage index of a building calibrated with historic data. The seismic losses are then converted to equivalent cost and the reliability level that produces minimum expected cost is calculated. Benthien and Winterfeldt (2002) developed a decision analysis framework to find the best solution among several alternative rehabilitation schemes. They considered multiple objectives and combined the building fragility curves with a financial cost model to find an alternative with lowest overall expected cost. Both studies, however, focused on the decision analysis itself, using a fixed decision model based on financial cost. Unfortunately, research on development of a decision support framework that can be customized to meet the needs of a wide range of decision makers while allowing a flexible choice of decision models is scarce in the field of earthquake engineering.

This study develops a decision support framework for making decisions about appropriate structural interventions against seismic hazard, along with its application to the Mid-America region. Winterfeldt and Edwards (1986) offer the following definitions regarding a decision support system: “A management information system is the one that organizes the information the decision maker needs in such a way that it is accessible and easy to understand. A decision support system is a management information system that also has some processing capability designed to help the decision maker use the information." The decision support system presented herein is an extensive procedure for generating data for making decisions on seismic rehabilitation of structural systems, and to support the decision process itself. The Mid America Earthquake Center (MAEC, 2002) is currently developing an interactive visualization system (named MAEViz) for risk assessment across regions using advanced data mining tools. This study develops a probabilistic decision framework, in which data that can inform and improve seismic rehabilitation decisions for structural systems are identified and manipulated, such that they can be incorporated into the visualization system being developed by MAEC. The intention of this decision support system is that it be used by stakeholders with technical assistance, to minimize expected life and economic losses from earthquakes in regions of low probability and high consequence earthquakes such as Mid-America, and maximize decision maker's other objectives in this context.

1.1.1 Consequence Based Engineering

Consequence based engineering (CBE) is a new paradigm proposed by the Mid-America Earthquake Center to provide practicing engineers with a new approach for minimizing losses to human life and property, and also indirect losses associated with business interruption (Abrams et al., 2004). Use of CBE should result in better-informed earthquake mitigation decisions and in reduced risk. The main objective of CBE is to identify critical components of the system within a region of interest and inform decision makers of effective interventions and the expected benefits thereof to minimize seismic risks. It should be noted that CBE is intended to be applied to minimize the risk across an entire system of interest as opposed to a performance based engineering approach where the performance of a single structure is usually of main interest. The adverse consequences of an earthquake on such a group of buildings within a region can potentially be reduced more effectively by providing intervention schemes available to selected classes of buildings (e.g., based on building usage or structural type) rather than applying various interventions to every single building.

One important aspect of the CBE process is the treatment of uncertainty. Uncertainty comes from a number of sources such as unknown or uncertain values of material properties, structural dimensions, and mass or mass distribution, as well as unknown or variable construction practices, the random nature of earthquake excitation, etc. Therefore, uncertainty must be considered and integrated into the decision process.

While CBE provides a well-conceived paradigm for mitigation of earthquake risks, the overall concept of the CBE is intended to be flexible and is open to change and improvement. For example, the current CBE implicitly assumes that the stakeholder is solely in charge of defining the acceptance level of consequences. In reality, however, defining the acceptance level is not a simple task because the definition of acceptable levels of consequences usually impacts a large number of people, either directly or indirectly, and their interests must be included in the decision framework (Bostrom et al., 2003).

1.1.2 Need of Decision Support in CBE

Making technical decisions is a necessary part of engineering planning and design (Ang & Tang, 1984). This statement is true in CBE as well, because every action within the CBE process is taken such that the benefit can be maximized with minimum cost, and this goal can only be achieved with good decision making process at each stage of the CBE process. A good decision making process is the one that leads you to the best solution with a minimal loss of time, energy, money, and composure (Hammond et al., 1999). The term ‘benefit’ and ‘cost’ have broad meanings because they can be defined differently depending on the concerns of the decision maker. Decision problems in the CBE framework generally require the consideration of non-technical factors, such as social preference or acceptance, environmental impact, and sometimes even political implications, depending on what kinds of decision makers are involved in the problem. For example, insurance executives will be most concerned about the profit they can make, whereas the city manager may be more concerned about citizens’ welfare and the continued function of the city. Moreover, the number of attributes of concern to a decision maker is usually more than one, and these attributes are generally conflicting with each other. Good decision-making requires superior insight into the system of interest and clear identification of the values of multiple attributes involved in the problem, and the role of a decision support tool is to fulfill these requirements.

1.2 Research Issues

Having recognized the general requirements of a decision support system mentioned in the previous section, what specific issues must be considered for decision problems on seismic rehabilitation of structural systems? The potential problems and barriers involved in decision-making in seismic rehabilitation of structural systems must be identified so that the decision support tool can be tailored to the specific field of interest.

First, the decision problems in seismic rehabilitation of structural systems generally have more than one criterion (or objective). If there is only one criterion for a decision problem, the formulation and the analysis of the decision problem will be relatively easy. However, in reality, a general decision problem has more than one criterion, and these criteria often conflict. A decision problem with more than one criterion is called a multi-criteria decision-making (MCDM) problem. In MCDM problems, conflicts often arise from the desire to achieve more functionality in a system, which, however, generally costs more. Another conflict can result from the use of different units of measure. For instance, the construction cost of a fire station can be measured in dollars, whereas the functionality of the fire station can be measured by the number of available fire engines or the number of personnel. Here, the relative importance of each value is different as well. Conflicting multiple criteria and different units usually make the decision more difficult and more complex.

Second, uncertainties inherent in the problem must be considered. Uncertainty exists in most engineering decision problems and makes the decision more difficult. In problems of seismic rehabilitation of structural systems, uncertainties (either epistemic or aleatory) exist in hazard demand, assessment of structural capacity and damage, and various social and economic factors associated with the loss estimation. In order to cope with this uncertainty, one needs explicit measurement of uncertainties so that rational criteria for trade-offs can be provided. Unless solutions on how to measure uncertainty and how to manipulate the measured uncertainty are available, a good decision support process cannot be developed.

The third issue to be considered is the fact that earthquakes are events with low probability but high consequences. As a result, the probability distributions of the consequences usually have a high degree of skewness. In this case, the conventional expected value approach for decision analysis does not account for risk aversion, in other words, the fact that the decision maker may want to avoid possible extreme high consequences even though the probability is very low. Therefore, analyses and data that explicitly account for the probabilistic characteristics and show the consequences of different levels of earthquake must be available in order to give the decision maker a better idea of the seismic consequences associated with the structural system of interest.

The last consideration is that the decision maker should be able to choose from a variety of multi-criteria decision making (MCDM) models. A decision support system must be developed in such a way that the decision maker can select a MCDM model that is appropriate to a given decision problem. To accomplish this, the decision support system must utilize multiple MCDM models that are known to be effective in decision problems with uncertainty and guidelines must be provided for selection of an appropriate MCDM model.

1.3 Research Objectives

Taking the issues mentioned above into consideration, the objectives of this study are stated as follows:

- Investigate how to incorporate social and economic attributes associated with decision problems on seismic rehabilitation of structures and their quantification into the decision analysis and the decision support tool.

- Explore uncertainty inherent in seismic hazard, structural response, structural damage assessment, social and economic loss estimation, and decision-making, and identify methods to incorporate the high degree of uncertainty into the decision support framework.
- Explore multi-criteria decision-making (MCDM) models and theories for problems with uncertainty, identify advantages and disadvantages in their application to decision problems in seismic rehabilitation of structural systems, and present a guideline for selection of a MCDM model appropriate to a given decision problem.
- Develop a decision support framework for seismic rehabilitation of structural systems that effectively shows the consequences due to different levels of earthquakes and compares the results among multiple alternative rehabilitation schemes.
- Apply the decision support framework to a realistic, comprehensive decision problem for seismic rehabilitation of structural systems, and examine the possible differences and impacts in decisions that might arise from the choice of decision models.
- Perform sensitivity analyses to demonstrate how to identify factors and assumptions that are likely to significantly affect decisions for the particular application.

With the aid of decision support, a decision maker can have better insight into the problem by clarifying his/her values and objectives, identifying a set of alternatives and their consequences with uncertainties incorporated, and identifying the possible trade-offs thereafter.

1.4 Outline of Thesis

This thesis consists of nine chapters, which are organized as follows:

Chapter 1 presents the problem statement, research issues and objectives.

Chapter 2 introduces the basic knowledge of decision analysis and discusses factors that need to be considered for decision analysis applications in this thesis.

Chapter 3 introduces the MCDM models that are used in this study and discusses their dynamic aspects in reconfiguration of values and in manipulating the probability distribution, followed by identification of strengths and weaknesses of each model for use in this study.

Chapter 4 investigates the methods for probabilistic evaluation of seismic performance of structural systems. Issues include uncertainties in hazard definition and structural capacity assessment, structural modeling, and stochastic analysis of structures.

Chapter 5 formulates the decision procedure for seismic rehabilitation of structural systems and the techniques and theories required for each step are identified .

Chapters 6, 7, and 8 present applications of the decision support framework using the three different MCDM models explored in Chapter 3 to hospital systems in the Memphis, Tennessee area, and also address the effect of dynamic decision analysis.

Chapter 9 critically evaluates the decision support framework developed in this study. The functionalities and limitations of the decision support framework are identified and the use of the integrated decision support framework is demonstrated with examples.

Finally, Chapter 10 presents a summary and suggestions for future work.

CHAPTER 2

BACKGROUND ON DECISION ANALYSIS

There are two major questions in decision research, regardless of the fields that the problems are associated with. The first question is ‘how do people make decisions?’ and research in this area focuses on what is called ‘descriptive decision theories.’ The second question in decision research is ‘how should decisions be made?’ and research addresses what are often termed ‘normative decision theories’ or ‘prescriptive decision theories’ (Edwards and Fasolo, 2001). In this chapter, the basic elements in decision analyses (applicable to both descriptive and prescriptive) are briefly discussed along with simple examples.

2.1 Basic Elements of Decision Analysis

According to Hammond et al. (1999), “an effective decision-making process should focus on what’s important, be logical and consistent, acknowledge both subjective and objective factors, blend analytical with intuitive thinking, require only as much information and analysis as is necessary to resolve a particular dilemma, encourage and guide the gathering of relevant information and informed opinion, and be straightforward, reliable, easy to use, and flexible.” Based on the above criteria, Hammond et al. suggest an approach for making decisions called ‘PrOACT’, which stands for Problem, Objectives, Alternatives, Consequences, and Tradeoffs. These are the main elements of an effective decision-making process. This general approach is applicable to an engineering decision problem, and the development of the decision support framework in this study is also based on this approach. The whole issue of decision analysis is about how to define and coordinate these elements to construct an appropriate decision structure for a specific problem. The basic elements of decision analysis are discussed in the following sub sections and an illustrative example is added throughout.

2.1.1 Problem

Identifying the problem is the starting point of the decision process. “A good solution to a well-posed decision problem is almost always a smarter choice than an excellent solution to a poorly posed one (Hammond et. al, 1999)”. Without well-structured understanding of the nature of the problem, an effective and rational decision can never be made no matter how good a decision-making tool is used for the problem. Sometimes even the decision maker does not know exactly what his or her problem is in the initial phase (Winterfeldt and Edwards, 1986). Since defining the problem is the first and the most important step of the decision analysis, it is crucial for the person who performs the decision analysis (decision analyst and/or engineer) to have early interviews with the decision maker to gain further insight into the problem. Failure to arrive at a solid definition of the problem will result in a poor decision. Considering the opinions of others or reexamination of the problem definition will also help to formulate the right decision problem.

A fire station example

A local government of a region must solve the problem of a fire station, which has structural vulnerability to seismic excitation. Of course, the characteristics of earthquakes within the region have to be identified first and a set of representative earthquakes, to be used in the decision analysis, should be provided. If the fire station loses its functionality in an earthquake, the secondary effect of the earthquake will be larger because of the absence of the rescue actions expected from the fire station. The local government comes to the decision analyst (engineer or CBE professional) and asks for a solution. The triggering problem here is, 'how can we make sure the fire station stays intact after an earthquake?' However, this statement can be revised to include broader thinking such as 'how can we ensure that the fire station services can be effectively delivered after an earthquake?' because the ultimate objective of the local government may be to reduce the secondary loss, not simply to strengthen the fire station. This change of the problem statement addresses the consequences rather than simply the performance of the building and will affect the accompanying elements such as objectives, alternatives, etc, potentially resulting in different decisions, as will be seen in the following sections.

2.1.2 Objectives and Attributes

Once the decision problem is formulated, the next step is to clarify the decision maker's objectives. The decision criteria derive from the objectives, which are what the decision analysis is intended to help achieve. In decision problems related to seismic rehabilitation, the decision maker's objective would typically be minimizing the overall seismic loss. In general, there are several types of seismic losses and these can be considered to be the attributes in the decision analysis. Possible criteria for decision problems on seismic rehabilitation of structural systems may include monetary loss such as rehabilitation cost, repair cost, building relocation cost, loss of rent, etc. Life loss (death) and/or injury can be another major attribute. Building functionality can be of great concern as well, especially for essential facilities such as fire stations, hospitals, etc.

In addition, other attributes not mentioned above may include time for construction or aesthetics.

Even though a set of attributes are identified and the decision problem established, it is necessary to refine the attributes and corresponding objectives further after the problem is identified because the objectives will directly affect formulation of the alternatives. That is, careful identification of objectives can improve the formulation of alternatives (Corner et al., 2001). Conversely, defining better alternatives will aid in refining objectives. As a result, dynamic interaction in defining the objectives and alternatives can improve the quality of decisions. This issue will be discussed in more detail in Section 2.4.

A fire station example- continued

Continuing with the example of the previous section, the assumed objective of the decision problem is to reduce the expected secondary effects of an earthquake possibly through rehabilitation of the fire station. In addition, because of limited resources, it is assumed that the rehabilitation cost has to be minimized. Thus, for illustrative purposes, the objectives for this example are identified as follows:

1) Maximize the functionality of the fire station after the occurrence of a major earthquake.
2) Maximize the accessibility to the community from the fire station
3) Minimize the monetary cost needed for rehabilitating, repairing, moving, etc., the fire station.

One important issue in decision analysis is determination of metrics for non-monetary value. For example, the functionality of the fire station can be represented by the percentage of available fire engines and/or personnel. The accessibility can be estimated by the percentage of available roads (possibly weighted by importance) the fire engines must take to reach damaged sites within the area that the fire station is responsible for. Note that even if the fire station remains fully functional after an earthquake, if the equipment and the personnel from the fire station cannot reach damaged sites due to collapse of a bridge nearby, the functionality of the fire station itself will not be meaningful. It should be noted that the second objective would not be included if the problem statement were confined to 'how to make sure the fire station stays intact after an earthquake', rather than 'how to ensure that fire station services can be delivered after an earthquake.'

2.1.3 Alternatives

The alternatives are the options that the decision maker can choose from in pursuit of the objectives. For there to be a decision, there must be at least two alternatives. Failure to identify well-constructed alternatives will mean that the best decision cannot be made. A best alternative can never be chosen if it is not considered. Therefore, the alternatives have to be identified with great caution in the formulation of a successful decision analysis.

A large number of alternatives can be considered for seismic rehabilitation of structural systems and effective rehabilitation schemes can be identified based on the type of the structure. For example, for masonry structures, which are considered to be highly vulnerable to earthquake but still constitute a large portion of residential facilities in many areas of the world, the seismic risk can be reduced by reducing asymmetry, improving the connections, strengthening the walls, strengthening the diaphragms, or strengthening the foundations. For reinforced concrete structures, strength can be provided to the structure by adding shear walls, strengthening the principal members and connections, etc (Coburn et al., 1992).

The above mentioned rehabilitation schemes are known to be effective in terms of the structural performance, or physical damage of the structure. However, as mentioned in Section 2.1.2, the decision must be made considering not only the structural performance but also many other criteria such as monetary cost.

A fire station example - continued

Based on the above list of objectives, the following set of generic alternatives is provided with technical assistance from experts such as structural engineers.

1) *Demolish and reconstruct the fire station*: in this case, generally the best seismic performance can be expected if the fire station is reconstructed based on the most recent seismic code. However, this option can also entail high initial construction cost and long construction times.
2) *Provide structural rehabilitation of the fire station*: without major destruction of the structure, some level of strength can be assured by providing rehabilitation. Depending on the type of the rehabilitation, the building can remain functional during the rehabilitation process.
3) *Move the fire station to another location*: this option can prevent possible deterioration of the functionality of the fire station that could be caused by construction. However, high costs are to be expected for purchasing a building located elsewhere and moving the furnishings and equipment to the new location.

4) *Do nothing and leave everything as it is*

In fact, there are a number of sub options for the second alternative as various rehabilitation schemes are available, and each of them must be counted as an alternative. However, for simplicity, it is assumed in this chapter that there is only one rehabilitation scheme available. This also holds for the demolition and reconstruction, and relocation options.

2.1.4 Consequences

The better the consequences are predicted, the better the resulting decision, in general. In many cases a decision will become obvious if consequences are well described. However, for earthquakes, it is impossible to predict the consequences deterministically. Uncertainty is an integral part of the decision to be made. The treatment of uncertainty is discussed in more detail in Section 2.3 and later chapters.

A fire station example - continued

The anticipated consequences for possible earthquakes in the region for the alternatives listed above can be estimated using past research results in earthquake engineering. Table 2.1 shows the consequence table for the fire station problem. For now, uncertainty inherent in the problem is not considered and it is assumed that all consequences are measured deterministically (problems including uncertainty will be dealt with in the examples in later chapters). As discussed previously, the functionality of the fire station is measured by the percentage of available fire engines or personnel in the fire station, and the accessibility is measured by the percentage of available roads (weighted by importance) the fire engines can take to reach damaged sites within the area that the fire station is responsible for. Note that the consequences listed in the table are the expected values considering the probability of seismic activity. For example, the expected monetary cost for ‘Do Nothing’ is calculated considering the repair cost due to possible earthquakes even though no initial cost is expected for the option.

Table 2.1. Consequence Table for the Firehouse Example

	Loss of Function (%)	Loss of Accessibility (%)	Dollar Cost (M$)
Rebuild	2%	30%	1.5
Rehabilitate	6%	30%	0.6
Move	9%	10%	1.0
Do nothing	13%	30%	1.2

2.1.5 Trade-offs

Since earthquake risk problems include more than one objective, we usually have to deal with conflicting objectives. In many cases, an alternative may be better than any other in meeting some objectives, but worse in satisfying others. Analyzing such trade-offs requires considering the decision maker’s valuation of the attributes of the decision problem. Hence, a well-defined decision analysis tool must provide a method to aid the decision maker in evaluating the alternatives by considering the value and weight assigned to each objective, including trade-offs between the objectives.

A fire station example- continued

As Table 2.1 shows, there is no straightforward way to identify which option is best. For instance, in terms of functionality, rebuilding the fire station will be the best option, whereas moving the fire station to a new location is the best option in terms of accessibility. When it comes to dollar cost, rehabilitating the fire station will be less expensive than any other option. However, the best option among the four alternatives can still be chosen. First, we can reduce the number of options by eliminating the dominated options. In this example, the 'do nothing' option is apparently dominated by the 'rehabilitate' option, that is, none of the consequences from the 'do nothing' option are better than those from the 'rehabilitate' option. Therefore, we can eliminate the 'do nothing' option. Now three options remain and none of them is dominated. At this point the decision maker must make trade-offs. Effective trade-offs among multiple objectives can be aided by multi-criteria decision-making (MCDM) models. In Chapter 3, a number of MCDM models that are especially useful for cases where uncertainties are incorporated, such as in this study, are discussed.

2.2 Value

Winterfeldt and Edwards (1987) define the term 'value' as follows: "*values are abstractions that help organize and guide preferences. They are most often expressed as statements of desired states, positive intentions, or preferred directions. The actions or objects of value may be such diverse things as social policies, marketing strategies, or individual consumer choices.*" Values are subjective and reflect the decision maker's unique thought on the importance of specific attributes. Decisions on seismic rehabilitation are made from a set of alternatives and depend on the values assigned to the attributes of each alternative. It is obvious that how an attribute is valued can differ greatly from one person to another.

A fire station example

In the fire station example, the decision maker who is more concerned about monetary cost is likely to choose the “Rehabilitation” option. In contrast, if the decision maker were more concerned about the function of the fire station, he or she would consider either the “Rebuild” option. To perform an effective decision analysis, it is important to quantify decision maker’s values associated with a decision problem. Detailed issues on quantification of different values are discussed in Chapter 3.

2.3 Probability and Uncertainty

Not surprisingly, decisions in earthquake engineering are based on uncertain predictions due to information that invariably entails uncertainty (Ang & Tang, 1984). The fundamental step for making good decisions in problems under uncertainty is to acknowledge the existence of the uncertainties. A large number of sources of uncertainty arise in design and assessment of engineering systems and various hazards, and impact technical, economic and social decisions (Wen et al., 2003). The quantification and assessment of the probability associated with various outcomes can be achieved by using personal judgment, consulting existing information, collecting new data, or asking experts (Hammond et al., 1999). A good way of manipulating this information must be accompanied in order to measure the outcomes of the problem systematically. Through probabilistic modeling and analysis, uncertainties may be modeled and assessed consistently, and their effects on a given decision can be accounted for systematically

(Ang & Tang, 1984). In this study, uncertainties inherent in seismic inputs, assessment of structural capacity and damage, and social and economic loss estimations are taken into account, and the corresponding random variables are identified and described probabilistically. The consequences will then be estimated and if the mathematical expressions for the probabilistic estimation of the consequences are not explicitly available, simulation techniques such as Monte Carlo simulation (Kleijnen, 1974) will be used. More details about treatment of uncertainty in this study are discussed and revisited in the chapters that follow.

2.4 Dynamic Decision-making

Structuring of the decision problem is the most important activity in the decision-making process (Corner et al., 2001). Two different ways to structure decision problems are value-focused thinking (VFT) and alternative-focused thinking (AFT). In VFT, decision criteria are identified first, then decision alternatives are designed taking into account the criteria, and finally a selection is made. In AFT, the values and preferences of the decision maker are identified from the pre-specified available alternatives, and then the best alternative is selected. However, both methods are static because once the alternatives and the decision criteria are defined following either of above procedures, they remain unchanged until the decision is made. Corner et al. (2001) propose a dynamic way of thinking about problem structuring, in which the interactive nature of criteria and alternatives is considered. That is, thinking about alternatives helps generate criteria, and vice versa. Neither AFT nor VFT can be effective alone, independent of the other. Figure 2.1 shows the concept of this dynamic approach to decision problem structuring. The key idea of dynamic decision problem structuring is that the decision makers learn as they redefine their values and iteratively search for the corresponding alternatives, and this is then incorporated within the framework.

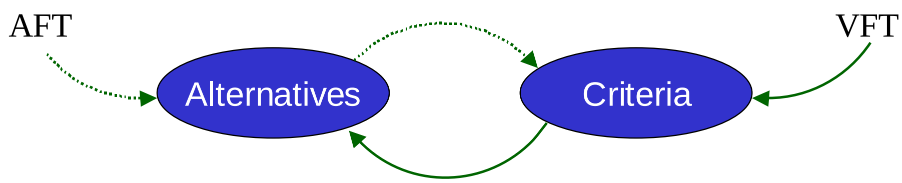


Figure 2.1 A dynamic approach to decision problem structuring (Corner et al., 2001)

<u>A fire station example - continued</u>

The fire station example discussed throughout the previous sections is static because the alternatives are given based on pre-defined criteria, which are functionality, accessibility, and dollar cost. Assume the 'move' option is chosen as the best option. That is, 'Move' is the best option based on the decision criteria described in Section 2.1.2. This implies that the decision maker would be concerned more with accessibility than other attributes. However, as consequences are estimated and the decision maker is informed more on the problem, the value of the decision maker may change. For example, the decision maker may become more stringent on functionality because the estimated loss to the community due to lack of the rescue activity of the fire station turns out to be substantial. Moreover, criteria that have not been initially considered might be newly taken into account as well (e.g., aesthetics or working environment). As a result, the alternatives must be re-evaluated based on the updated value, and expanded set of alternatives might have to be considered as well.

Unexpected changes in surrounding systems or environment would require dynamic decision-making as well. For example, news can be heard a day after the decision is made saying that a bridge nearby will be strengthened so that it can remain functional in case of an earthquake. With the bridge strengthened, the expected accessibility of the location of the current fire station would be improved. As a result, a change in decision might result from the updated estimation of consequences. .

CHAPTER 3

REVIEW OF MCDM MODELS FOR PROBLEMS UNDER UNCERTAINTY

If there is only one criterion for a decision problem, the formulation and the analysis of the decision problem will be relatively straightforward. However, in reality, decision problems generally have more than one criterion, and these criteria conflict. A decision problem with more than one criterion is called a multi criteria decision-making (MCDM) problem. In structural seismic rehabilitation, for example, achievement of better seismic performance costs more. Another problem in multi criteria decision-making is comparing different measurement units. For instance, the construction cost of a fire station will generally be measured in dollars, whereas the functionality of the fire station is more readily measured by the number of available fire engines or personnel. In addition, the relative importance of each of these is likely to differ.

Over the past 30 years, many MCDM models, theories, algorithms, and applications have been developed in various fields, such as management, economics, psychology, engineering, and medicine. (e.g., Gal et al., 1999, Triantaphyllou, 2000, Keeney and Raiffa, 1993, Sen and Yang, 1998, and Pomerol and Barba-Romero, 2000). According to Triantaphyllou (2000), one way of classifying MCDM methods is by the type of data they use. For instance, some MCDM methods can only deal with deterministic data, whereas some are capable of handling data both with and without uncertainty. Another way of classifying MCDM methods is based on the number of decision makers involved in the process: either a single decision maker or a group of decision makers. In this study, it is assumed that there is a single decision maker, though in practice this may not be the case.

In the following subsections, MCDM models that can incorporate uncertainties are discussed. These include: equivalent cost analysis (ECA, frequently called cost-benefit analysis), Multi Attribute Utility Theory (MAUT) and Joint Probability Decision-making (JPDM). These models are known to be applicable to problems under uncertainty. However, their approaches to value measurement and decision criteria differ. ECA and MAUT are MCDM models that have been widely used in the field of decision analysis, whereas JPDM is a relatively new decision model originally developed for probabilistic system design (Bandte, 2000). The theories for these models are briefly introduced, and their capabilities and functionalities illustrated with simple examples. The advantages and disadvantages of the models for decision problems in seismic rehabilitation of structural systems are also discussed. In addition, a defect of JPDM regarding treatment of relative weights is identified and an alternative approach is suggested to overcome this defect.

3.1 MCDM Models

For ease of discussion of MCDM models, the decision problem of seismic intervention of the fire station that has been covered in the last chapter is re-visited throughout this chapter. The seismic consequence of the fire station is estimated first and the results are used as inputs for discussion of each MCDM model.

3.1.1 Seismic Consequence Estimation of the Firehouse

A fire station example

In comparison to the fire station example in the previous chapter, a different sets of attributes and alternatives are considered in this chapter to illustrate the functionalities of the MCDM models more effectively. For simplicity, let's assume only two attributes are considered – monetary cost and functionality. Also assume that the available alternatives are "No Action", 'Rehabilitation', and "Rebuild". Note that fictitious hazard inputs and loss functions are used for the purpose of illustration in this example. For earthquake inputs, four levels of scenario earthquakes are considered and their corresponding probabilities of occurrence during the next 50 years are shown in Table 3.1. It is assumed that the structural damage probability of each alternative due to an earthquake is normally distributed. Note that the damage index ranges from 0 to 1, 0 indicating no damage and 1 indicating complete destruction. Table 3.1 shows the parameters for the probability distribution of the damage of each alternative corresponding to each level of earthquake. For example, if "No Action" is chosen (i.e., no rehabilitation action is provided to the existing structure), and a minor earthquake occurs, the anticipated probability distribution of the damage index of the structure is a normal distribution with a mean of 0.48 and a standard deviation of 0.072. This can be more intuitively seen in the decision tree shown in Figure 3.1.

The anticipated losses (repair cost and functional loss) can then be estimated from the assessed damage index using the assumed loss functions shown in Table 3.2. Note that the price fluctuation factor (I) is multiplied for calculation of the repair cost in order to consider the uncertainty in fluctuation of the price in the future. The price fluctuation factor is assumed to have a uniform distribution with the minimum value of 0.5 and the maximum value of 1.5. The initial cost required is \$0.0 for "No Action", \$1,300,000 for 'Rehabilitation', and \$3,000,000 for 'Rebuilding'.

Table 3.1 Probability Distributions of Damages of Alternative Systems for Different Levels of Earthquakes

EQ levels \ Alternative	No Action	Rehab	Rebuild
No EQ ($p=0.86$)	$D=0.0$	$D=0.0$	$D=0.0$
Minor ($p=0.08$)	$D \sim N(0.48,0.072)$	$D \sim N(0.3,0.048)$	$D \sim N(0.12,0.03)$
Moderate ($p=0.04$)	$D \sim N(0.64,0.096)$	$D \sim N(0.40,0.064)$	$D \sim N(0.16,0.04)$
Major ($p=0.02$)	$D \sim N(0.8,0.12)$	$D \sim N(0.5,0.08)$	$D \sim N(0.2,0.05)$

Table 3.2 Losses Expressed as a Function of Damage Index (denoted as *D*)

Repair Cost, C (\$)	$C = \$3{,}000{,}000 \cdot D \cdot I$ where, I = price fluctuation factor that follows $U(0.5,1.5)$
Functional loss, F (%)	$F = 100 \cdot D^2$

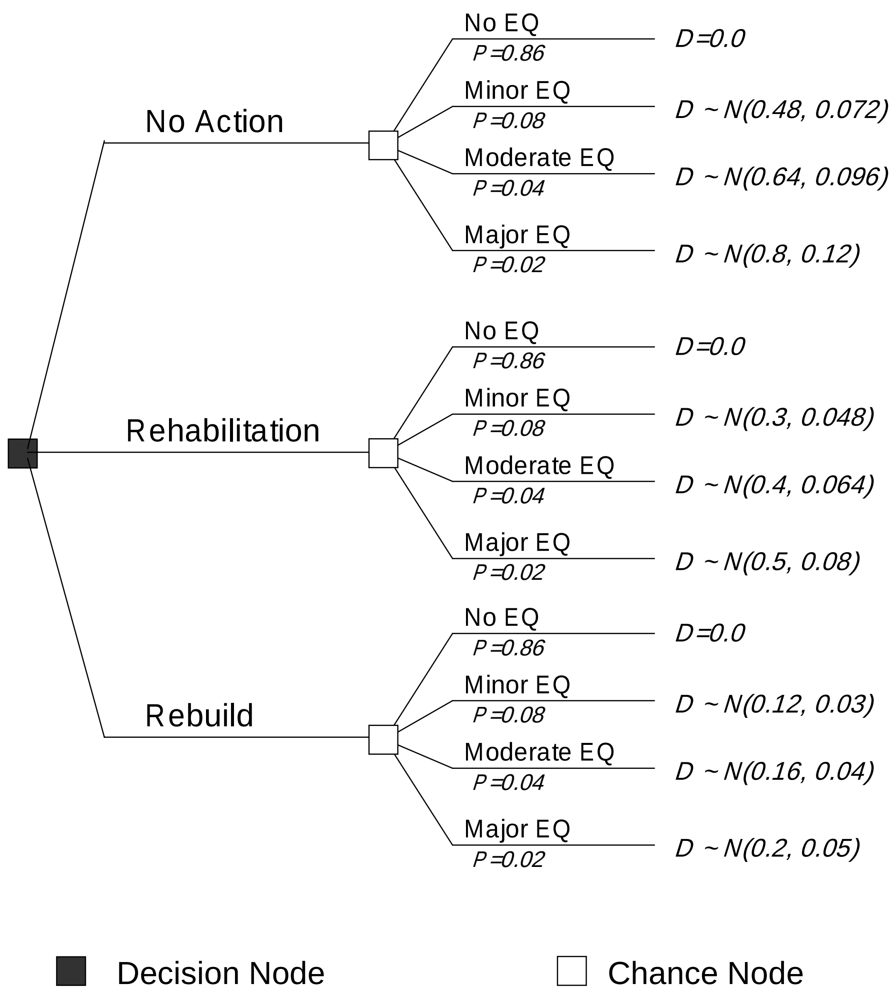
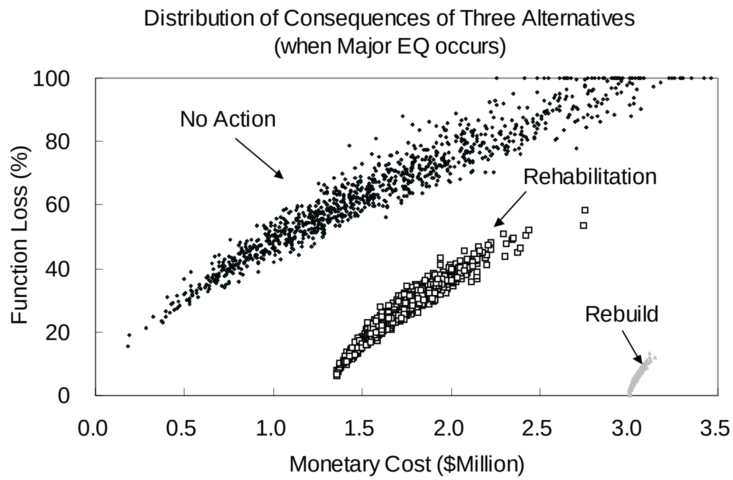


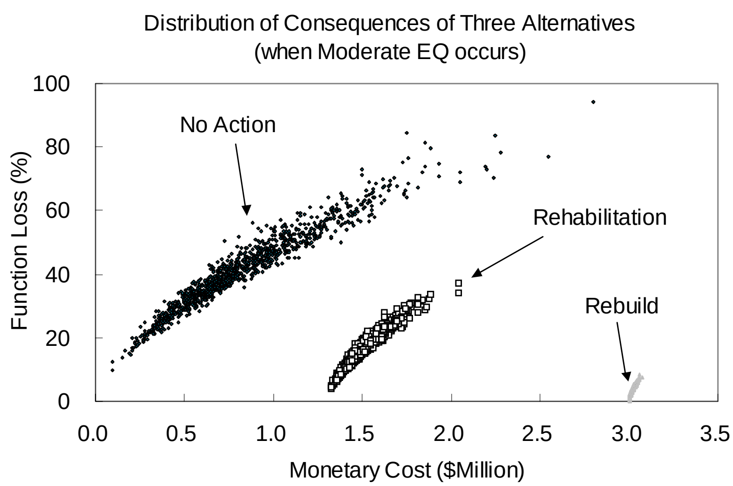
Figure 3.1 Decision Tree for Firehouse Example

The seismic losses are then probabilistically estimated. As shown in Table 3.2, the monetary loss is a function of building damage index (*D*) and price-fluctuation factor (*I*), whereas the function loss is a function of building damage index only. It is assumed that *D* and *I* are statistically independent each other. Since both the monetary loss and function loss are functions of D, they are not statistically independent, but have stochastic dependency among each other. To obtain the joint distribution of the losses, a Monte Carlo simulation (Kleijnen, 1974) is performed taking *D* and *I* as independent random variables. Crystal Ball (1998) is used as a tool for the Monte Carlo simulation. Crystal

Ball is a computer simulation tool that can be used in the analysis of the risks and uncertainties. In addition to classical Monte Carlo sampling technique, Crystal Ball also supports Latin Hypercube sampling (Imam and Conover, 1980) for computing efficiency. In the examples throughout this chapter, Latin Hypercube sampling technique is used with 1,000 intervals. Note that a large number of intervals is chosen for more refined visualization of the probability distributions. As a result of the simulation, the distributions of the consequences of the three alternative systems due to various levels of earthquakes are obtained as shown in Figure 3.2. Note that the monetary loss estimated includes both initial cost and repair cost. Therefore, the distribution of the monetary loss of ‘Rehabilitation’ and “Rebuild” have minimum value of $1,300,000 and $3,000,000, respectively, which are same as their initial costs.

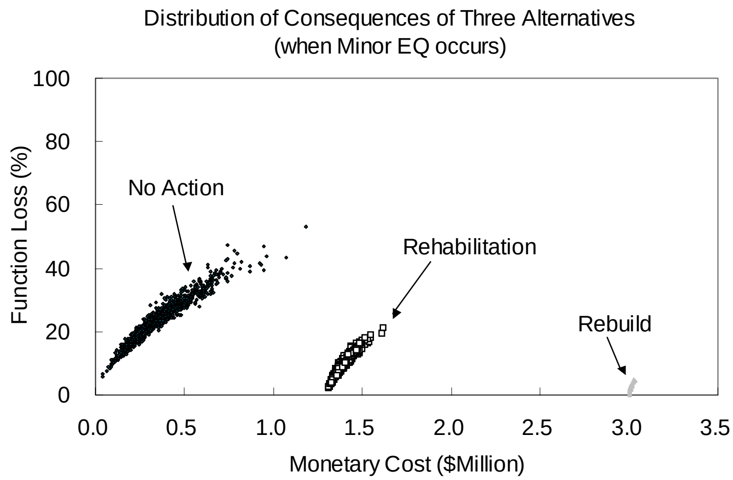


(a) when Major EQ occurs

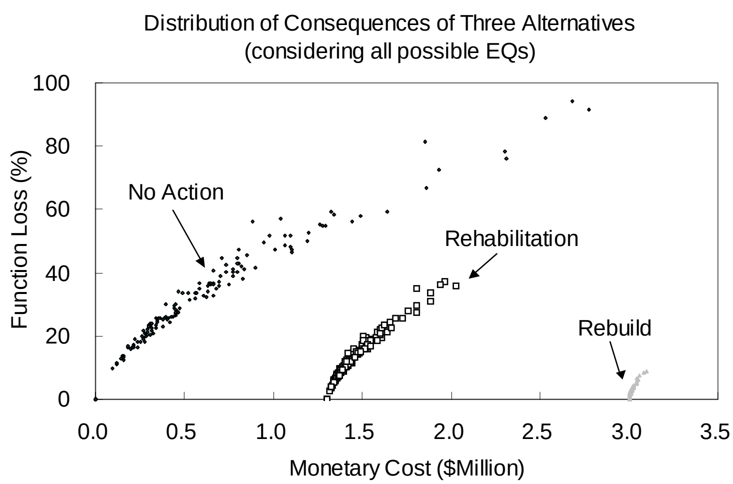


(b) when Moderate EQ occurs

Figure 3.2 Distribution of Consequences of Three Alternatives due to Different Levels of Earthquakes



(c) when Minor EQ occurs



(d) considering all possible earthquake levels

Figure 3.2 Distribution of Consequences of Three Alternatives due to Different Levels of Earthquakes - continued

Although the losses (both monetary and function losses) are relatively high for each earthquake scenario (Figure 3.2(a)–(c)), the overall expected losses considering all possible levels of earthquakes along with their probabilities would become considerably less because the event of an earthquake itself has a very low probability of occurrence. In fact, the probability of not having an earthquake at all in the next 50 years is 86%, for this example. Therefore, in Figure 3.2(d), 86% of the consequences of each alternative fall into the point where the monetary loss is the initial cost and the function loss is zero (i.e., ($0.0, 0.0%) for "No Action", ($1.3M, 0.0%) for "Rehab", and ($3.0, 0.0%) for "Rebuild"). The overall expected losses of the alternatives considering the probability of the occurrence of earthquakes are then calculated as shown in Table 3.3. "No Action" has the lowest expected monetary cost but the highest expected loss of function, whereas "Rebuild" has the lowest expected loss of function but highest expected monetary cost. Both losses for 'Rehabilitation' lie in between.

Table 3.3 Overall Expected Losses of the Alternatives (considering all EQ levels)

Losses / Alternatives	Initial + Repair Cost	Loss of Function
No Action	**$ 0.093 M**	4.856 %
Rehabilitation	$ 1.322 M	1.869 %
Rebuild	$ 3.002 M	**0.319 %**

Among the alternatives, "No Action" would be chosen if a decision is to be made based on minimum monetary cost criterion, whereas "Rebuild" would be chosen based on minimum function loss criterion. What would be chosen if both monetary and function loss must be considered at the same time? The following sections discuss this issue demonstrating three different MCDM models. The seismic losses estimated in this section will be used as inputs for the decision analyses.

3.1.2 Equivalent Cost Analysis

As mentioned earlier, many engineering decision problems include multiple criteria, or objectives. The consequences associated with these criteria may be measured in different units (e.g., temperature, time, etc). Often, consequences measured in different units are converted into a single composite measure – usually a monetary measure – by introducing conversion factors. For example, number of days of construction delay can be priced out in terms of monetary value. Decision analysis using this technique is called 'cost-benefit' analysis (Keeney and Raiffa, 1993). However, it is called 'equivalent cost analysis' in this study because in decision problems regarding seismic events, such problems are more readily formulated as loss minimization rather than benefit maximization. In equivalent cost analysis, all consequences are priced out and summed up to yield an overall consequence expressed as a monetary value. The alternative with minimum expected overall cost, or maximum expected overall benefit (in terms of monetary value) is preferred. Not surprisingly, many decision analyses use this method since it is easy to estimate and compare consequences with this method. Cost-benefit analysis gives the decision maker a clear picture of consequences. However, there are several problems with this method (Keeney and Raiffa, 1993). In order to use the simple additive method for estimating the 'priced out' consequences, several assumptions must be verified. These assumptions are: 1) the monetary value of an attribute can be determined without considering other attributes, 2) the monetary value of an attribute does not depend on the overall monetary value level. These required assumptions for validating cost-benefit analysis are often overlooked. Even when these assumptions are considered valid, many important attributes, such as the value of a life, are difficult, if not impossible, to price out. Moreover, attributes may be ignored or excluded from analysis when it is hard to convert them into monetary values using market mechanisms (e.g., aesthetics). Despite its drawbacks, the simplicity and the straightforwardness of the method still make it an attractive decision model.

A fire station example

In order to perform an equivalent cost analysis, the equivalent (monetary) value of functional loss would have to be determined. Based on the fact that the functionality of the fire station is directly related to the safety and emergency rescue of people after an earthquake, the value of the function of the fire station in case of emergency is assumed to be $500,000 per one percent loss of function. For example, if the fire station were 50% functional after an earthquake, the equivalent loss due to the malfunction of the fire station would be $25,000,000. Overall equivalent cost for a set of seismic losses is then calculated using the conversion factor above. For example, if a seismic event causes monetary loss of $3,000,000 and 5% of functional loss, then the equivalent cost for these seismic losses would be $\$3,000,000 + 5 \times \$500,000 = \$5,500,000$.

The effect of the value of functional loss will be briefly discussed with sensitivity analysis in Section 3.2.1. As in the previous section, Monte Carlo simulation with the Latin Hypercube sampling technique is performed for 1,000 intervals taking the damage indices and the price fluctuation factor as random variables. The expected losses along with the total converted cost for each alternative are obtained as shown in Table 3.4.

According to the expected value criterion, the equivalent cost analysis suggests that ‘rehabilitation’ is preferable, as it has the lowest expected total cost. Note that none of the attributes of the ‘rehabilitation’ option dominate the attributes of other alternatives. That is, “No Action” is best in terms of initial and repair costs, and “Rebuild” is best in terms of functional loss. However, rehabilitation is least costly considering both monetary costs and functional loss.

Table 3.4 Consequence Table for Firehouse Example Using Equivalent Cost Analysis

Consequences / Alternatives	Initial + Repair Cost	Loss of Function	Total Converted Cost
No Action	**$ 0.093 M**	4.856 %	$ 2.521 M
Rehabilitation	$ 1.322 M	1.869 %	**$ 2.257 M**
Rebuild	$ 3.002 M	**0.319 %**	$ 3.161 M

3.1.3 Multi-Attribute Utility Theory (MAUT)

Quantifying value for the majority of attributes can be challenging, even though well-established scales of value are available for some attributes, such as monetary value (Ang & Tang, 1984). Utility theory is a value-measuring theory that can incorporate risk attitude in quantification of values. Utility is defined as a true measure of value to the decision maker. Utility theory converts a decision maker's value to a quantified relative number so that the effect of the values of the decision maker can be reflected within the decision model. In addition, utility theory can also be used for comparison of different kinds of values by taking into account the weight information that the decision maker assigns to each value and vice versa. The method and usage of utility theory are briefly described here; more detailed explanations of utility theory can be found in numerous references (Keeney & Raiffa, 1993, Ang & Tang, 1984, Winterfeldt & Edwards, 1986, Winston, 1993, Hiller & Lieberman, 2001).

A utility function represents a mapping of the degree of preference onto a mathematical function, thus permitting preference to be expressed numerically (Ang & Tang, 1984). Generally, a utility function can be formulated for the value of an attribute. A utility function can be constructed by investigating and comparing the decision maker's preferences. The technique to be used in the formulation of the utility function is detailed in selected references (Raiffa, 1970, Winterfeldt & Edwards, 1986).

As stated in the previous section, even monetary value needs to be converted to a utility value because the value of money depends on the decision maker's unique preference associated with a specific problem. As an example of a utility function, consider a construction cost for a facility, where the anticipated consequence of the dollar cost ranges between 0.7 and 1.2 million dollars, and where less cost is preferable. However, the value of the cost is measured in terms of a nonlinear utility function, i.e., what the decision maker feels about the difference between 0.7 million dollars and 0.8 million dollars can differ from his or her feeling about the difference between 1.1 and 1.2 million dollars. A sample utility function plot for the cost is shown in Figure 3.3. Note that in general, utilities are normalized such that they range from zero to one. In this figure, the difference in utilities between $0.7M and $0.8M, that is, the difference between $u(0.7)$ and $u(0.8)$ is less than 0.1. On the other hand, the difference in utilities between $1.1M and $1.2M is more than 0.3.

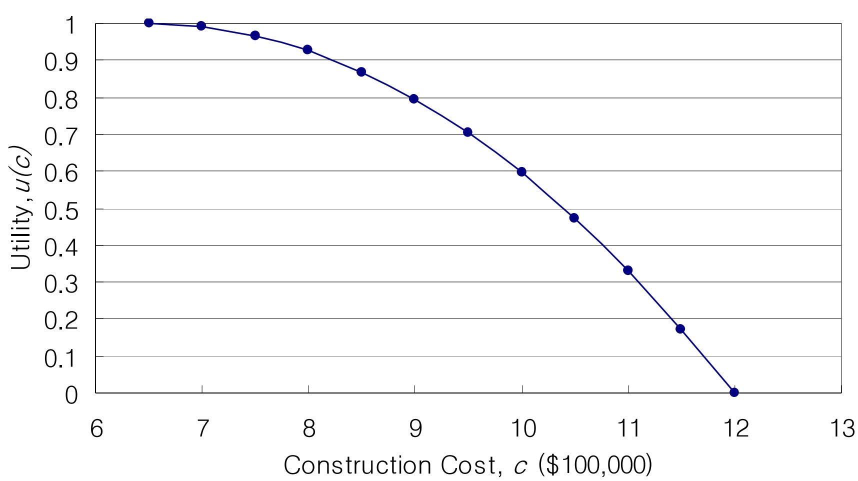
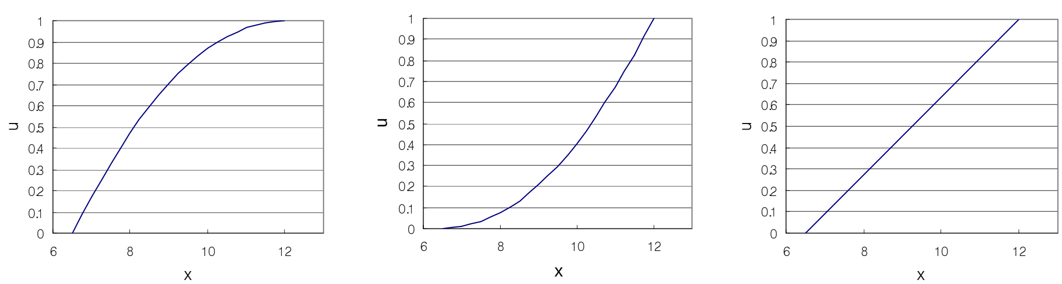


Figure 3.3 A Sample Utility Function for Dollar Cost

A decision maker's utility function contains information about his or her attitude toward risk (Winston, 1993, Keeney and Raiffa, 1993). A decision maker whose utility function for a value looks like Figure 3.3 is said to be risk-averse because the utility function shows his or her tendency to behave conservatively. That is, if the decision maker is facing a lottery yielding either a consequence x_1 or a less preferable consequence x_2, with equal probability, and he or she is asked to state a preference between receiving $\bar{x} = (x_1 + x_2)/2$ for certain and the lottery, $< x_1, x_2 >$, the risk averse decision maker would choose $\bar{x}$ since there is no risk associated with it. An insurance buyer is generally risk-averse for the corresponding risk because he or she usually pays more than the expected cost to avoid a large negative consequence. According to Baker and Miller (2000), empirical evidence indicates that policy makers and taxpayers tend to be risk averse. If a decision maker thinks both sides indifferent, then the decision maker is called ‘risk neutral’ decision maker. This would apply to ‘large firms’ that have enough money to sustain a possible loss on a business where they can make a substantial profit otherwise (Stewart and Melchers, 1987). On the other hand, a decision maker who would choose the lottery < x_1, x_2> is called a ‘risk-seeking’ decision maker. For example, a gambler in Las Vegas is risk seeking because he or she pays more than the expected gain hoping for a large positive consequence.

The shape of a utility function for a risk-averse decision maker is concave, as shown in Figure 3.4 (a). Conversely, the utility function is convex if the decision maker is risk-seeking and linear if the decision maker is risk-neutral, as shown in Figure 3.4 (b) and Figure 3.4 (c), respectively.



(a) risk-averse (b) risk-seeking (c) risk-neutral

Figure 3.4. Utility functions showing decision maker’s attitude toward risk

If the probability of a set of consequences is defined, the expected value of a random variable X can be calculated as follows.

$$E(X) = \sum_k p_k x_k \qquad [3.1]$$

where, X is the random variable and p_k is the corresponding probability of x_k. In the same manner, the expected monetary value (EMV) can be calculated if the value of concern is money. However, making a decision based on the expected monetary value may not be always the rational way to make such a decision. A more general criterion for decision is the use of the maximum expected utility criterion. The expected utility of *i*th alternative is computed as follows.

$$E(U_i) = \sum_j p_{ij} \cdot u_{ij} \qquad [3.2]$$

where u_{ij} is the utility of the *j*th consequence associated with alternative *i*, p_{ij} is corresponding probability, and U_i is the utility of alternative *i*. Therefore, if a decision has to be made among a set of alternatives, the alternative with the maximum expected utility value should be chosen. If the consequence is represented by a continuous random variable X, the expected utility of *i*th alternative is given by:

$$E(U_i) = \int_{-\infty}^{\infty} u_i(x) f^i{}_X(x) dx \qquad [3.3]$$

where, $f^i{}_X(x)$ is the probability distribution function of X corresponding to alternative *i*. In this equation, the random variable X is the only attribute of concern. However, in a case where a decision maker is concerned about more than one attribute, the calculation of the expected utility is multidimensional. For instance, if the values that the decision maker is concerned with are time, monetary cost, and safety, each of these values has different units of measurement and a utility function accounting for this characteristic should be used for the calculation of the expected utility. Therefore,

$$E(U_i) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} u_i(x_1, x_2, \cdots, x_n) f^i{}_{X_1, \cdots X_n}(x_1, x_2, \cdots, x_n) d_{x1} \cdots d_{xn} \qquad [3.4]$$

where X_1 to X_n are the random variables that describe the values of n different attributes associated with the alternatives *i*. Also $f^i{}_{X_1, \ldots X_n}(x_1, x_2, ..., x_n)$ is the joint probability distribution function, and $u(x_1, x_2, ..., x_n)$ is the multi-attribute utility function of the random variables X_1 to X_n. The joint probability function can be obtained either by explicit mathematical expression or can be approximated using simulations. The problem is then how to obtain the multi-attribute utility function $u(x_1, x_2, ..., x_n)$. The task of obtaining the multi-attribute utility function is usually cumbersome, especially when the number of attributes is large. With several assumptions, however, the procedure for the determination of the multi-attribute utility function can be simplified. These assumptions are:

- Preferential Independence: trade-offs between any two attributes are not affected by the value of other attributes;
- Utility Independence: the relative utility of an attribute can be determined regardless of the utility determination of other values.

These assumptions are appropriate in many realistic problems, and are operationally verifiable in practice (Keeney and Raiffa, 1993). With these assumptions, the multi-attribute utility function for the *n*-dimension case (i.e., *n* attributes) can be expressed as a function of the single utility functions as follows:

$$1 + ku(x_1, ..., x_n) = \prod_{l=1}^{n} \left[1 + kk_l u_l(x_l)\right] \quad [3.5]$$

where, x_l is a marginal consequence corresponding to *l*th attribute, $u_l(x_l)$ is the marginal utility function for *l*th attribute, and k and k_l are constants to be evaluated. If ${}^*x_l$ and x_l^* are defined as the values of x_l that give the minimum and maximum values of $u_l(x_l)$, respectively, the following expression can be derived.

$$\begin{aligned} 1 + ku({}^*x_1, ..., x_l^*, ..., {}^*x_n) \\ &= [1 + kk_1 u_1({}^*x_1)] \times ... \times [1 + kk_l u_l(x_l^*)] \times ... \times [1 + kk_n u_n({}^*x_n)] \\ &= 1 + kk_l \end{aligned} \quad [3.6]$$

This equation implies that $k_l = u({}^*x_1, ..., x_l^*, ..., {}^*x_n)$, and leads to the following equation, in which the value of k can also be found.

$$1 + k = \prod_{l=1}^{n} \left(1 + kk_l\right) \quad [3.7]$$

As a result, one can find the multi-attribute utility function of arbitrary dimension if the single utility function of each value can be obtained, as long as the assumption of preferential independency and utility independency is provided. In a special case where $\sum_{l=1}^{n} k_l = 1.0$, the utility function is additive and the multi-attribute utility function is expressed as follows.

$$u(x_1,...,x_l,...,x_n) = k_1u_1(x_1) + ... + k_lu_l(x_l) + ... + k_nu_n(x_n) \qquad [3.8]$$

The advantage of the additive utility function lies in its simplicity. However, the additive utility function can be used only under certain conditions. Additive utility holds if preferences over attributes depend only on their marginal probability distributions and not on their joint probability distribution. For more discussion on additive utility functions, see Keeney and Raiffa (1993).

A fire station example – continued

In the example discussed in the previous section, the decision maker's value (both monetary and functional loss) is represented by equivalent monetary value. Now, in this section, risk attitudes are incorporated and monetary costs and functional losses are expressed in terms of utilities. As mentioned earlier, policy makers and taxpayers, who are likely to be decision makers in this example tend to be risk averse (Baker and Miller, 2000). Therefore, a set of risk-averse utility functions is assumed for both monetary value and loss of function as shown in Figure 3.5. In reality, risk attitudes would have to be elicited. However, a set of risk-averse utility functions is assumed with reasonable degree of risk attitude to investigate the effect of incorporating risk attitudes into the analysis, as value elicitation is not within the scope of this study. In addition, a set of risk-seeking utility functions will be used to investigate the effect of different risk attitudes (i.e., risk-seeking vs. risk-averse) and this will be addressed in Section 3.2.2.

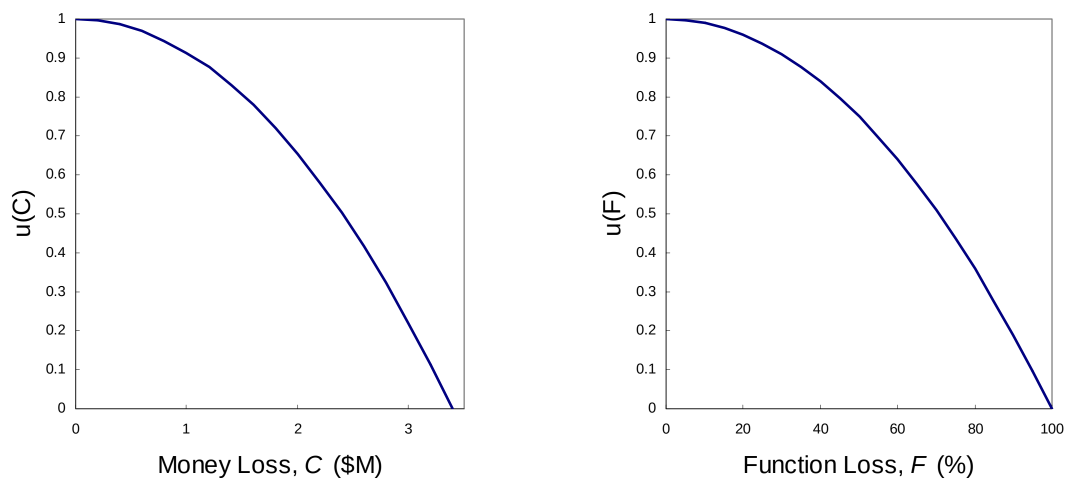
Additive utilities are assumed for simplicity and for more direct comparison with equivalent cost analysis. The scaling factor for functional loss, k_f, and the scaling factor for monetary loss, k_m, would have to be elicited as well considering trade-offs among the attributes. However, the scaling factors are assumed in this example for the same reason that the utility functions are assumed. As discussed earlier, a scaling factor is indicating the impact of the possible change of the consequence of an attribute to overall utility. Therefore, the scaling factors in this example are assumed such that the ratio between the scaling factors is the same as the ratio between the maximum equivalent costs of the attributes. This relationship can be expressed as follows.

$$\frac{k_m}{k_f} = \frac{M_{\max}}{F_{\max} \cdot V_f} \qquad [3.9]$$

where, k_m = scaling factor for monetary cost, k_f = scaling factor for function loss, M_{max} = maximum monetary cost, F_{max} = maximum function loss, and V_f = value of function loss in ECA. Since the monetary loss ranges from $0 to $3.3M and the functional loss ranges from 0% to 100% as shown in Figure 3.2, the scaling factors can be calculated from the following expressions.

$$k_m = \frac{3.3}{100 \times value\,of\;\; function\,(in\,\$M)} \times k_f$$
$$k_m + k_f = 1.0 \qquad [3.10]$$

where, the value of function is $0.5 M as used in the previous example, which makes k_m = 0.062 and k_f = 0.938 .



(a) Utility Function for Monetary loss
$[u(C) = 1 - 0.2941 \cdot C^2]$

(b) Utility Function for Functional loss
$[u(F) = 1 - 0.001 \cdot F^2]$

Figure 3.5 Utility Functions (risk-averse) for Firehouse Example

The multi-attribute utility function can then be determined using Equations 3.5 and 3.7. Using Monte Carlo Simulation on Equation 3.4 with 1,000 samples, the expected utilities for the alternatives are calculated, which produces the consequence table shown in Table 3.5. This shows ‘Rehabilitation’ is preferable, as it has highest expected multi-attribute utility. A comparison of the results of ECA and MAUT shows that the preference does not change by incorporation of risk attitude (risk-averse) in this example. More investigation of incorporation of risk attitude is discussed in Section 3.2.2.

Table 3.5 Consequence Table for Firehouse Example Using Utility Analysis (risk-seeking utility functions)

Consequences / Alternatives		Initial + Repair Cost ($M)	Loss of Function (%)	Expected Multi-Attribute Utility
No Action	Expected Value	$ 0.093 M	4.856 %	0.9799
	Expected Marginal Utility	0.9913	0.9791	
Rehabilitation	Expected Value	$ 1.322 M	1.869 %	**0.9876**
	Expected Marginal Utility	0.8481	0.9968	
Rebuild	Expected Value	$ 3.002 M	0.319 %	0.9516
	Expected Marginal Utility	0.2206	0.9516	

3.1.4 Joint Probability Decision-making (JPDM)

Bandte (2000) developed the Joint Probabilistic Decision-making (JPDM) technique as a tool for multi-objective optimization and product selection problems in aerospace system design. In this method, a joint probability distribution function for multiple objectives, or criteria, can be obtained by means of either mathematical expressions or empirical distribution functions. Using joint probability distribution functions, a unique value, called Probability of Success (POS), which indicates the probability of satisfying specified levels of decision maker's objectives, can be calculated to provide a barometer with which the decision can be made. The POS can be mathematically expressed as:

$$POS = P\{ (z_{1_{\min}} \le z_1 \le z_{1_{\max}}) \cap (z_{2_{\min}} \le z_2 \le z_{2_{\max}}) \cap ... \cap (z_{N_{\min}} \le z_N \le z_{N_{\max}}) \}$$
$$= \int_{z_{1\min}}^{z_{1\max}} ... \int_{z_{N\min}}^{z_{N\max}} f_{Z_1 Z_2 ... Z_N}(z_1, z_2, ... z_N) dz_1 dz_2 ... dz_N \quad [3.11]$$

where, z_i is the consequence value of *i*th attribute, $f_{Z_1 Z_2 ... Z_N}(z_1, z_2, ... z_N)$ is the joint probability density function of the criteria, and z_{imin} and z_{imax} are the objective limits that define the minimum and maximum thresholds for the area of interest (or acceptable consequence).

It is possible to analytically calculate a POS through direct integration if a joint probability density function of the criteria is available in a closed mathematical form. If a closed form expression for the joint probability density function is not available or hard to obtain, which is mostly the case for seismic consequences, the POS can be numerically obtained using techniques such as Monte-Carlo simulation (Kleijnen, 1974). The numerical approach generally requires more computing resources and time, but can cover more cases compared to analytical solution. For the case with *N* criteria, the POS of an alternative is expressed as:

$$POS = P\{ (z_{1_{\min}} \le z_1 \le z_{1_{\max}}) \cap (z_{2_{\min}} \le z_2 \le z_{2_{\max}}) \cap ... \cap (z_{N_{\min}} \le z_N \le z_{N_{\max}}) \}$$
$$= \frac{1}{M} \sum_{j=1}^{M} I\left[(z_{1_{\min}} \le z_{1j} \le z_{1_{\max}}) \cap (z_{2_{\min}} \le z_{2j} \le z_{2_{\max}}) \cap ... \cap (z_{N_{\min}} \le z_{Nj} \le z_{N_{\max}}) \right] \quad [3.12]$$

where, M is the number of samples for the simulation, z_{1j}, z_{2j}, … , z_{Nj}, are the consequence values of *N* criteria corresponding to the *j*th sample, z_{1min}, z_{2min}, … , z_{Nmin} and z_{1max}, z_{2max}, … , z_{Nmax} are the criterion values that define the minimum and maximum thresholds of area of interest, and *I(x)* returns one if *x* is true, zero otherwise. For example, *F* and *C* in Table 3.2 are the consequence values of the function loss and monetary loss. *F* is a function of the damage index. *C* is a function of the damage index and price fluctuation factor, which are random variables. A Monte Carlo simulation can then be performed assuming that these random variables are statistically independent.

For JPDM, the decision value supplies the minimum and maximum thresholds for each criterion – that is, which values of a criterion would qualify as success – asking a target value of z_i for each criterion. The concept of JPDM is more intuitively shown with joint PDFs of alternatives. If there are more than one alternative, the PDF of the consequences associated with each alternative is different. Figure 3.6, for example, shows the PDF plots of two criteria corresponding to two alternatives. In this figure, the area of interest defined with criterion values is represented by gray area. A larger portion of the PDF of alternative #2 than alternative #1 falls into the area of interest defined with the criterion values (z_{1min}, z_{1max}, z_{2min}, and z_{2max}). That is, the POS of alternative #2 is larger than the POS of alternative #1. However, the preference can change for different set of criterion values. Figure 3.7 shows the same PDF plots of the two alternatives but with different sets of criterion values. In this figure, alternative #1 has higher POS than alternative #2. These figures illustrate that decisions can be made differently depending on the determination of the criterion values.

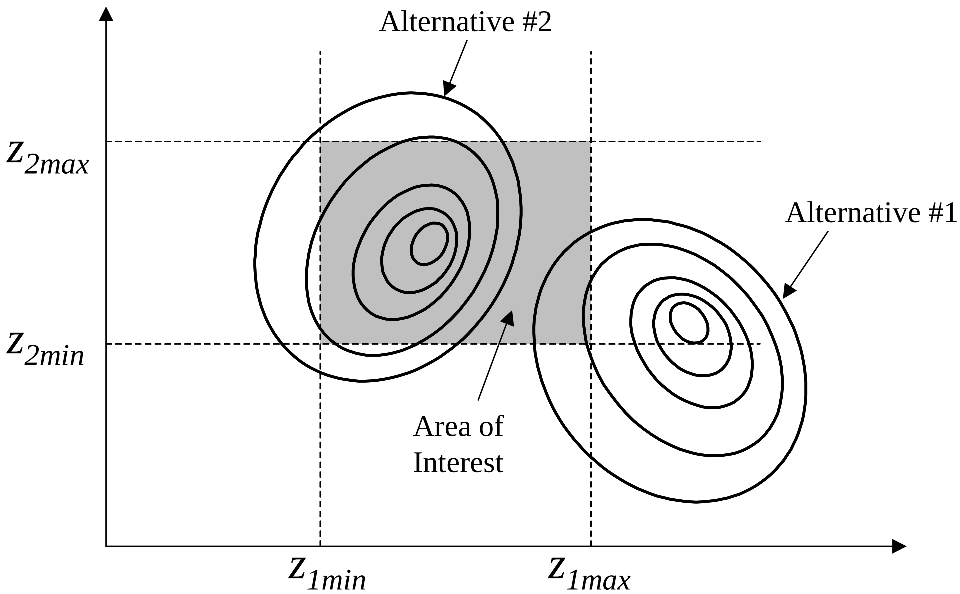


Figure 3.6 Illustration of POS

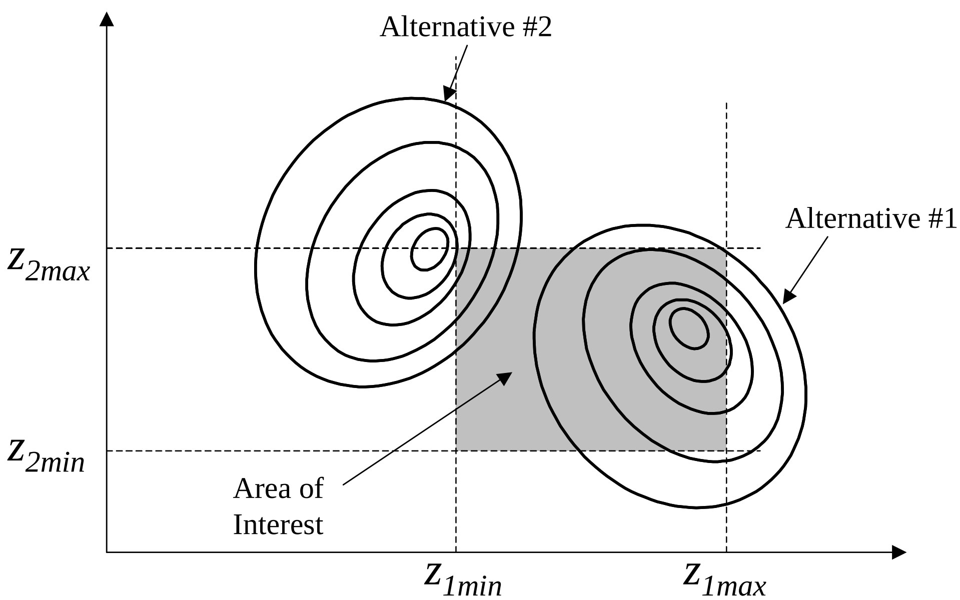


Figure 3.7 Illustration of POS – Different Set of Criterion Values

JPDM also manipulates each criterion value based on the relative weight assigned to the criterion. That is, the higher the preference weight, the narrower the range of the acceptable consequence, which results, for a given design alternative, in a smaller value of POS than would be the case without consideration of relative weights. Likewise, for a criterion with a lower preference weight, the objective range is widened, resulting in larger POS than would be the case without weighting. This approach is expressed as follows. If w = weight, N = number of criteria,

$$\begin{aligned} POS(w/o\,weight) &= \int_{z_{1\min}}^{z_{1\max}} \cdots \int_{z_{N\min}}^{z_{N\max}} f_{Z_1 Z_2 \ldots Z_N}(z_1, z_2, \ldots z_N)\,dz_1 dz_2 \ldots dz_N \\ POS(w/\,weight) &= \int_{t_{1\min}}^{t_{1\max}} \cdots \int_{t_{N\min}}^{t_{N\max}} f_{Z_1 Z_2 \ldots Z_N}(z_1, z_2, \ldots z_N)\,dz_1 dz_2 \ldots dz_N \end{aligned} \qquad [3.13]$$

where

$$\begin{aligned} t_{i\min} &= (w_i \cdot N) \cdot z_{i\min} \\ t_{i\max} &= \frac{z_{i\max}}{(w_i \cdot N)} \end{aligned} \qquad [3.14]$$

and

$$\sum_i w_i = 1.0 \qquad [3.15]$$

JPDM is essentially a decision model in which the alternative that maximizes probable positive consequences is preferred. Note that because of the different decision criteria, a preferred decision in JPDM may not be the same as that resulting from an expected value (or expected utility) approach.

A fire station example - continued

In order to perform JPDM analysis, the criterion values (z_{imin} and z_{imax} in Equation 3.13) from which the POSs of the alternatives are calculated must be pre-defined. In this example, the criterion values are defined as shown in Table 3.6.

Table 3.6. Criterion values for Firehouse Example

	Z_{imin}	Z_{imax}
Monetary loss	$0.0	$1.5M
Functional loss	0.0%	40%

Then, using Equation 3.13, the POS for each alternative can be calculated. It is assumed that equal weights (0.5) are assigned to monetary loss and functional loss. With the input criterion values and the relative weights, the POS values of the alternatives are computed using simulation with the Latin Hypercube sampling technique with 1,000 intervals. The resulting POS values are shown in Table 3.7 along with the marginal POS values of the attributes. In this example, the “Rebuild” option is most preferable as it has the highest overall POS. Note that the POS values are calculated considering probabilities of all possible levels of earthquakes, including the probability of not having an earthquake.

Table 3.7 Consequence Table for fire station Example Using JPDM Analysis (with equal weights)

Consequences / Alternatives		Initial + Repair Cost	Loss of Function	POS (overall)
No Action	Expected Value	$ 0.093 M	4.856 %	0.9550
	Marginal POS	0.9910	0.9550	
Rehabilitation	Expected Value	$ 1.322 M	1.869 %	**0.9610**
	Marginal POS	0.9610	1.0	
Rebuild	Expected Value	$ 3.002 M	0.3019 %	0.0
	Marginal POS	0.0	1.0	

This result is more intuitively seen with the consequence distribution plots as shown in Figure 3.8. That is, 95.5% of the consequences of “No Action” fall into the area of interest, and 96.1% of the consequences of ‘Rehabilitation’ fall into the area of interest. It is clearly seen that none of the consequences of “Rebuild” falls into the area of interest, implying the POS=0. Note again that probability of not having an earthquake is 86%, so 86% of the consequences of the alternatives fall on the points corresponding to the initial costs of the alternatives (i.e., ($0.0, 0.0%) for “No Action”, ($1.3M, 0.0%) for “Rehab”, and ($3.0, 0.0%) for “Rebuild”).

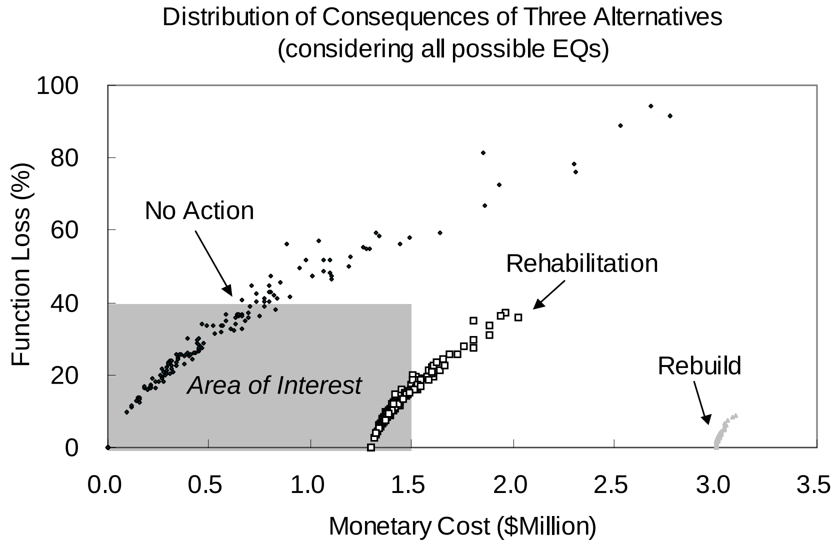
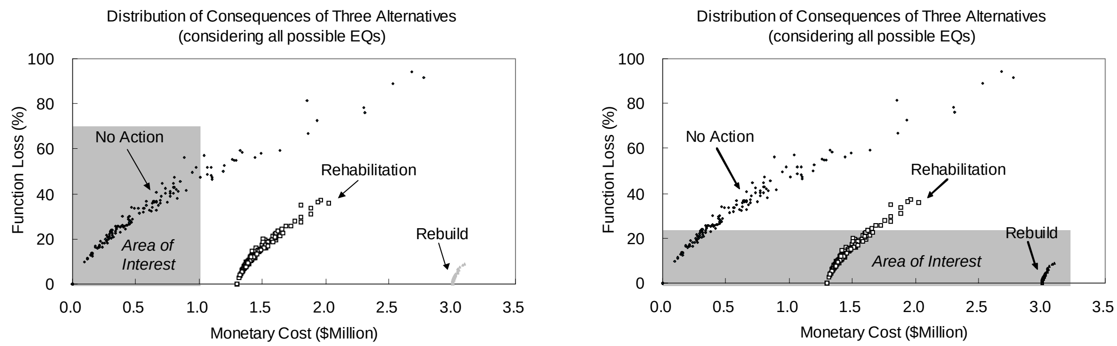


Figure 3.8 Consequence Distribution Plots with Area of Interest

It is also possible to anticipate the change of preferences based on different sets of criterion values as shown in Figure 3.9. If the decision maker is stricter on monetary cost than functional loss (i.e., smaller upper bound for monetary loss and larger upper bound for functional loss) as shown in Figure 3.9(a), "No Action" is preferable. The consequence distributions of 'Rehabilitation' and "Rebuild" are out of the area of interest, as their initial costs are more than the tolerance level of the decision maker ($1,000,000). On the other hand, if the decision maker has higher tolerance level for monetary loss, but is strict on functional loss as shown in Figure 3.9(b), "Rebuild" becomes the preferable option, as all the consequences fall into the area of interest.



(a) (b)

Figure 3.9 Change of Preferences Based on Different Sets of Criterion Values

3.2 Sensitivity Analyses of MCDM Models

The examples illustrated in the previous section are static applications of MCDM models, where decisions are based on initial configuration of values and no further reconfiguration follows. However, most of actual decisions are made after investigating effects of different configurations of values and other social and economic parameters that are uncertain.

A decision maker's value is quantified in numerous ways depending on the MCDM models. Regardless, the quantification of value is generally not an easy task. A transparent market mechanism for calculating the conversion factors for equivalent cost analysis may not be available. Value elicitation in MAUT may not produce consistent results over time. The determination of the objective criteria values in JPDM does not necessarily have an intuitively obvious basis. Furthermore, a slight change in the value-measuring index (e.g., criterion values in JPDM, conversion factors in ECA, etc.) may cause substantial changes in decisions. Therefore, it is important to identify the critical ranges of measured values that can cause a decision to change. By doing this, the value can be more effectively measured, leading the decision maker to more reliable decision. In this section, the effect of change of values for each MCDM model is addressed with illustrative examples.

3.2.1 Equivalent Cost Analysis

A fire station example – continued

Values in an equivalent cost analysis are expressed in terms of converted monetary values. To illustrate the effect of the converted value of functional loss in this example, the conversion factor is varied and corresponding decisions are investigated. The value of functional loss varies within the range between $100,000 and $1,000,000 per % loss. Figure 3.10 shows the sensitivity plot of the value of functional loss that shows how the decision is sensitive to the change of the assigned value of the functional loss. In Figure 3.10, the variation of the expected equivalent cost for "No Action" option is relatively sensitive to the change of the value of functional loss. This tendency makes the "No Action" option the most preferred option with a value of functional loss less than about $0.4M. On the other hand, the "Rebuild" option is not preferred unless the value of function is very high (beyong $1.0M). Given the information from the sensitivity analysis, the value quantification can be re-visited with updated insight and the decision can be made thereafter with more reliability.

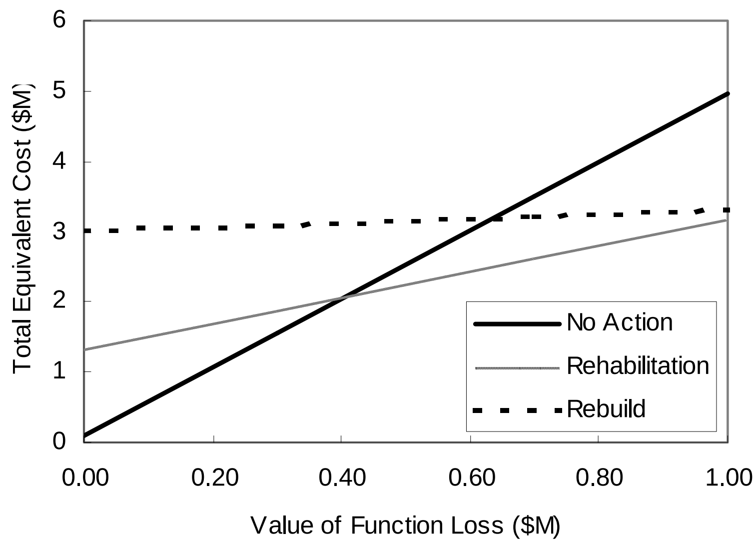


Figure 3.10 Sensitivity of Total Expected Cost to Value of Functional loss

3.2.2 MAUT Analysis

A fire station example – continued

Values in MAUT analysis are measured in terms of utility function. Utility functions have information on the decision maker's risk attitudes as discussed in Section 3.1.3. In addition, relative importance among multiple values is measured in terms of scaling factors. In this example, the change of preferred decision is investigated by varying the scaling factors of the values. In the end, the effect of using different risk attitudes is illustrated as well.

The determination of the scaling factors is based on Equation 3.10 over the range of the value of loss of function used in the equivalent cost analysis ($100,000 - $1,000,000 per 1% loss of function). As a result, the scaling factor for functional loss, k_f, is examined from the minimum value of k_f =0.7519 to the maximum value of k_f =0.9681. Note that the scaling factor for monetary loss, k_m, is equal to 1-k_f, as additive utility is assumed in this example. A sensitivity plot that shows a sensitivity of the decision to the change of the assigned scaling factor for the functional loss is presented in Figure 3.11. Note that this plot is for the case where the assumed risk-averse utility functions shown in Figure 3.5 are used.

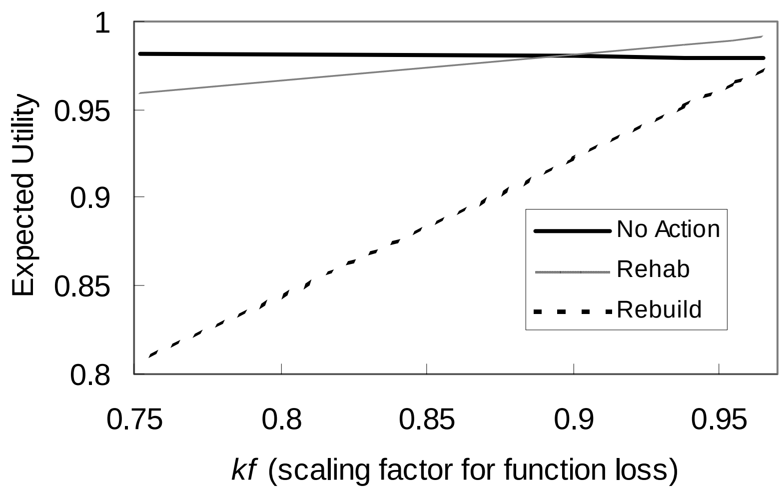


Figure 3.11 Sensitivity of Expected Utility to Scaling Factor for Functional loss (risk-averse decision maker)

In Figure 3.11, the "No Action" option becomes preferable to other options as the scaling factor for the functional loss (k_f) decreases (or relative weight for monetary loss increases), whereas the "Rehab" option becomes preferable with high values of k_f. This means that if the decision maker cares more about the functionality of the system in case of an earthquake, the "Rehab" option is suggested. If not, "No Action" option, which is to leave the system as it is without providing any rehabilitation action, is preferred.

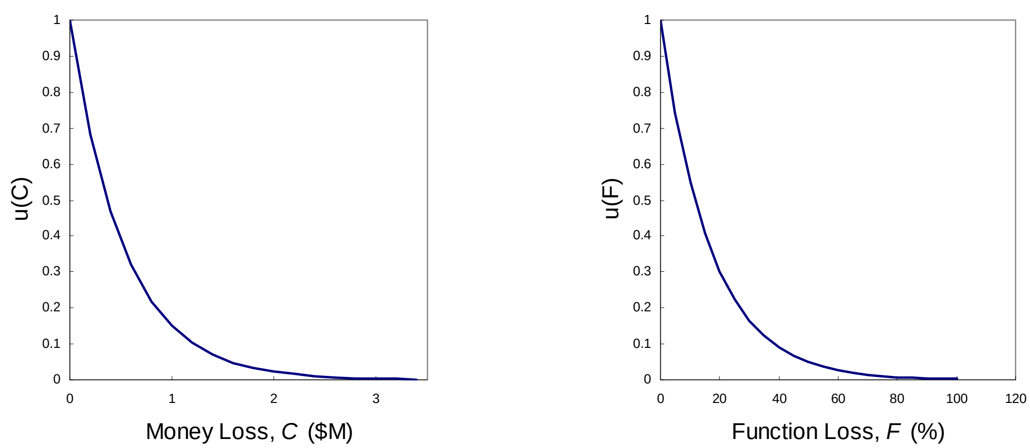
However, the relative difference of the expected utilities of the two options is small, implying that the preference levels of the two options do not differ by much in this example. From the plot, the decision point for “No Action” vs “Rebuild” occurs at approximately k_f =0.9. This can be explained more intuitively with a lottery question given to the decision maker as follows.

$$\begin{matrix}\textit{Function Loss} = -0.0\% \\ \textit{Money Loss} = -\$3.3M\end{matrix} \quad \boldsymbol{(100\%)} \quad \sim \begin{cases} \begin{matrix}\textit{Function Loss} = -0.0\% \\ \textit{Money Loss} = -\$0.0M\end{matrix} & \boldsymbol{(p)} \\ \\ \begin{matrix}\textit{Function Loss} = -100\% \\ \textit{Money Loss} = -\$3.3M\end{matrix} & \boldsymbol{(1-p)} \end{cases} \qquad [3.16]$$

In this lottery, there is a certain consequence that the function loss is 0.0% and monetary loss is \$3.3M on one side. On the other side, a consequence with function loss of 0.0% and monetary loss of \$0.0M can be resulted with a probability of p, and a consequence with function loss of 100.0% and monetary loss of \$3.3M can be resulted with a probability of 1-p. If the subjective probability value of p that makes both sides of the lottery indifferent to the decision maker is less than 0.9, then the “No Action” option is preferred. If the required p that makes the both sides indifferent is larger than 0.9, then the “Rebuild” option is preferable based on the risk attitude and value information of the decision maker. Note that in the lottery method shown above, the probability is adjusted with the values fixed. This method is often called ‘certainty equivalence method’. In fact, another approach exists where values are adjusted with probabilities fixed, and the approach is called ‘probability equivalence method’. It has been shown that the two approaches could give different results. More details can be found in Bleighrodt et al. (2001) and Kahneman and Tversky (1979).

The result above is based on the assumed risk attitudes (risk-averse) represented by the utility functions shown in Figure 3.5. It should be noted that the amount of risk aversion is arbitrarily chosen and the result can be different if different amount of risk aversion (i.e., more risk averse or less) is chosen. In fact, the risk attitude of a decision maker can be risk-seeking. Moreover, a decision maker can have different risk attitudes on different kinds of attributes.

In the following example, a set of risk-seeking utility functions (Figure 3.12) is assumed in order to investigate the effect of different risk attitudes.



(a) Utility Function for Monetary loss $[u(C) = e^{-1.9C}]$

(b) Utility Function for Functional loss $[u(F) = e^{-0.06F}]$

Figure 3.12 Utility Functions (risk-seeking) for Firehouse Example

With the risk-seeking utility functions incorporated, a sensitivity analysis is performed for the scaling factor for functional loss as in the case with risk-averse utility functions, and the resulting sensitivity plot is shown in Figure 3.13.

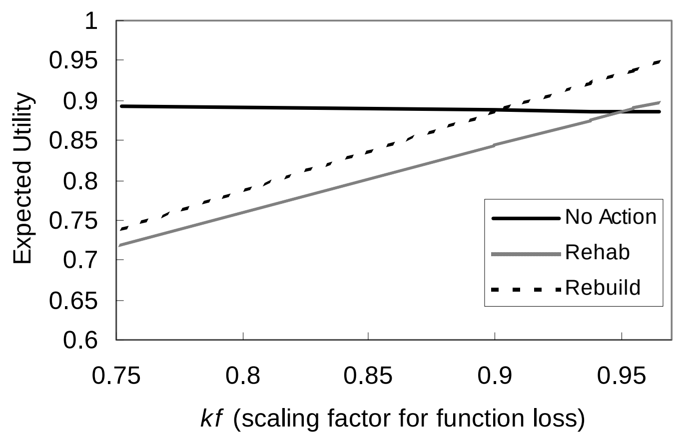


Figure 3.13 Sensitivity of Expected Utility to Scaling Factor for Functional loss (risk-seeking decision maker)

As shown in Figure 3.13, the "No Action" option is preferable for scaling factors for functional loss less than 0.9, and the "Rebuild" options is preferable otherwise. The example shown in this section demonstrates the potential difference in decisions that might arise by incorporating different risk attitudes.

3.2.3 JPDM Analysis

A fire station example – continued

In JPDM, criterion values are assigned to each attribute, from which the POS is calculated. These criterion values are then calibrated based on the relative weights as shown in Equation 3.13. Therefore, the decision maker's values in JPDM are defined in terms of both the criterion values and the relative weights. In this example, sensitivity of the decision to the change of the relative weights is investigated first. The relative weight for money loss is varied from 0.1 to 0.9 and the change of the POS's of the alternatives is shown in Figure 3.14. Note that the same criterion values are used as the ones used in Section 3.1.4. The POS of the "Rebuild" option suddenly drops at the relative weight for monetary loss (w_m) of about 0.583. This is because the upper bound of the criterion value for monetary loss becomes less than the initial cost for rebuilding the system, which is $3,000,000, when w_m is larger than 0.583. That is, from Equation 3.13, the relative weight larger than 0.583 for monetary loss makes the upper bound of the criterion value for monetary loss less than $3,000,000. In this case, because the initial cost required for the "Rebuild" option is $3,000,000, the corresponding POS becomes zero. This effect can be seen more directly in Figure 3.15 where the criterion value (for monetary loss) is changed rather than the relative weight (keeping the relative weight at 0.5). Sudden jump of POS is observed at the place where the upper bound for monetary loss is same as the initial cost for either the "Rebuild" option or the 'rehabilitation' option. On the other hand, Figure 3.16 shows the change of POS of each alternative for different upper bound for functional loss without losing the stability in the change of POS of the alternatives.

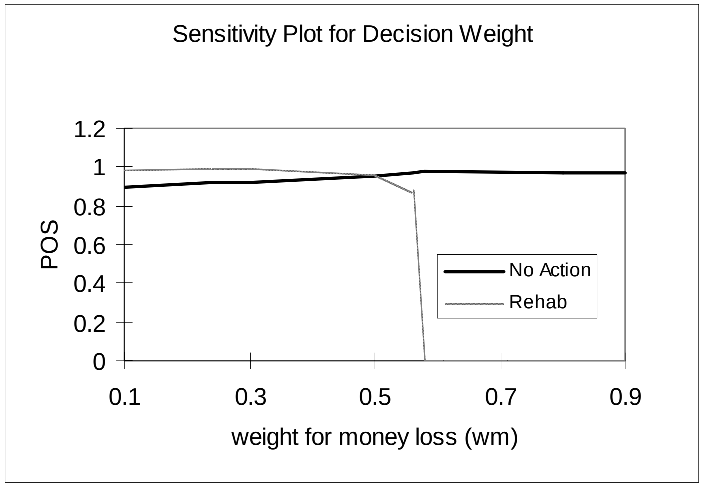


Figure 3.14 Sensitivity of POS to Relative Weight of Monetary loss, w_m (note that w_f=1-w_m)

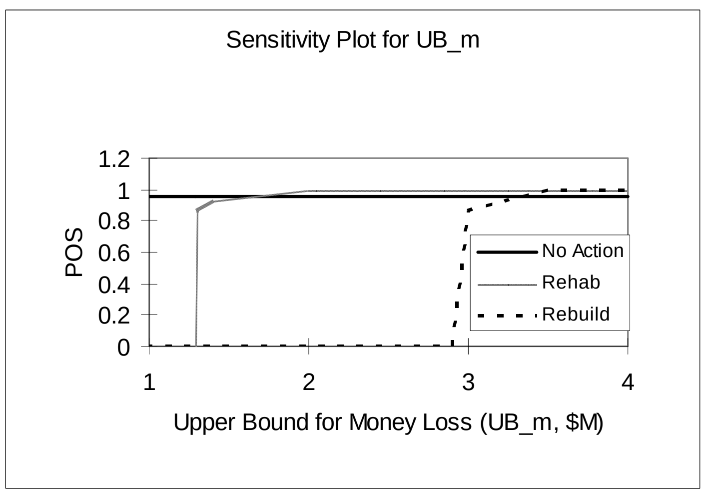


Figure 3.15 Sensitivity of POS to Upper Bound for Monetary loss

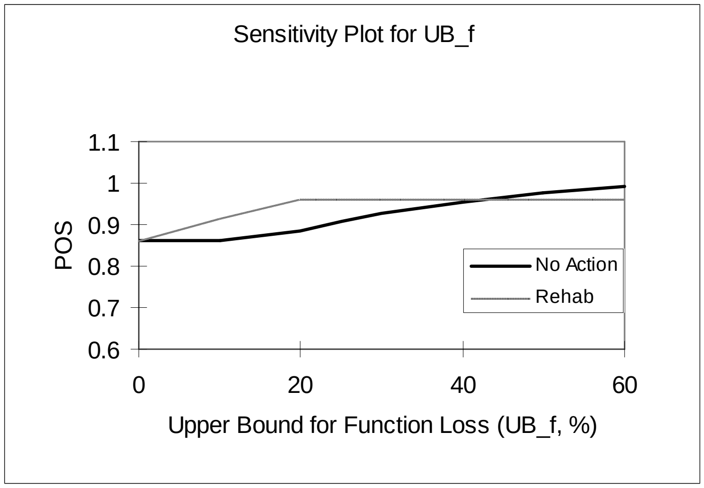


Figure 3.16 Sensitivity of POS to Upper Bound for Functional loss

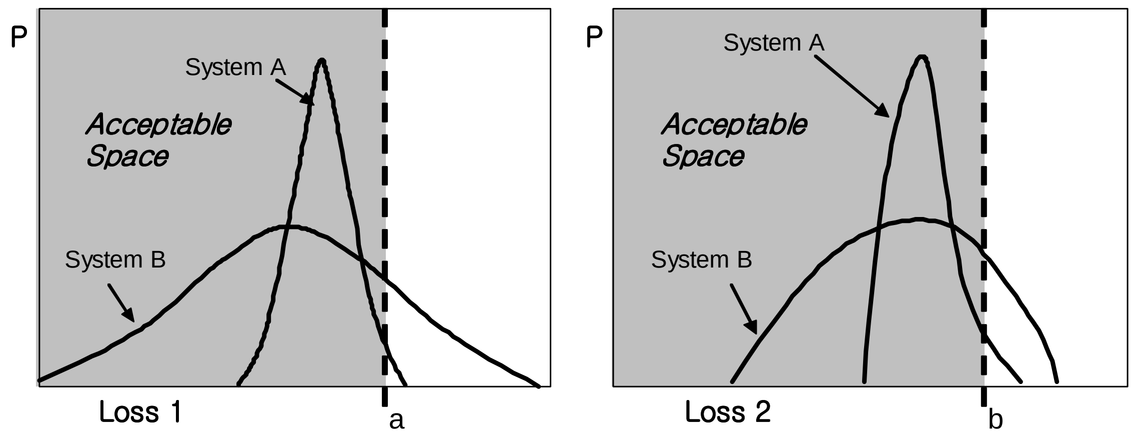
3.2.4 Additional Issues of JPDM

Shortcoming of JPDM

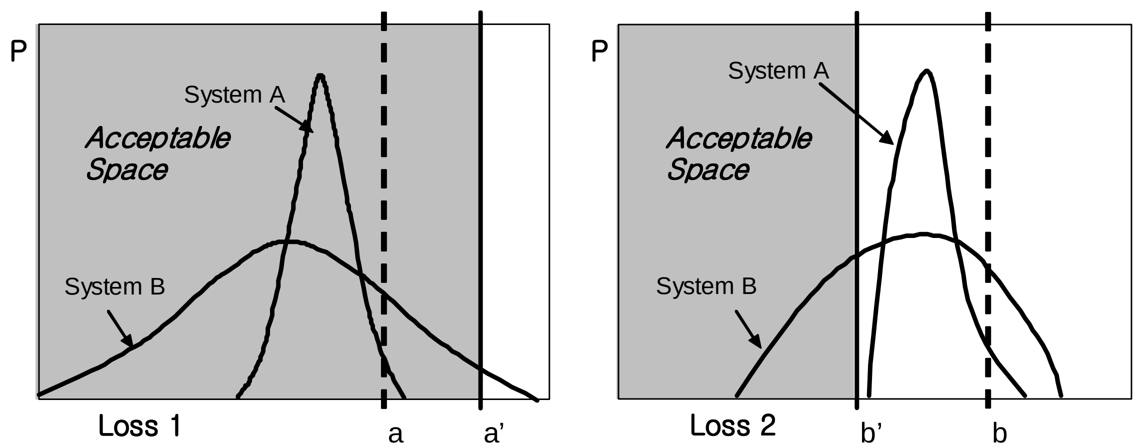
Without considering relative weights, JPDM can be effectively used for decision problems where the strong perception of the decision maker exists for the level of acceptable consequence (i.e., constraints). JPDM then can directly measure the performance of a system by producing the probability of the system satisfying the requirements. However, this approach does not allow trade-offs among the attributes (i.e., equal weights). Trade-offs among multiple attributes are possible in JPDM utilizing relative weights as discussed in Section 3.1.4. In Figure 3.14, however, discontinuity in POS is observed as the relative weight for monetary loss (w_m) increases. That is, the 'Rehabilitation' option is preferred when w_m is less than 0.5, but the POS suddenly becomes zero when w_m is slightly larger than 0.5. This sudden drop of POS due to small change in relative weights is not desirable and may lead to a wrong decision. Figure 3.17

schematically shows this effect. Without consideration of relative weights, System A appears to be a better option based on JPDM since it has apparently larger POS than System B for both Loss 1 and Loss 2 (Figure 3.17 (a)). Now, if the consideration of relative weights moves the criteria value from *a* to *a'* for Loss 1 and *b* to *b'* for Loss 2 (Figure 3.17 (b)), which means that relatively higher weight is assigned to Loss 2 and lower weight is assigned to Loss 1, System B becomes the better choice because of its larger POS. In fact, POS of System A is anticipated to be zero (or very close to zero if the PDF is not limited), since the PDF of Loss 2 lies outside the acceptable space defined by the calibrated criterion value (*b'*). In this case, JPDM can lead the decision maker to a wrong decision that might cause higher risk.

For decision problems on seismic rehabilitation of structural systems, in particular, a typical PDF of a seismic loss generally looks like a continuously decreasing function as shown in Figure 3.18 (a). If initial cost is associated with the attribute (e.g., initial rehabilitation cost), the PDF of the attribute is shifted to the right as shown in Figure 3.18 (b). Now assume that the initial criterion value (constraint) for this loss is determined and represented by a dotted line shown in Figure 3.19 (a). If the relative weight for this loss (attribute) is relatively high, the criterion value will be shifted to the left and could go below the initial cost, as shown in Figure 3.19 (b). In this case, the JPDM yields the overall POS of zero although the actual performance might be acceptable to the decision maker.

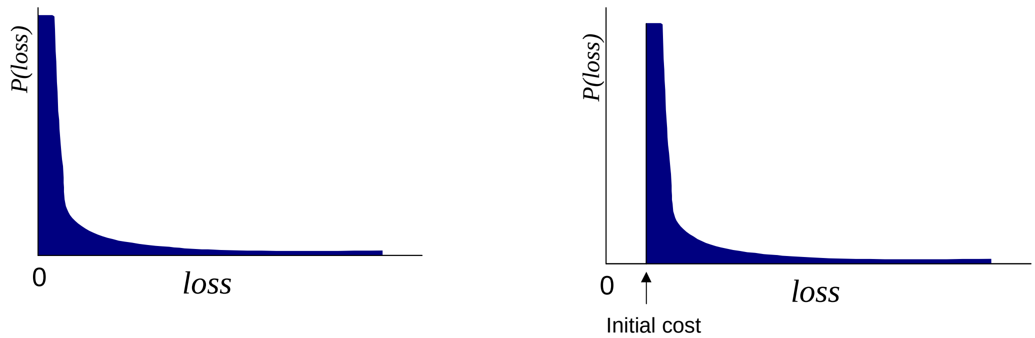


(a) before the relative weights are considered



(b) after the relative weights are considered

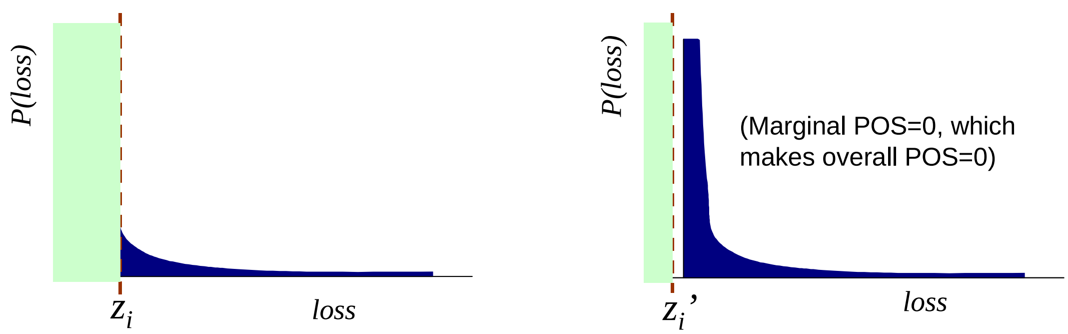
Figure 3.17 Shift of Preferred Option due to Redefinition of the Criterion value



(a) PDF of a seismic loss without initial cost

(b) PDF of a seismic loss with initial cost

Figure 3.18 Typical PDFs of Seismic Losses

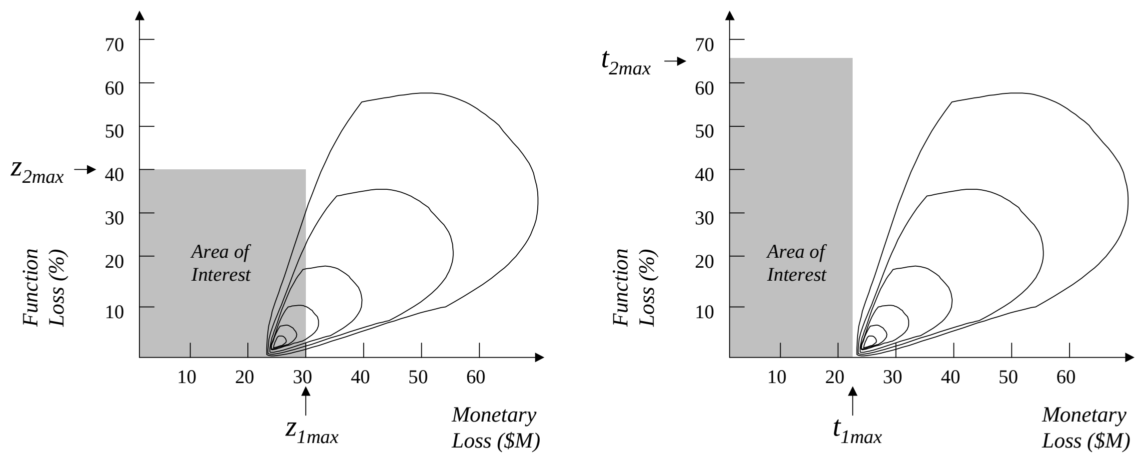


(a) Initial criterion value (z_i)

(b) Recalculated criterion value (z_i') based on relative weight

Figure 3.19 Shift of Criterion Value Based on Relative Weight

This can be better illustrated with a multi criteria decision problem. Assume a joint probability contour plot of an alternative drawn on a consequence space where monetary loss and function loss are considered, as shown in Figure 3.20. Note that the consequence has a minimum monetary value of $24M and this would be the cost initially needed (e.g., initial rehabilitation cost). An area of interest is then defined by criterion values z_{1max} (upper criterion value for monetary loss) = $30M and z_{2max} (upper criterion value for function loss) = 40% as shown in Figure 3.20(a), and they are $30M and 40%, respectively. The figure shows that large portion of the joint probability contour lie in the area of interest (note that the PDF is skewed to the lower left), which implies high POS.



(a) Before applying relative weights (b) After applying relative weight

Figure 3.20 Probability Contour Plot of an Alternative with Initial Criterion Values

Now consider the relative weights are determined such that w_1 (weight for monetary loss) is 0.7 and w_2 (weight for function loss) is 0.3. If the relative weights are incorporated based on the traditional JPDM approach using Equation 3.14, the criterion values are recalculated as follows.

$$t_{1\max} = \frac{z_{1\max}}{w_1 \cdot N} = \frac{\$30M}{0.7 \cdot 2} = \$21.4M \tag{3.17}$$

$$t_{2\max} = \frac{z_{2\max}}{w_2 \cdot N} = \frac{40\%}{0.3 \cdot 2} = 66.67\% \tag{3.18}$$

where, t_{1max} and t_{2max} are recalculated criterion values for monetary loss and function loss, respectively, and N is the number of attributes (2 in this case). As shown in Figure 3.20 (b), this makes the POS of the alternative zero, as no portion of the PDF lie in the adjusted area of interest. To prevent this sudden change of POS due to adjusted criterion values, an alternative approach to treat relative weights must be presented. While the main focus of this study is not the development of a remedy for JPDM, a suggestion is briefly made here and further issues related to modifications of JPDM (such as validation) are recommended for future work.

It is undesirable to have an adjusted criterion value based on relative weights become less than minimum consequence value (or larger than maximum consequence value). Therefore, Equation 3.14 should be modified such that the following requirements are satisfied. For each criterion with a boundary C,

$$\lim_{w \to 0} t_{\max} = \infty \quad \left(\lim_{w \to 0} t_{\min} = -\infty \right) \tag{3.19}$$

$$\lim_{w \to 1} t_{\max} = C_{\min} \quad \left(\lim_{w \to 1} t_{\min} = C_{\max} \right) \tag{3.20}$$

$$t_{\max} = z_{\max} \; \left(t_{\min} = z_{\min} \right) \text{ if } \; w = \frac{1}{N} \tag{3.21}$$

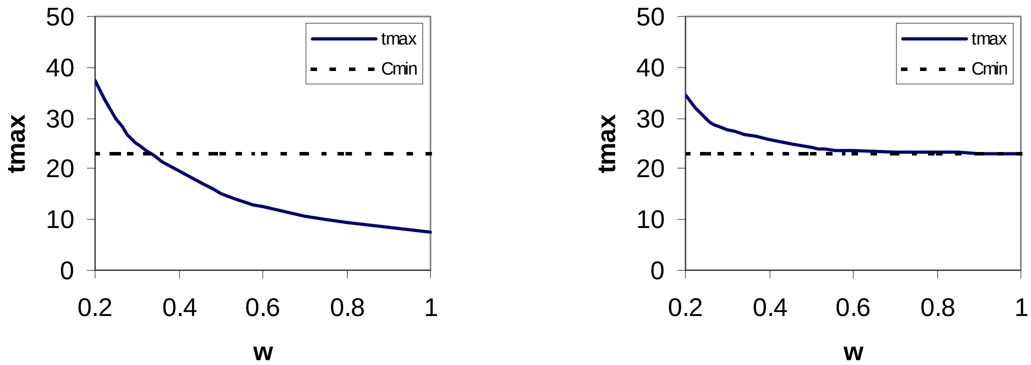
where t_{max} and t_{min} are adjusted target criterion values, z_{max} and z_{min} are original target criterion values, and C_{min} and C_{max} are maximum and minimum boundary of consequence, respectively.

An alternative way to adjust criterion values that satisfies above requirements is proposed as follows. If a maximum (or minimum) boundary exists in the consequence distribution,

$$t_{\max} = C_{\min} + \frac{z_{\max} - C_{\min}}{(w \cdot N)} \cdot \frac{1 - w}{w \cdot (N - 1)} \quad [3.22]$$

$$t_{\min} = C_{\max} - \frac{C_{\max} - z_{\min}}{(w \cdot N)} \cdot \frac{1 - w}{w \cdot (N - 1)} \quad [3.23]$$

These equations are established such that the three requirements stated above (Equation 3.19- 3.21) are satisfied. To illustrate the difference between the original and revised approach, the relationship of the relative weight and the adjusted criterion value for a case where N=4, C_{min}=23, and z_{max}=30 using the traditional approach (as depicted in Equation 3.13) and the revised approach (Equation 3.22 and 3.23) is shown in Figure 3.21 (a) and (b), respectively. Use of the traditional approach (Figure 3.21 (a)) yields t_{max} less than C_{min} when w is larger than approximately 0.32. On the other hand, the revised approach makes t_{max} go toward C_{min} with increasing w, which is one of the requirements. When w=0.25, which should not make an adjustment of the criterion value, both the original and revised approaches give $t_{max} = z_{min} = 30$.



(a) with traditional approach (b) with revised approach

Figure 3.21 Relationships of Adjusted Criterion Value and Relative Weight

Although Equations 3.22 and 3.23 above seem to be adequate solutions for treatment of relative weights by satisfying the requirements, further exploration regarding trade-offs in JPDM is needed. For example, criterion values may have to be adjusted considering the range of possible consequence as well as relative weights. Further discussion regarding the issue of trade-offs in JPDM is suggested for future work, as the main focus of this study is not on the remedy of JPDM.

CHAPTER 4

PROBABILISTIC EVALUATION OF SEISMIC PERFORMANCE OF STRUCTURAL SYSTEMS

In Chapter 2, it is discussed that in order to perform a decision analysis, the decision problem must be defined followed by identification of the objectives and the alternatives, and the predicted consequences should be estimated so that the trade-offs among the values can be possible. The consequences associated with the seismic damage to structural systems may include various losses such as life loss, structural/nonstructural repair cost, contents loss, business interruption, function loss, etc. In order to perform a decision analysis, these losses must be measured quantitatively. In decision problems on seismic rehabilitation, these losses are functions of input earthquake, structural capacity of the system, and social and economical factors of the system such as the occupancy (building usage) type, number of occupants, replacement value of the structure(s), discount rate, etc. It should be noted that the uncertainties inherent in each step should be incorporated into quantification of the losses.

In many cases, the seismic losses associated with structural systems are estimated from the physical damage of the systems (HAZUS, 1999, Ang and De Leon, 1997, Thiel, 1997). Therefore, the damage assessment analysis must be performed first in order to estimate the seismic losses. Obviously, the characteristics of the earthquakes with respect to the location of the system should be previously identified in order to perform the damage assessment of the system. Figure 4.1 shows the schematic view of the steps required to develop the data associated with seismic losses needed for decision analyses in seismic rehabilitation. Among them are the methods and procedures for assessing the damage of structural systems due to seismic hazards which are described in this chapter. Incorporation of uncertainty inherent in the seismic hazard and the system demand and capacity is emphasized. Procedures for identifying hazard inputs are discussed first, followed by damage assessment of structural systems utilizing the fragility curves of the structural systems. Issues on seismic loss estimation will be discussed in Chapter 6.

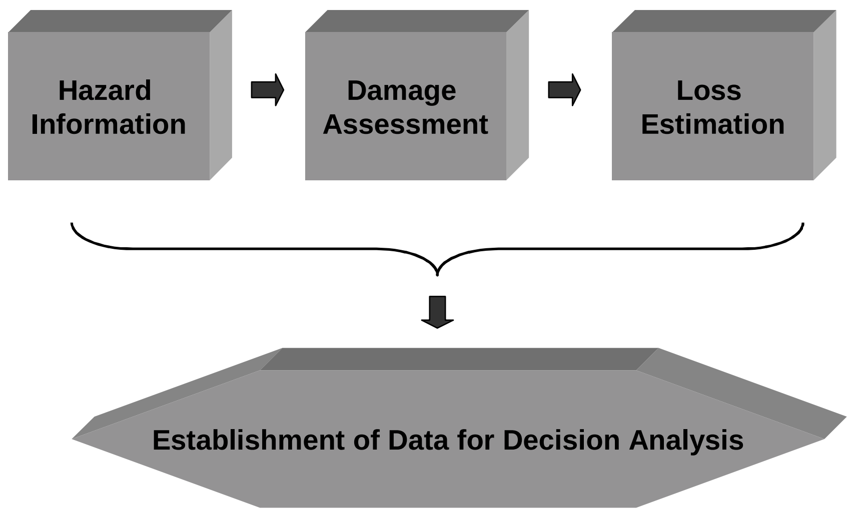


Figure 4.1 Steps Required to Develop Data Associated with Seismic Losses for Decision Analysis

4.1 Consideration of Earthquakes

Before the damage assessment analysis is performed, representative earthquakes for the location of the system of concern must be defined for use in the damage analysis. The ground motion intensity is often characterized in terms of spectral displacement (S_d) or spectral acceleration (S_a). However, since the earthquake itself is a random event, which depends on location, it is also necessary to identify the probabilistic characteristics of the earthquake intensity as well. Usually the likelihood of earthquake levels is expressed in terms of probability of exceedance within a certain time limit. For example, 10% probability of exceedance in 50 years can be used to describe the likelihood of the level of an earthquake. In this case, the annual probability of exceedance of this earthquake can be obtained from the following expression.

$$1-(1-p)^{50}=0.1 \qquad [4.1]$$

where, p is the annual probability of exceedance. In this case the annual probability of exceedance of the earthquake is 0.00210499. Therefore, the return period of this earthquake is,

$$\lambda=\frac{1}{p}=\frac{1}{0.0021}=475\,(years) \qquad [4.2]$$

In other words, an earthquake which equals or exceeds this level is expected to occur once every 475 years.

In order to characterize seismic demand on building structures, response spectra can be used. FEMA (1997) provides a procedure for generating a response spectrum corresponding to a specific probability level (e.g., 2% of probability of exceedance in 50 years). Note that the response spectrum is developed in such a way that the damping level of the structure and the hysteretic energy effect are considered. Once the location of the system is identified, the spectral acceleration of the structure corresponding to the location can be defined. USGS (2003) provides an interactive website (http://eqhazmaps.usgs.gov/) where the spectral accelerations of several probabilistic earthquake hazard levels (10%, 5%, and 2% probability of exceedance in 50 years) corresponding to several different period values (0.2, 0.3, and 1.0 second) can be obtained for any particular location within the US by entering the zip code. Based on the resulting spectral accelerations, the site class information for the location is used to construct a response spectrum of an earthquake with an arbitrary probability of exceedance. Figure 4.2 shows an example response spectrum (or demand spectrum) generated for Memphis, TN 38103 area with a probability of exceedance of 2% in 50 years for 5% damping. The detailed procedure can be found in FEMA (1997).

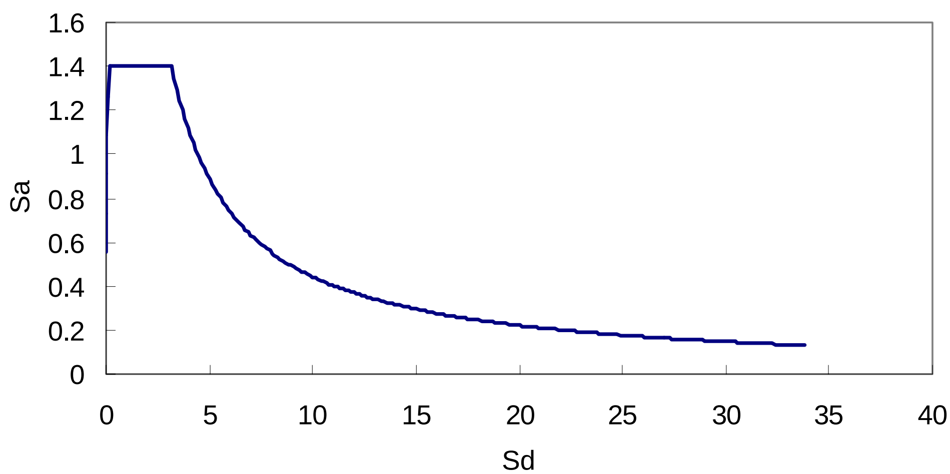
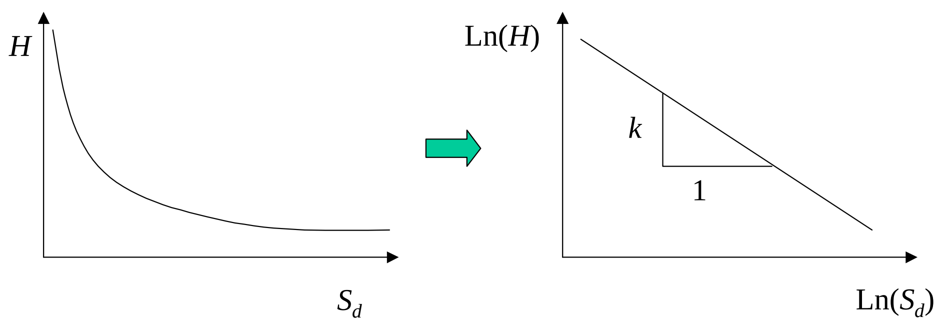


Figure 4.2 Response Spectrum for an Earthquake with 2% PE in 50 years (Memphis, TN38108)

The relationship between the earthquake intensity and its likelihood can be represented by a hazard function *H* (Cornell et al., 2002, Yun et al., 2002). The annual probability of exceedance for a given earthquake intensity (generally s_a or s_d) at the site can be obtained from the hazard function. According to Cornell et al. (2002), the hazard function can be approximated as a linear function on a log-log plot. That is, if the hazard function is defined in terms of spectral displacement s_d, the hazard function can be expressed in the form

$$H(s_d) = P[S_d \geq s_d] = k_0 s_d^{-k} \qquad [4.3]$$

Parameters k_0 and k are to be determined and are location-specific. The hazard curve is shown schematically in Figure 4.3.



$$H(s_d) = P[S_d \geq s_d] = k_0 s_d^{-k}$$

Figure 4.3 Hazard Curve

4.2 Damage Assessment of Structures

To estimate losses due to a possible seismic hazard, a damage assessment of corresponding structural system must be performed first. If the damage state of a building is obtained, the damage state can be used as an input for calculation of various seismic losses. The procedure for obtaining the probabilistic damage state of a structure or a group of structures due to a hazard input is discussed in this section.

In order to discuss the damage assessment, the seismic performance objective for a structure must be defined. A performance objective can be defined by the structural performance level and corresponding probability that the performance level can be exceeded within certain time limit (Yun et al., 2002). According to SAC (2000), for example, the performance objective level for a new building is less than 2% chance of damage exceeding Collapse Prevention (CP) in 50 years. In other words, the seismic performance level of a structure can be represented in terms of the seismic damage probability.

According to Cornell et al. (2002), a closed form solution is available for description of the damage probability of a structure under several assumptions. As a starting point, three major sources of uncertainty in seismic damage assessment of structural systems are identified: (1) the ground motion intensity, the likelihood of which can be represented by hazard curve as described in the previous section, (2) structural demand and (3) capacity (Cornell et al., 2002). There are a number of ways to measure the structural demand and capacity such as the maximum inter-story drift or various types of damage indices. The generic expression for the annual probability, that the demand *D* exceeds a specific value *d*, or $H_D(d)$, is as follows:

$$\begin{aligned} H_D(d) = p[D \ge d] &= \sum_{all\ x_i} P[D \ge d \mid S_d = x_i]P[S_d = x_i] \\ &= \int P[D \ge d \mid S_d = x] \left| dH(x) \right| \end{aligned} \qquad [4.4]$$

The damage probability (annual probability of exceeding certain damage level) P_{PL} can then be expressed as:

$$P_{PL} = P[C \le D] = \sum_{all\ d_i} P[C \le D \mid D = d_i] P[D = d_i] \quad [4.5]$$

where *C* is the structural capacity. If it is assumed that the capacity level is independent of a specific demand level (Cornell et al., 2002), the equation can be expressed as follows:

$$P_{PL} = \int P[C \le d] \left| dH_D(d) \right| \quad [4.6]$$

As discussed in the previous section, it can be assumed that the hazard curve is expressed as in Equation 4.3. The structural demand for a given earthquake level and the structural capacity can be assumed to follow a lognormal probability distribution (Cornell et al., 2002). Given the earthquake intensity, S_d, the probability of demand exceeding a certain level *d* can be approximated as follows:

$$P[D \ge d \mid S_d = x] = 1 - \Phi\left(\frac{\ln\left(d / \hat{D}\right)}{\beta_{D|Sd}} \right) \quad [4.7]$$

where $\hat{D}$ is the median demand level given the spectral displacement level S_d and $\beta_{D|S_d}$ is the standard deviation of the natural logarithm of the demand level. The structural capacity is assumed to follow lognormal distribution with a median $\hat{C}$ and standard deviation β_C. Therefore, the probability of structural capacity less than certain level *d* is as follows:

$$P[C \leq d] = \Phi\left(\frac{\ln\left(d / \hat{C}\right)}{\beta_C}\right) \qquad [4.8]$$

As a result, the damage probability (annual probability of exceeding certain damage level) in Equation 4.6 can be approximated as follows:

$$P_{PL} = H(S_d{}^{\hat{C}}) \exp\left[\frac{k^2}{2}\left(\beta^2{}_{D|S_d} + \beta^2{}_C\right)\right] \qquad [4.9]$$

where $S_d{}^{\hat{C}}$ is the spectral displacement corresponding to the median capacity and *k* is determined as shown in Figure 4.3. Therefore, if the demand hazard curve is defined for the region and if the median capacity can be obtained along with the dispersions of the capacity and the demand, the damage probability distribution of a structure located in a particular region can be obtained. The probability distribution of seismic losses for the structure can then also be obtained from the damage distribution. It should be noted that this closed form solution for the damage distribution should be used for a single structure. In order to use the formula for a class of structure with same structural type, the structures must be located close to each other within a region, so the seismicity for the structures can be represented by a single hazard curve. For aggregation of losses of different types of structures, the closed form expression for the damage distribution is rarely available. The issue of aggregation of losses will be discussed again in Chapter 6.

HAZUS Damage Assessment

The spectral displacement of a particular structure due to a specific level of earthquake can be obtained from the capacity spectrum method, which is the method used in HAZUS (1999) for physical damage assessment of building structures. HAZUS, which stands for "Hazards U.S.", is an integrated computer-based framework developed by the Federal Emergency Management Agency (FEMA) that estimates and represents the expected losses and risks in a region due to seismic hazard throughout the U.S. For performing damage assessment of multiple building systems, the buildings must be classified based on the structural type and height, on which the physical damage assessment of a structure can be based. In HAZUS, 36 model-building types are provided based on the building structural type and the building height, as shown in Table 4.1 along with the description of each type. In HAZUS, the determination of the building damage state probability makes use of the building fragility curves and the building capacity curves. The fragility curves for a particular structural type can be obtained for four different design code levels used for designing the building (pre, low, moderate, and high code level). HAZUS provides an extensive list of parameters that are needed to generate fragility curves for all 36 types of structures and for four different code levels. The fragility curves can then be generated for four different damage states – slight, moderate, extensive, and complete damage. For detailed description of the damage states, see HAZUS (1999). For a given spectral displacement, the fragility $F_{R,ds}$ of a structure is defined in HAZUS as follows:

$$F_{R,ds}(s_d) = \Phi\left(\frac{\ln\left(s_d / \hat{s}_{d,ds}\right)}{\beta_{ds}}\right) \qquad [4.10]$$

where Φ is the cumulative distribution function of a standard normal variate, s_d is the given spectral displacement upon which the probability of exceeding a damage state is calculated, $\hat{s}_{d,ds}$ is the median spectral displacement at which the building reaches the damage state *ds*, and β_{ds} is the standard deviation of the lognormal distribution of the spectral displacement of the damage state. HAZUS provides a list of values for these parameters.

The peak building response due to a specific level of earthquake, which is expressed in terms of spectral displacement for building structures, is obtained from the intersection of the corresponding response spectrum and the building capacity curve, which is determined from a static nonlinear pushover analysis. Then from the fragility curves, the probability of being in or exceeding various damage states can be obtained. The schematic view of extracting the damage probability is shown in Figure 4.4.

Table 4.1 Building Structure Types (HAZUS, 1999)

No.	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1 2	W1 W2	**Wood, Light Frame (≤ 5,000 sq. ft.)** **Wood, Commercial and Industrial (> 5,000 sq. ft.)**		1 - 2 All	1 2	14 24
3 4 5	S1L S1M S1H	**Steel Moment Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
6 7 8	S2L S2M S2H	**Steel Braced Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
9	S3	**Steel Light Frame**		All	1	15
10 11 12	S4L S4M S4H	**Steel Frame with Cast-in-Place Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
13 14 15	S5L S5M S5H	**Steel Frame with Unreinforced Masonry Infill Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
16 17 18	C1L C1M C1H	**Concrete Moment Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
19 20 21	C2L C2M C2H	**Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
22 23 24	C3L C3M C3H	**Concrete Frame with Unreinforced Masonry Infill Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
25	PC1	**Precast Concrete Tilt-Up Walls**		All	1	15
26 27 28	PC2L PC2M PC2H	**Precast Concrete Frames with Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
29 30	RM1L RM2M	**Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms**	Low-Rise Mid-Rise	1-3 4+	2 5	20 50
31 32 33	RM2L RM2M RM2H	**Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
34 35	URML URM M	**Unreinforced Masonry Bearing Walls**	Low-Rise Mid-Rise	1 - 2 3+	1 3	15 35
36	MH	**Mobile Homes**		All	1	10

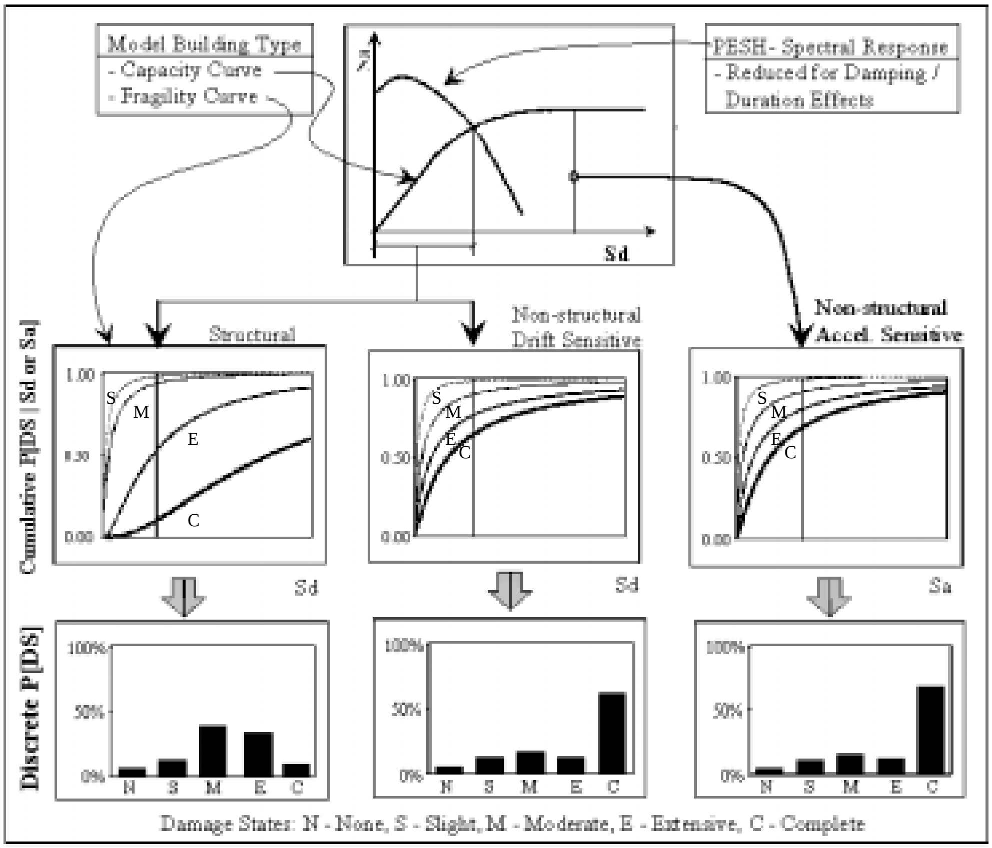


Figure 4.4 The HAZUS Building Damage Assessment Procedure (HAZUS, 1999)

In order for a decision problem to take effect, the consequences of the alternative systems also must be known. In the decision problems in seismic rehabilitation of structural systems, different rehabilitation options must be identified as alternatives. For a particular individual structure, detailed rehabilitation options that are appropriate for the structure can be identified considering its specific characteristics such as detailed configuration and dimensions. However, in the HAZUS approach where a large number of structures are under consideration and the damage is assessed for each class of structures, and not for an individual structure alone, specific rehabilitation options cannot be defined because the varying specific characteristics of individual buildings cannot be taken into account. In this case, the rehabilitation options can instead be defined in terms of target performance levels that the corresponding rehabilitation can achieve for a particular class of structures. In this way, the performance and required cost of a rehabilitation action can be obtained and used for decision analysis. For example, FEMA (1995) provides typical costs for different seismic rehabilitation options for specific classes of structures to achieve a specific performance level. The consideration of rehabilitation options using this approach is discussed in more detail in Chapter 6.

Example

An illustrative example of physical damage assessment of a building system using fragility information provided in HAZUS is now presented. In fact, fragility curves can be generated for both structural damage and nonstructural damage using HAZUS damage assessment data. The nonstructural damage fragility curves consist of acceleration-sensitive component fragility curves and drift-sensitive component fragility curves (HAZUS, 1999). In this way, the structural, acceleration-sensitive nonstructural, and drift-sensitive nonstructural damage can be assessed separately using their own fragility curves. In this example, however, only structural damage assessment will be performed because the purpose of the example is to illustrate the basic methodology. For this example, a C1M type (mid-rise concrete moment frame) structure located in Memphis, TN38103 (zip code is arbitrarily chosen for illustration purpose) is considered. It is assumed that the code level of the building is corresponding to the Low-Code level in HAZUS. From USGS (2003), the spectral accelerations of several probabilistic earthquake hazard levels (10%, 5%, and 2% probability of exceedance in 50 years) corresponding to several different period values (0.2, 0.3, and 1.0 second) are obtained for the location as discussed in Section 4.1. Three different hazard levels are considered for generation of the hazard curve corresponding to the region, and they are 2%, 5%, 10% of probability of exceedance (PE). The response spectra for the three levels of earthquakes are generated following steps in FEMA 273 (1997), and the capacity spectrum of Low-Code C1M type structure is also generated using the parameters provided in HAZUS. The resulting response spectra and the capacity spectrum are shown in Figure 4.5. The fragility curves for low-code C1M type structures can be generated for four different damage states using the parameters from HAZUS listed in Table 4.2, and the resulting fragility curves are shown in Figure 4.6. Note again that the fragility curves are generated assuming log-normal distributions, without performing detailed structural analyses.

Table 4.2 Fragility Parameters for C1M Structures
(extracted from HAZUS, 1999)

damage state / parameter	Slight	Moderate	Extensive	Complete
Median Spectral Displacement ($\hat{s}_{d,ds}$, inches)	1.5	2.4	6	15
Standard Deviation (β_{ds})	0.7	0.74	0.86	0.98

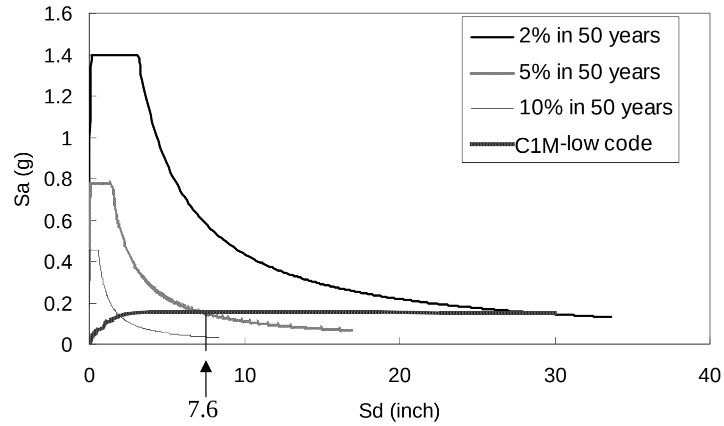


Figure 4.5 Response and Capacity Spectra for TN 38103

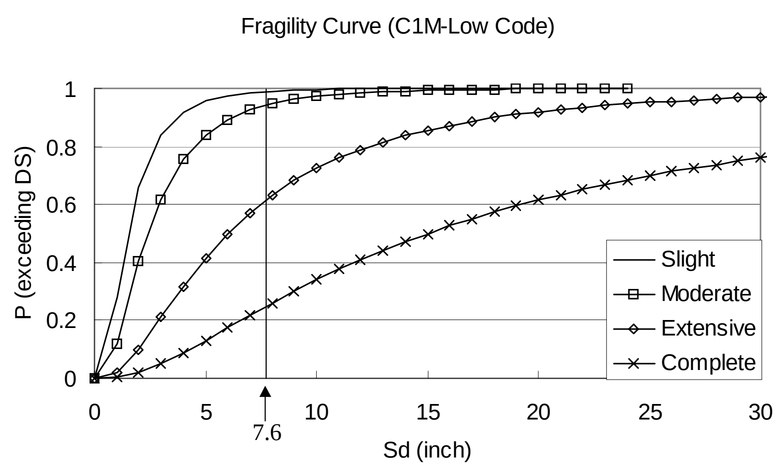
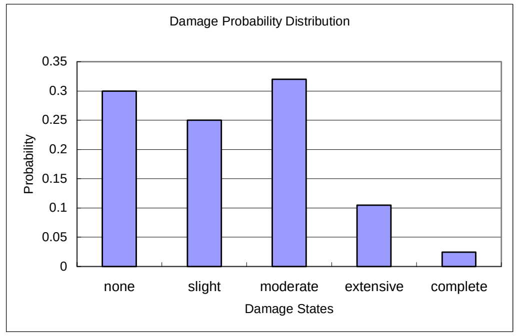


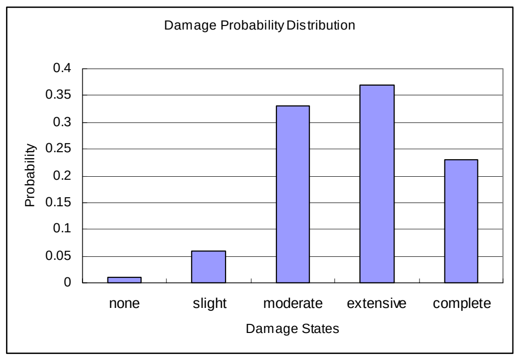
Figure 4.6 Fragility Curves for Structural Damage of Low-Code C1M Type Structures

The spectral displacement of the structure for each earthquake level is obtained from the intersection of the corresponding response spectrum and the capacity spectrum (Figure 4.5), and the damage probability distribution of the structure for each level of earthquake can be read from the corresponding fragility curve. For example, the spectral displacement corresponding to earthquakes with 2% probability of exceedance in 50 years is 7.6 inches in Figure 4.5. Then the probability of exceeding a particular damage level is read from the fragility curve as shown in Figure 4.6. The probabilities of exceeding slight, moderate, extensive, and complete damage are 0.99, 0.94, 0.61 and 0.24, respectively. Therefore, the probabilities of the structure being less than slight damage, in slight damage, in moderate damage, in extensive damage, and in complete damage are 0.01 (=1-0.99), 0.06, 0.33, 0.37 and 0.24, respectively. As a result, the discrete probability distribution of the structure due to specific levels of earthquake can be obtained as shown in Figure 4.7. For a complete decision analysis, the nonstructural damage distributions must also be obtained so that various kinds of losses can be estimated based on the associated damage distributions.

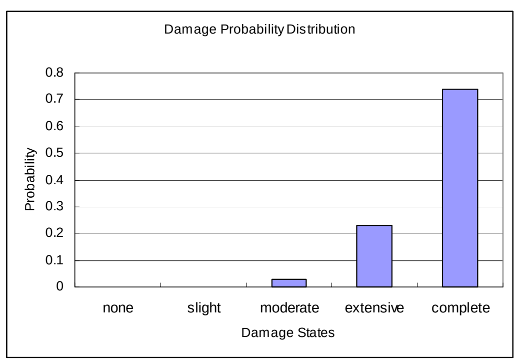
The damage distributions obtained and shown in Figure 4.7 are conditional probability distributions given the specified earthquake levels. However, the damage distribution within a certain time period considering all possible levels of earthquake can be also obtained using Equation 4.9. By matching the peak spectral displacements corresponding to the hazard levels, and obtained from Figure 4.5, to the annual probability of exceedance, the hazard function shown in Figure 4.8 can be defined.



(a) Damage Distribution due to Earthquake with 10% PE in 50 years



(b) Damage Distribution due to Earthquake with 5% PE in 50 years



(c) Damage Distribution due to Earthquake with 2% PE in 50 years

Figure 4.7 Damage Probability Distributions for Low-Code C1M Structures used in the Example

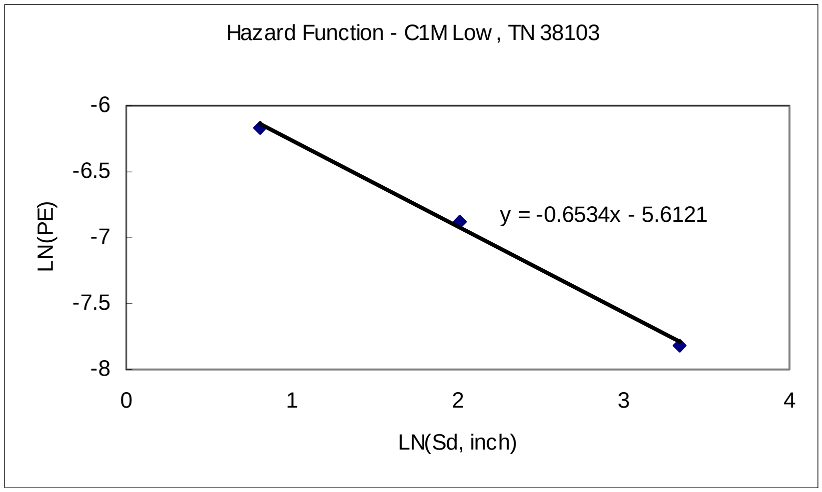


Figure 4.8 Hazard Curve for C1M (Low Code) Structure Generated for TN 38103

From the regression line, the required parameters in Equation 4.3 can now be defined as follows: $k_0 = 1/e^{5.6121} = 0.0036534$ and $k = 0.6531$. Substitution of these values to Equation 4.5 yields the damage probabilities that are coupled with the hazard levels within a particular time period. Table 4.3 shows the damage probabilities that are obtained for 50-year time period. Note that the numbers in the table are the probabilities of exceedance. That is, for example, the probability that the damage state will exceed an extensive damage state (i.e., being either extensive or complete damage) within 50 years is 6.42%. Therefore, the probability of the damage states being extensive damage will be 6.42% - 3.75% = 2.67%.

Table 4.3 Damage Probability within 50 years

	Slight	Moderate	Extensive	Complete
$\hat{s}^c{}_d$	1.5	2.4	6	15
β	0.7	0.74	0.86	0.98
Annual PE	0.003112	0.002318	0.001327	0.000764
PE within 50 years	14.43%	10.95%	6.42%	3.75%

Physical damage of structural systems due to earthquakes is estimated considering uncertainties on seismic hazard and structural systems. Outputs from damage assessment are key inputs for estimation of various seismic losses, which are essential part of decision analyses for seismic rehabilitation. The application of probabilistic damage assessment to the decision analyses is demonstrated in detail in Chapters 6 to 8.

CHAPTER 5

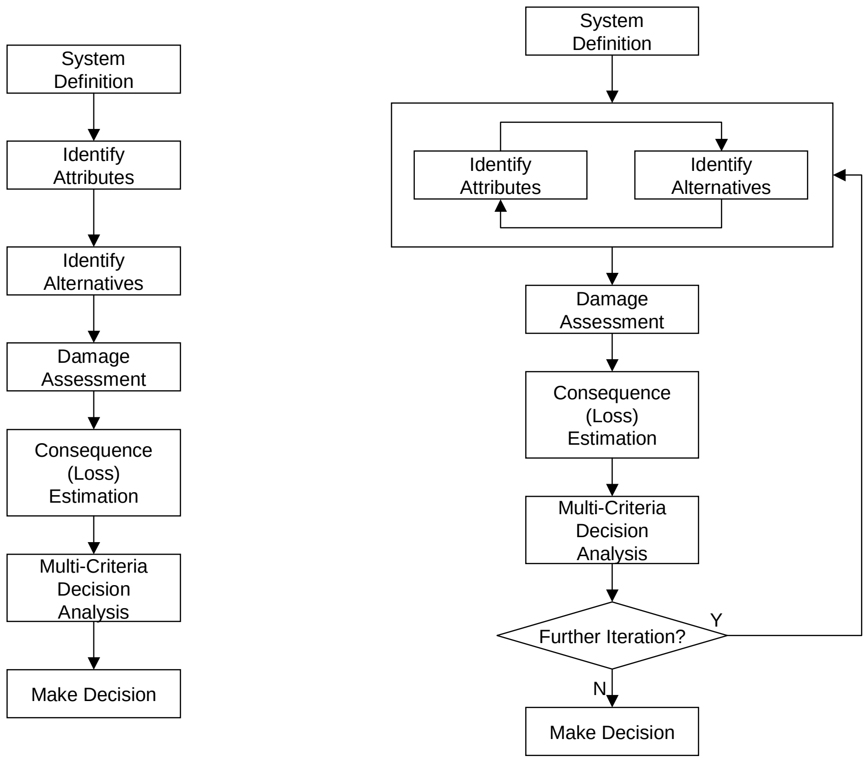
PROCEDURE FOR DECISION ANALYIS IN SEISMIC REHABILITATION

In the previous chapters, the supporting theories and techniques required for decision analysis in problems of seismic rehabilitation are discussed. Basic knowledge about decision analysis and multi-criteria decision-making techniques that are applicable for problems with uncertainties are discussed along with some examples. In addition, the importance of dynamic problem structuring in making decisions is addressed. In addition, the procedures of different approaches for probabilistic evaluation of seismic performance of structural systems, where the uncertainties inherent in both the structural systems and the seismic hazard are incorporated, are illustrated.

In this chapter, a decision procedure for seismic rehabilitation of structural systems is developed. To accomplish this, the techniques and procedures mentioned in the prior chapters are utilized. Detailed explanation is provided for each step of the decision procedure. The data (either deterministic or probabilistic) that are needed in each step, the procedure for manipulating the data, and the outputs from each step will be identified. The application of this framework will be given as well in the chapters to follow.

5.1 Dynamic Decision Structure

As mentioned in Chapter 2, the structuring of decision problems is the most important part of the decision making process. The decision framework developed in this study focuses on the dynamic decision structuring, where the decision maker's values and alternatives can be re-defined as the decision maker obtains better insight into the problem. The schematic view of the decision procedure is illustrated in Figure 5.1. Figure 5.1 (a) and (b) are decision flowcharts for seismic rehabilitation of structural systems based on static structuring and dynamic structuring, respectively. In the static decision problem structuring shown in Figure 5.1 (a), the attributes and alternatives are first identified, and the damage and losses are assessed for the alternative systems. A MCDM technique is then utilized, and the values of the attributes are elicited and quantified. Finally, the best alternative is determined based on the chosen decision analysis approach considering the estimated consequences and the elicited quantified values. However, in the static decision flowchart, the decision is made solely based on initially defined attributes and alternatives. In addition, the decision maker's subjective values of the attributes are extracted (or quantified) only once and there is no further update of the values. Therefore, the fact that the decision makers can learn and have better insight into the problem as they iteratively re-define the attributes and alternatives, re-assess the consequences, and re-elicit the corresponding values, is not taken into consideration in the problem structuring. In Figure 5.1 (b), a dynamic decision-making process is achieved, in which attributes and alternatives of a problem are configured iteratively. In addition, another iteration loop exists for re-formulation of the multi-criteria decision analysis. By doing this, the decision maker will be able to see and compare various consequences based on different configurations of his/her values and alternatives. Thus the dynamic decision procedure can be formulated as the following six components: 1) system definition, 2) identification of attributes and alternatives, 3) damage assessment, 4) consequence (loss) estimation, 5) multi-criteria decision making, and 6) further iteration. The explanation of each step of the dynamic decision flowchart is described in the following sections.



(a) Static Decision Flowchart (b) Dynamic Decision Flowchart

Figure 5.1 Static vs. Dynamic Decision Flowcharts

5.2 System Definition (Step 1)

The first step is system definition, where the system of interest is identified. The structural properties, locations, and functions of the building systems are defined at this stage. The locations of the systems are necessary information used for definition of the hazard. For example, the response spectrum corresponding to an arbitrary earthquake level can be generated for a particular location. The structural properties are then needed to anticipate the seismic damage of the system. As mentioned in Section 4.2, different kinds of information on the structural properties are needed depending on the damage assessment approach. If the system of interest consists of a large number of building systems, where building-specific analyses are impractical, the damage assessment can be performed for each type of structure whose responses are assumed to be the same so the damage states can be obtained from the representative fragility curves. On the other hand, if the system of concern is a particular individual structure, it would be necessary to perform a number of dynamic analyses taking the uncertainties inherent in the system into consideration to obtain the parameters needed to generate the fragility curves so that the building-specific damage assessment can be obtained.

Along with structural properties, the functionality of the system and any other critical attributes of interest to the decision maker (e.g., nonstructural properties) must be identified in this step. Once the likely physical damage to the system is assessed from the seismic hazard and system's structural properties, expected seismic losses (or consequences) associated with the system can be estimated from information on both the physical damage and the functional type of the system. There are many different types of building structures and an appropriate way of measuring the functionality of each type of structure must be available. For example, the functionality of a fire station might be measured in terms of the number of the available fire engines, personnel, or any other measure of capacity to handle some standard or peak number of fires.

The social and economic aspects of the system must be defined in this step as well. The number of the occupants, building replacement value, building contents value, etc, should be estimated if it is of interest to the decision maker so that the consequences of a scenario earthquake can be estimated as accurately as possible.

5.3 Identification of Attributes and Alternatives (Step 2)

Once the system is defined, the attributes and the alternatives that are suitable for the problem can be identified. The attributes of concern for a specific decision analysis can vary depending on who the decision maker is and what kind of building system is of concern to the decision maker. These attributes of concern can be referred to as the assets at risk in the event of an earthquake. The California Seismic Safety Commission (CSSC, 1999) defines the assets at risk as 'whatever a decision maker is responsible for, is what is at risk from earthquakes', and provides an extensive list of the assets at risk for both the private and public sector along with the corresponding mitigation actions (see Table 5.1 and Table 5.2). However, these attributes are not static because at different stages of the decision analysis, the decision maker may be concerned with attributes other than those listed in the table. In addition, the attributes of concern to a decision maker may change after the decision maker reviews the seismic consequence (losses) of the system and the decision analysis results, as described in the following sections.

As shown in Figure 5.1, the selection of attributes and alternatives for analysis should be a dynamic, recursive process, where the determination of one can affect the determination of the other. However, at the initial phase of this process, usually only the attributes are identified. The alternatives are considered after going through at least one iteration of the damage assessment and loss estimation of the system. That is, if the system seismic risk appears unacceptable to the decision maker after evaluation, the decision maker might consider possible intervention methods to reduce the seismic risk to the system. From the viewpoint of structural engineering, there can be a number of intervention options, which include strengthening the structural components, using base isolation, providing damping, ground foundation improvement, etc. For example, the seismic deficiencies of reinforced concrete shear wall buildings include insufficient shear wall strength, inadequate coupling beams, overturning potential, poor frame and wall interconnection. The typical rehabilitation measures for these deficiencies could include filling in existing openings, thickening walls to add strength, adding lateral-force-resisting elements to reduce loads on existing members, or increasing flexural strength of walls by increasing the size of boundary elements. Total replacement of the building or changing the usage of the building is other intervention option.

If the system of interest consists of multiple building systems where an approximate damage assessment approach is used, the building stock can be divided into several classes based on their structural model type, function (usage) type, or dimensions, for example. Effective options for a specific class of building can then be provided to reduce the seismic risk. Research is needed to identify possible effective intervention schemes for either a single building or a specific class of buildings. It should be noted that the task of identifying appropriate intervention options is beyond the scope of this study, and generic options will be assumed (e.g., rehabilitation to life safety performance level), if insufficient information is available. The cost of seismic rehabilitation of building systems depends on many factors, such as building type, earthquake hazard level, desired performance level, occupancy or usage type, location, or time required to complete the construction. Some FEMA documents (FEMA, 1992, FEMA, 1995) provide the typical costs for rehabilitation of existing structures taking into account the factors mentioned above. In this study, the cost for seismic rehabilitation is adopted from these documents and used in this investigation.

For the case where the system of concern is a single building, the alternative rehabilitation schemes can be identified more specifically. For example, adding bracing systems, shear walls, or replacing weak structural components can strengthen the structures. Accordingly, the cost for the rehabilitation and corresponding performance level can also be determined with better accuracy. The value of each intervention scheme is compared with that of the existing system in the decision analysis.

Table 5.1 Private Sector Assets at Risk (CSSC, 1999)

Asset / Loss	Earthquake Threat	Mitigation Alternatives
❑ People/ death and injury	♦ Building damage/collapse, via ground shaking, fault rupture, or other earthquake hazard	▪ Strengthen the building ▪ Base isolate the building ▪ Provide supplemental damping ▪ Provide ground or foundation improvements, if ground failure is the issue ▪ Replace the building (i.e., move, or new construction)
	♦ Building contents damage	▪ Inventory all contents and brace or otherwise reduce damage
	♦ Equipment malfunction	▪ Identify and review critical equipment for continuity of functionality during and after and earthquake (e.g., check for relay chatter, backup power, water, fuel etc) ▪ Assure equipment will not be damaged (i.e., brace etc) ▪ Provide redundant equipment ▪ Develop emergency plans and procedures for equipment malfunction
	♦ Offsite threats	▪ Identify and review neighborhood for earthquake hazards (e.g., tsunami, landslide) and threats (e.g., nearby hazardous operations, such as a chemical process plant) ▪ Develop Emergency plans and procedures, including possible warning mechanisms ▪ Build protective barriers ▪ Acquire protective equipment and training (e.g., fire brigades) ▪ Modify offsite threat (e.g., earthmoving, for a landslide; or buy out nearby hazardous operation; or move)
❑ Building, equipment damage/ financial loss	♦ Same as above ♦ Inventory	▪ Same as above, plus ▪ Emergency plans and procedures to minimize damage (e.g., recovery of inventory; quick shut-down of broken sprinklers) ▪ Earthquake insurance
❑ Function/ BI, loss of revenue, market share	♦ Same as above plus loss of infrastructure (e.g., transportation), loss of vendors	▪ Contingency planning for loss / replacement or recovery of facilities (e.g., backup sites or suppliers, rapid recovery via pre-arranged inspection and repair contractors) ▪ Financial planning for loss of revenue ▪ Earthquake / Loss of profits insurance ▪ Planning for alternative production / transportation to maintain market share

Table 5.2 Public Sector Assets at Risk (CSSC, 1999)

Asset / Loss	Earthquake Threat	Impacts
❑ People/ death and injury	♦ Structure damage/collapse, via ground shaking, fault rupture, or other earthquake hazard ♦ Building contents damage ♦ Equipment malfunction	▪ Residential – single family dwellings, apartments, hotels, dormitories ▪ Commercial – offices, stores, factories, restaurants ▪ Public facilities – schools, correctional facilities, offices ▪ Public assembly – theaters, halls, stadiums ▪ Essential facilities – hospitals, police / fire stations ▪ Lifelines – power, water, sewer, gas and liquid fuels, highways, ports, airports, railroads, telephone and other communications ▪ Hazardous Facilities – dams, industrial facilities
❑ Structure, equipment damage/ financial loss	♦ Same as above	▪ For public sector, portion of repair costs not reimbursed by state / federal aid
❑ Function/ BI, loss of revenue, market share	♦ Same as above	▪ Employment – private sector loss of jobs (closed factories, loss of tourism, …) ▪ Tax base / revenues (sales, real estate, …)
❑ Reputation	♦ Lack of timely recovery	▪ Loss of population ▪ Existing business decides to rebuild elsewhere ▪ Loss of new investment, development, tourism… ▪ Breakdown in political process – squabbling as to best path to recovery … ▪ Loss of political office

5.4 Damage Assessment (Step 3) and Loss Estimation (Step 4)

In Chapter 4, the probabilistic seismic evaluation of damage to structural systems is discussed in detail. The physical damage of structural systems is quantified probabilistically as an input for the loss estimation of the system. In this study, the HAZUS (HAZUS, 1999) loss estimation method is utilized. The HAZUS loss estimation methodology is based on the assumption that there are strong relationships between building damage and various kinds of losses. The major losses that are pertinent to earthquake events can be classified into social losses and economic losses. The social losses include death and injury to occupants, loss of housing habitability, short term shelter needs, etc, whereas the economic losses include structural repair cost, nonstructural repair cost, building contents loss, business inventory loss, loss of building function, initial rehabilitation cost, etc.

It should be noted that the loss estimation for structural systems should be performed based not only on the type of the structure and associated damage assessment but also the occupancy type of the structure. That is, if a hospital and an office building are located in the same seismic location and the structural configurations are identified, the seismic damage due to an earthquake will be same. However, the losses will differ because of other important differences, such as the number of occupants, building contents, and function of the building. To incorporate the effects of different occupancy types of structures, HAZUS also provides 28 building occupancy category classes in addition to the 36 building structures types. Table 5.3 shows the building occupancy category classes along with example descriptions. For each building occupancy class, and for each building structural type, various seismic losses such as structural/nonstructural repair cost, contents loss, time to repair, life loss, etc, can be estimated from the seismic damage. Figure 5.2 shows the influence diagram for loss estimation. The structural and nonstructural damage state probabilities can be obtained from the hazard inputs and building structural type. The loss estimation can then be performed based on the building structural type, occupancy type, and the damage states. Note that physical seismic damage of a structure is probabilistically assessed in HAZUS. However, seismic losses are deterministically estimated from damage states. That is, uncertainties associated with conversion of physical damage to seismic losses are not considered. Although this study utilizes the current HAZUS approach, the loss estimation method will be subject to more refinement as HAZUS evolves.

Table 5.3 Building Occupancy Classes (HAZUS, 1999)

Label	Occupancy Class	Example Descriptions
	Residential	
RES1	Single Family Dwelling	House
RES2	Mobile Home	Mobile Home
RES3	Multi Family Dwelling	Apartment/Condominium
RES4	Temporary Lodging	Hotel/Motel
RES5	Institutional Dormitory	Group Housing (military, college), Jails
RES6	Nursing Home	
	Commercial	
COM1	Retail Trade	Store
COM2	Wholesale Trade	Warehouse
COM3	Personal and Repair Services	Service Station/Shop
COM4	Professional/Technical Services	Offices
COM5	Banks	
COM6	Hospital	
COM7	Medical Office/Clinic	
COM8	Entertainment & Recreation	Restaurants/Bars
COM9	Theaters	Theaters
COM10	Parking	Garages
	Industrial	
IND1	Heavy	Factory
IND2	Light	Factory
IND3	Food/Drugs/Chemicals	Factory
IND4	Metals/Minerals Processing	Factory
IND5	High Technology	Factory
IND6	Construction	Office
	Agriculture	
AGR1	Agriculture	
	Religion/Non/Profit	
REL1	Church/Non-Profit	
	Government	
GOV1	General Services	Office
GOV2	Emergency Response	Police/Fire Station/EOC
	Education	
EDU1	Grade Schools	
EDU2	Colleges/Universities	Does not include group housing

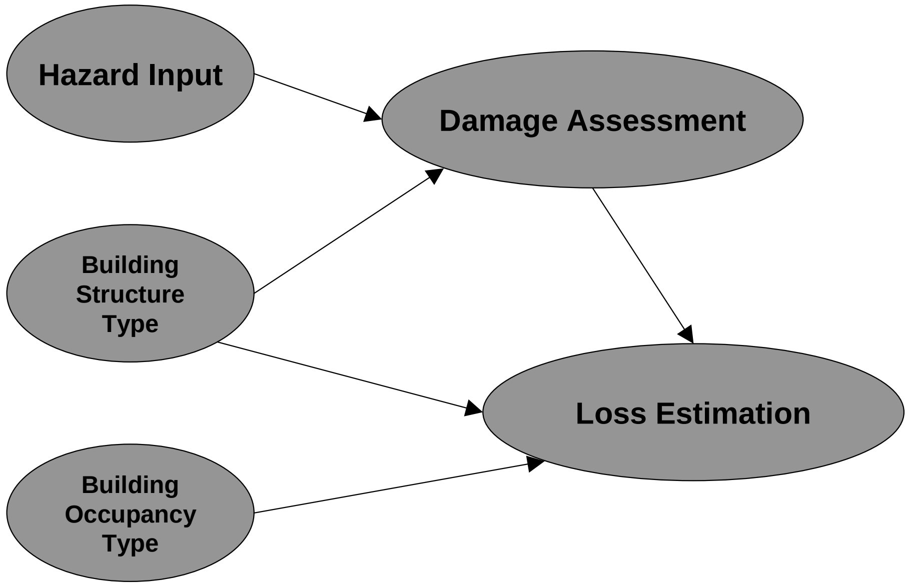
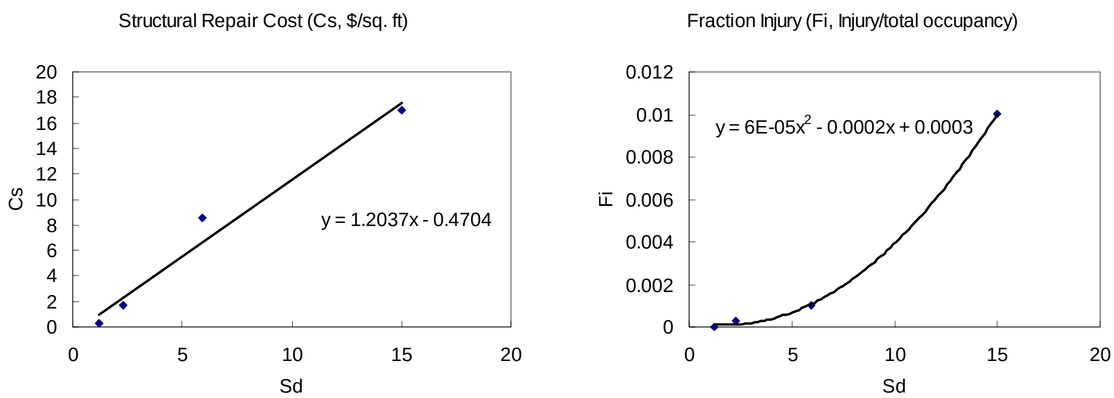


Figure 5.2 Influence Diagram for HAZUS Loss Estimation

As discussed in Chapter 4, a closed-form solution for the damage probability of a structure or a class of structures subject to an earthquake can be obtained assuming lognormal distributions for seismic demand and capacity. For estimation of losses, however, generic closed form solution is rarely available because the relationships between the damage and the losses are hard to generalize and vary depending on the kind of losses and structures. For example, Figure 5.3 shows the relationship between the physical damage expressed in terms of the spectral displacement and selected seismic losses, which are estimated for low code C2M type structures using HAZUS loss estimation data. The structural repair cost appears to vary linearly with S_d, whereas the fraction of injury (injury/total occupancy) appears to vary nonlinearly with S_d. Moreover, the relationships between the damage and losses are different for different types of structures.



(a) Structural Repair Cost (b) Fraction Injury

Figure 5.3 Relationships between Physical Damage and Losses

The overall probability distribution of seismic losses of a structure or a type of structure within a time period considering all possible earthquake levels can be obtained by mapping directly from the damage distribution, which can be obtained as discussed in Section 4.2. However, if the system of interest for the loss estimation consists of multiple structures with different types, so that different damages are obtained for different systems, the probability distribution of seismic loss for the time period of the whole system cannot be mapped from the damage distributions of the systems. Without considering the interdependency among the losses of the systems, the overall loss will be estimated from the summation of the individual losses. However, the losses of individual buildings that are measured within a particular time period cannot be considered statistically independent of each other if the systems are located relatively close to each other. For example, if a system within a region undergoes severe seismic losses, it is highly probable that other seismically vulnerable systems within the region have also experienced severe losses because it is implied that a strong earthquake has occurred.

Because the seismic losses of individual systems within a region estimated over a time period are not statistically independent of each other, and the closed form expression for the estimated losses is absent, the expected value of a loss can be obtained from the loss-hazard curve. A loss-hazard curve is a curve that shows the relationship between a loss and the probability of exceedance in a particular time period (HAZUS, 1999). In order to generate a loss-hazard curve, the loss must be estimated for a number of earthquake levels to cover all possible earthquake levels. For example, Figure 5.4 shows a schematic example of typical loss-hazard curves, where seismic monetary losses are estimated for four earthquake levels: 20%, 10%, 5%, and 2% probability of exceedance in 50 years. In this plot, the overall expected seismic monetary loss is calculated from the area under the loss hazard curve. Note that the loss hazard curve in Figure 5.4 is generated for the time period of 50 years. For different time periods, the probability of exceedance of each earthquake level must be modified. This is illustrated in more detail in Chapter 6.

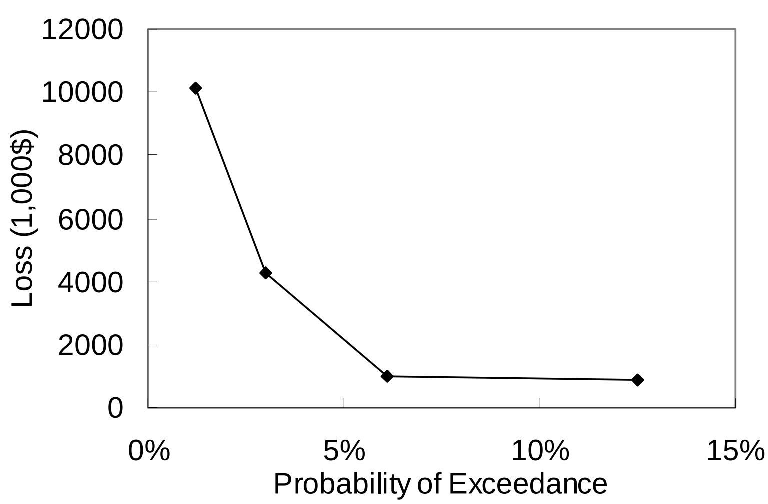


Figure 5.4 Sample Loss Hazard Curve

5.5 Multi-Criteria Decision Making (Step 5)

After the consequences of the seismic hazard are estimated, a multi-criteria decision analysis is performed to determine the best mitigation option. To do this, prescriptive multi-criteria decision-making techniques are utilized. One of the MCDM methods discussed in Chapter 3 can be chosen as a decision-making tool for use in this application. Therefore, the values of the attributes defined previously should be elicited and quantified for the decision analysis. However, as discussed in Chapter 3, the values are handled differently for each MCDM method. For equivalent cost analysis (ECA), all the non-monetary values are priced out and converted to equivalent monetary values. For multi-attribute utility analysis, marginal utility functions must be established first and a multi-attribute utility function is constructed taking into account the scaling factors of the attributes. For JPDM, the criterion values (usually upper and lower bounds of consequences) must be pre-defined along with the relative weights among the attributes. It should be noted that the results of the three decision analyses cannot be expected to be the same in all cases because of the difference in the value criteria.

As a result of each decision analysis, the decision index (e.g., expected equivalent cost, expected utility, or POS) is generated to determine the rank of the alternatives based on the value information that is quantified differently for each analysis. The quantified values are combined with the probabilistically evaluated consequence data to yield the decision-making indices. For detailed discussion on the MCDM models, see Chapter 3.

5.6 Dynamic Iteration (Step 6)

As one of the differences between the dynamic decision structure and the static decision structure, an iteration process is used for re-formulation of the decision analysis when a dynamic decision structure is used. The steps discussed above are performed for one set of attributes along with their quantified sets of values and alternatives. However, after going through these steps, it is necessary to iterate through the steps with different configurations. The possible reasons for this iteration are as follows.

- Updated set of attributes and alternatives: after reviewing the consequences of the alternative systems, attributes that have significant effect on the decision can be identified. Some of them may have been expected to have significant effect before the analysis and some of them may not. The decision maker may want to see the results from different sets of attributes. In addition, the alternatives can also be re-defined thereafter.
- Updated value information: within a set of attributes, the preferred decision can change depending on the value information of the attributes. The value information includes the risk attitudes and scaling factors for individual utility functions in MAUT, upper and lower bounds of the objective criteria and the relative weights among the attributes in JPDM, and conversion factor for non-monetary attributes in ECA.
- Further refinement of other parameters: there are other parameters that can affect the decision, such as engineering parameters. Some parameters related to the system capacity and/or seismic demand can have a significant effect of the seismic damage of the system, and the decision as well. Other parameters include social and economic parameters such as discount rate (explained in Chapter 6), time horizon, seismic rehabilitation cost, structural/nonstructural repair cost, etc.

After a decision analysis, the decision maker will be able to have better insight into the problem, and critical attributes that affect the decision can be identified thereafter. The decision maker may want to run the decision analysis again considering only the critical attributes. Or the decision maker may want to run the problem again with the critical attributes excluded. Or the decision maker may want to run the problem again with only one attribute considered. Furthermore, additional alternatives can be added to the problem, or some existing alternatives can be eliminated based on the updated attributes and values. As a result, there will be a number of sets of decision analyses with different configurations. In the iterative decision analysis for different configurations of attributes and alternatives, it is important to effectively compare the different schemes, where the most preferred alternatives for different sets of attributes and alternatives can be explicitly identified.

The decision procedure discussed in this chapter is demonstrated in the following chapters by applying to a test bed system. Decision analyses are performed utilizing the three decision models discussed in Chapter 3 and the results are compared and analyzed.

CHAPTER 6

APPLICATION TO A HOSPITAL SYSTEM – EQUIVALENT COST ANALYSIS

To illustrate the proposed decision support framework, an example is provided as an application of the framework. Among the three decision approaches utilized in this study, the equivalent cost analysis approach is illustrated in this chapter. Note that the system definition, hazard definition, physical damage assessment and seismic loss estimations are initially described in this chapter and then these results are used by all three decision model approaches in subsequent chapters.

6.1 System Definition

6.1.1 Description of Structures

Methodist Healthcare is a hospital system based in Memphis, Tennessee, serving the communities of Eastern Arkansas, West Tennessee, and North Mississippi, and consists of a number of hospitals and rural health clinics (Methodist, 2003). From these, the six hospital buildings shown in Figure 6.1 are selected and examined to demonstrate the decision support framework presented in Chapter 5. Table 6.1 shows the locations (by zip code) and the structural types of the hospitals. The location information is used to define the seismic hazard, and the structural types are used to define seismic vulnerability. Note that the table also shows the structural types based on HAZUS building classifications (HAZUS, 1999) as loss estimation in this study follows a HAZUS approach.

(a) Methodist Central Hospital

(b) Methodist North Hospital

(c) UT Bowld Hospital

(d) Methodist South Hospital

(e) Methodist Fayette Hospital

(f) Methodist Le Bonheur Germantown Hospital

Figure 6.1 Six Hospitals Selected for Decision Analysis

Table 6.1 Building Description

Hospital	ZIP	Structural Type	HAZUS Model Type
Methodist University Hospital	38104	Concrete Shear Wall (Mid-Rise)	C2M
Methodist North Hospital	38128	Concrete Shear Wall (Mid-Rise)	C2M
UT Bowld Hospital	38103	Concrete Shear Wall (Mid-Rise)	C2M
Methodist South Hospital	38116	Concrete Shear Wall (Mid-Rise)	C2M
Methodist Fayette Hospital	38068	URM (Low Rise)	URML
Le Bonheur Germantown Hospital	38138	Concrete Shear Wall (Low-Rise)	C2L

Some basic values involved in a description of the system – such as the number of occupants, building replacement value, etc. – are defined using standard references that are commonly used in seismic building loss estimation (e.g., HAZUS, 1999 and FEMA, 1992). The number of occupants per 1,000 square feet is assumed to be five in daytime and two in night time (FEMA, 1992). As a baseline, the time period (or time horizon) is set to be 30 years and a discount rate of 6% is assumed (discounting will be discussed further in Section 6.4.1). A time period for a decision analysis is based on a decision maker's interest in evaluating the alternatives. Although a 50-year time period could be chosen for evaluating the hospital systems, which might be consistent with a time period used for calculation of earthquake levels (e.g., as in 2% of probability of exceedance in 50 years), there may be a decision maker who is interested in shorter time period. Generally, building seismic rehabilitation is better justified with longer time period, because the expected seismic loss associated with a seismically vulnerable structure increases with longer time period. For example, rehabilitation can be hardly justified with one-year period because the probability of encountering a large earthquake within the time period is very low, whereas the probability increases with 50-year period so the rehabilitation becomes more cost-beneficial. Therefore, a decision maker would feel more favorable to rehabilitation of structures when the rehabilitation is justified with shorter time period. In this example, 30-year period is assumed as the baseline value and the effect of using different time periods (e.g., 10 years or 50 years) is investigated later through a sensitivity analysis. It is shown below that the results of decision analysis are dependent on these values. As this study aims to develop a decision support framework showing how to generate useful information with which the decision maker can make a correct decision in the problem of seismic structural intervention, the potential impact of these data values is evaluated by performing sensitivity analyses. The crucial values are then identified and re-evaluated by further investigation.

6.1.2 Attributes and Alternatives

Major losses pertinent to earthquake events can be classified into social and economic losses. Social losses include death and injury, loss of housing habitability, short term shelter needs, etc, whereas economic losses include structural repair costs, nonstructural repair costs, building contents loss, business inventory loss, loss of income, initial rehabilitation cost, etc. Among the large number of seismic losses, or attributes, several attributes that are typically considered to be crucial for hospital systems are selected for this study and are listed in Table 6.2 along with brief explanations of each.

Table 6.2 Losses (Attributes) Considered in This Example

Category	Loss	Description
Economic Loss	Initial Cost	Cost for seismic rehabilitation or rebuilding a new building to improve structural performance
	Structural Repair Cost	Cost for repairing damage to structural components such as beams, columns, joints, etc.
	Nonstructural Repair Cost	Cost for repairing damage to nonstructural components such as architectural, electrical and mechanical items.
	Loss of Building Contents	Cost equivalent to the loss of building contents such as furniture, equipment (not connected to the structure), computers, etc.
	Relocation Expenses	Disruption cost and rental cost for using temporary space in case the building must be shut down for repair.
Social Loss	Loss of Functionality	Loss of function for a hospital may result in additional human life losses due to lack of medical activity and capability
	Death	Number of people's deaths
	Injury	Number of seriously injured people

Note that the list of attributes is assumed for illustrative purpose and could be different depending on the decision maker. For example, 'loss of income' is assumed to be excluded because, 1) it is relatively less important in calculation of monetary loss for hospital system (less than 5% of the total monetary loss, and 2) the decision maker is a public policy maker and would be less concerned about the hospital's income. However, it would have been included if it is assumed that the decision maker is an owner of a private hospital. Note also that the losses mentioned above are direct losses, which are defined as losses occurred within the damaged system. On the other hand, losses that are caused in economic sectors not sustaining direct damage are called indirect losses. Indirect losses are caused in undamaged sectors by interruptions in operations of businesses that are linked to damaged sectors. Note that only direct losses are considered in this example.

Four generic alternatives (seismic rehabilitation alternative schemes) are considered for each structural type: 1) no action; 2) rehabilitation to life safety level; 3) rehabilitation to immediate occupancy level; and 4) construction of a new building to comply with the current code level. These rehabilitation levels are, as defined in FEMA 276 (1999), the target performance levels for rehabilitation against an earthquake with 10% probability of exceedance in 50 years. The required cost for rehabilitation generally increases as the target performance level becomes higher. That is, 'rehabilitation to immediate occupancy level' would require more initial cost for rehabilitation than 'rehabilitation to life safety level' does. On the other hand, less seismic losses are expected with higher performance level. The cost of seismic rehabilitation for building systems depends on many factors, such as building type, earthquake hazard level, desired performance level, occupancy or usage type, etc. The initial rehabilitation costs for the options considered here are obtained from FEMA 227 (1992) and FEMA 156 (1995), which provides typical costs for rehabilitation of existing structures taking into account above-mentioned factors. For damage assessment of the alternative systems, a specific code level, which is utilized in HAZUS, is assigned to each level of rehabilitation so that the fragility curves can be obtained for each rehabilitation alternative. Note that the rehabilitation levels defined in FEMA 276 mentioned above cannot be directly correlated to the HAZUS code levels. Therefore, the HAZUS code levels are assigned to the levels rehabilitation mentioned above with reasonable assumptions. It is assumed that the “No Action” option, which means retaining the existing structures, corresponds to the low code level. ‘Rehabilitation to life safety level’ option is assumed to be a moderate code level, and ‘rehabilitation to immediate occupancy level’ option is assumed to be a high code level. For the “Rebuild” option, a special high code is assumed because hospitals are classified as essential facilities. The alternatives and their corresponding code levels as assumed here are shown in Table 6.3 along with the total floor area of each type of structure. Note that the fragility curves for C2L are used for damage assessment of the seismic alternatives for a URML type structure, as they are not available in HAZUS. Note that although generic rehabilitation options are considered in this application for illustrative purposes, if more refined and specific configurations of the rehabilitation schemes are available and taken into account, the corresponding cost and seismic performance should be estimated accordingly for more accurate estimation of seismic losses. For example, Elnashai and Hueste (2004) are developing both rehabilitation alternatives and associated cost data at the time of this study.

Table 6.3 HAZUS Code Levels for Alternative Systems

Alternatives / Str. Type	No Action	Rehabilitation to Life Safety Level	Rehabilitation to Immediate Occupancy Level	Rebuild
C2M ($400,000\ ft^2$)	Low Code	Moderate Code	High Code	Special High Code
C2L ($40,000\ ft^2$)	Low Code	Moderate Code	High Code	Special High Code
URML ($40,000\ ft^2$)	Low Code	Moderate Code (using C2L)	High Code (using C2L)	Special High Code (using C2L)

6.2 Hazard Inputs

The hazard input must be identified before the seismic losses are estimated. The seismic hazards are defined at the location of each of the hospital systems under investigation here. As discussed in Chapter 4, a HAZUS approach for damage assessment requires that response spectra be specified to represent the appropriate seismic hazard inputs. Therefore, the locations of the six hospital buildings are identified first and the response spectra are generated for each of the locations. The locations of the hospitals are shown on the map of Memphis and surrounding area shown in Figure 6.2.

Figure 6.2 Locations of the Hospitals

Four different hazard levels are considered for generation of the loss-hazard curves to take into account a range of levels of earthquakes in the region. These levels include earthquakes with 2%, 5%, 10% and 20% of probability of exceedance (PE), and minor/no earthquake. It is assumed that no damage will occur due to minor earthquakes. This is a reasonable assumption because the analysis conducted later shows that the damage level of the structures due to an earthquake with 20% of PE are very low, as shown in Table 6.5 - Table 6.7.

Note that these probability levels are assigned based on a 50 year time horizon, and should be modified if a different time horizon is used, as follows.

$$PE_n = 1 - (1 - PE_{50})^{\frac{n}{50}} \qquad [6.1]$$

where, PE_n is the probability of exceedance in n years for a particular level of earthquake, and PE_{50} is the probability of exceedance in 50 years for the same earthquake level.

As explained in Section 4.2, the maximum building response, which is used for damage assessment, is obtained from the intersection of the demand spectrum (response spectrum) and the building capacity curve. The parameters needed to generate the response spectra are obtained from the USGS (2003) as discussed in Section 4.1. Table 6.4 shows the spectral accelerations corresponding to natural period values of 0.2, 0.3, and 1.0 seconds. For each period, spectral accelerations are given for three different probability of exceedance levels: 10%, 5%, and 2% in 50 years. The variation of the spectral accelerations over the different hospital locations appears to not be significant, as the structures are located close to each other. The response spectra of the locations corresponding to several probability levels (10%, 5%, and 2% of PE in 50 years) are generated following the method in FEMA (1997) and resulting spectra are shown in Figure 6.3. Note that although the response spectrum with 20% of PE in 50 years is not shown in this figure, it will be developed and used along with the other three earthquake levels in the loss estimation, which will be discussed later.

Table 6.4 The Probabilistic Spectral Accelerations for the Hospital Locations

The input zip-code is 38104.
ZIP CODE 38104
LOCATION 35.1394 Lat. -89.9992 Long.
DISTANCE TO NEAREST GRID POINT 4.3732 kms
NEAREST GRID POINT 35.1 Lat. -90.0 Long.
Probabilistic ground motion values, in %g, at the Nearest Grid point are:

	10%PE in 50 yr	5%PE in 50 yr	2%PE in 50 yr
PGA	13.727930	28.350281	62.477032
0.2 sec SA	27.211710	56.531830	123.460800
0.3 sec SA	20.110580	42.038540	103.139702
1.0 sec SA	6.426961	14.785540	37.238129

The input zip-code is 38128.
ZIP CODE 38128
LOCATION 35.2222 Lat. -89.9252 Long.
DISTANCE TO NEAREST GRID POINT 3.3687 kms
NEAREST GRID POINT 35.2 Lat. -89.9 Long.
Probabilistic ground motion values, in %g, at the Nearest Grid point are:

	10%PE in 50 yr	5%PE in 50 yr	2%PE in 50 yr
PGA	14.508240	30.534870	66.106903
0.2 sec SA	28.426460	59.142639	126.748100
0.3 sec SA	21.653830	43.787621	106.870903
1.0 sec SA	6.825978	15.548420	38.775169

The input zip-code is 38103.
ZIP CODE 38103
LOCATION 35.1511 Lat. -90.0351 Long.
DISTANCE TO NEAREST GRID POINT 6.3002 kms
NEAREST GRID POINT 35.2 Lat. -90.0 Long.
Probabilistic ground motion values, in %g, at the Nearest Grid point are:

	10%PE in 50 yr	5%PE in 50 yr	2%PE in 50 yr
PGA	15.253270	33.035061	72.763077
0.2 sec SA	29.182430	62.094791	139.793594
0.3 sec SA	22.289631	47.238270	114.620903
1.0 sec SA	6.936255	16.467791	42.338150

The input zip-code is 38116.
ZIP CODE 38116
LOCATION 35.0380 Lat. -90.0071 Long.
DISTANCE TO NEAREST GRID POINT 4.2616 kms
NEAREST GRID POINT 35.0 Lat. -90.0 Long.
Probabilistic ground motion values, in %g, at the Nearest Grid point are:

	10%PE in 50 yr	5%PE in 50 yr	2%PE in 50 yr
PGA	12.340830	25.342319	52.430519
0.2 sec SA	25.143311	50.383732	111.935402
0.3 sec SA	18.530649	38.617962	89.705887
1.0 sec SA	6.187472	13.730220	31.919050

The input zip-code is 38068.
ZIP CODE 38068
LOCATION 35.0380 Lat. -90.0071 Long.
DISTANCE TO NEAREST GRID POINT 4.2616 kms
NEAREST GRID POINT 35.0 Lat. -90.0 Long.
Probabilistic ground motion values, in %g, at the Nearest Grid point are:

	10%PE in 50 yr	5%PE in 50 yr	2%PE in 50 yr
PGA	12.340830	25.342319	52.430519
0.2 sec SA	25.143311	50.383732	111.935402
0.3 sec SA	18.530649	38.617962	89.705887
1.0 sec SA	6.187472	13.730220	31.919050

The input zip-code is 38138.
ZIP CODE 38138
LOCATION 35.0912 Lat. -89.7983 Long.
DISTANCE TO NEAREST GRID POINT 0.9935 kms
NEAREST GRID POINT 35.1 Lat. -89.8 Long.
Probabilistic ground motion values, in %g, at the Nearest Grid point are:

	10%PE in 50 yr	5%PE in 50 yr	2%PE in 50 yr
PGA	12.885040	25.470329	51.360828
0.2 sec SA	26.052780	50.702728	110.064400
0.3 sec SA	19.029800	38.772259	87.032227
1.0 sec SA	6.327973	13.756190	31.246719

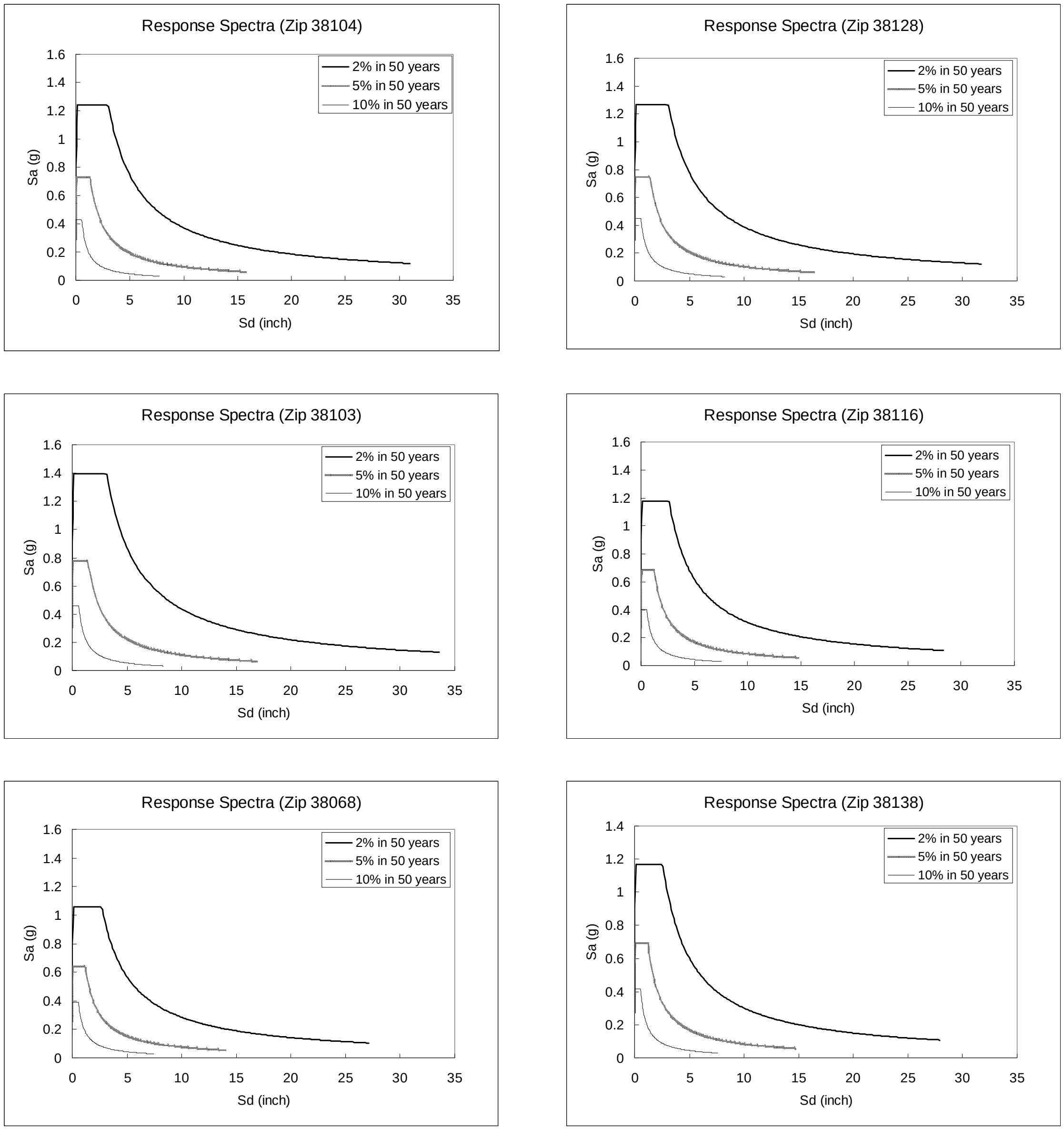
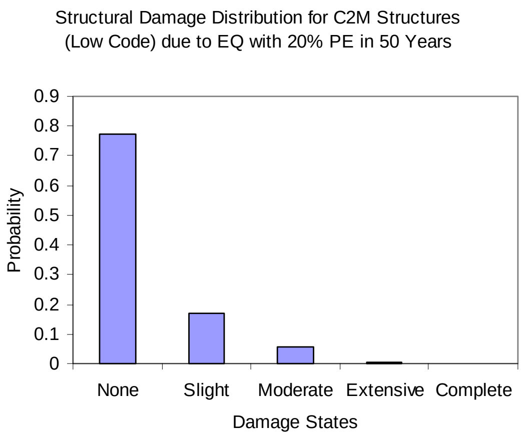


Figure 6.3 Response Spectra for the Hospital Locations

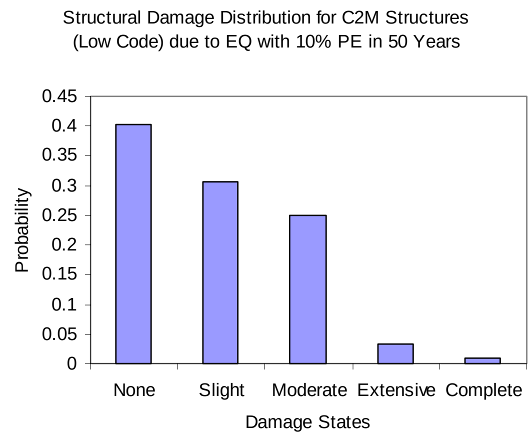
6.3 Damage Assessment

The damage probability distribution for a structure or type of structure is read from the fragility curves. From the intersections of the capacity curve and the demand spectrum, the maximum building responses due to the various levels of earthquakes are obtained. The maximum building responses are used in conjunction with the fragility curves to come up with the damage probability distributions. In HAZUS, fragility curves for both structural and nonstructural damage can be generated. The nonstructural fragility curves include drift-sensitive component fragility curves and acceleration-sensitive component fragility curves. Both structural and nonstructural fragility curves for C2L, C2M, and URML type structures for different code levels are generated. As shown in Figure 4.4, the damage probability corresponding to the maximum building response are read from the fragility curves. For example, Figure 6.4 shows the structural damage distribution of low-code C2M type structures corresponding to various earthquake levels. Using Equation 4.8, the overall damage distribution within a particular time period can then be obtained. Figure 6.5 shows the overall damage distribution of low-code C2M structures within a 30 year time period. Note that there should not be a confusion between a time period for a decision analysis and a time period used for calculation of earthquake levels. 50-year time period is often used for measure of earthquake levels (e.g., 2% of exceedance in 50 years). However, a decision analysis may have a time period other than 50 years. Therefore, the probabilities of earthquakes must be adjusted using Equation 6.1.

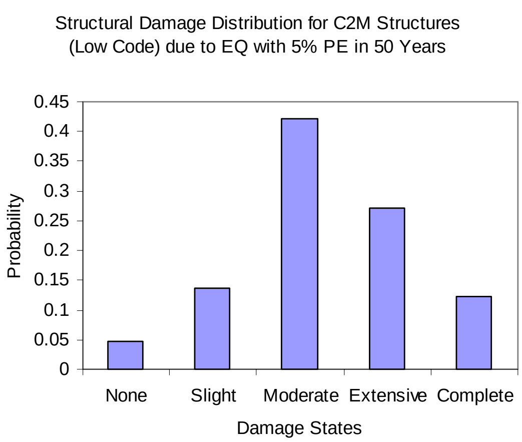
The damage probability distributions corresponding to various levels of earthquakes are obtained for all C2M, C2L, and URML type structures and their seismic alternative schemes are shown in Table 6.5 - Table 6.7. Note that it is observed that rehabilitation sometimes increases the probability of slight or moderate damage of the acceleration-sensitive nonstructural components. This is because a rehabilitated structure is typically stiffer than the original structure, so might have larger spectral acceleration (although it has smaller spectral displacement). Even considering the improved fragilities of the rehabilitated structures, some cases where rehabilitated structures produce more damage could be observed on the acceleration-sensitive components.



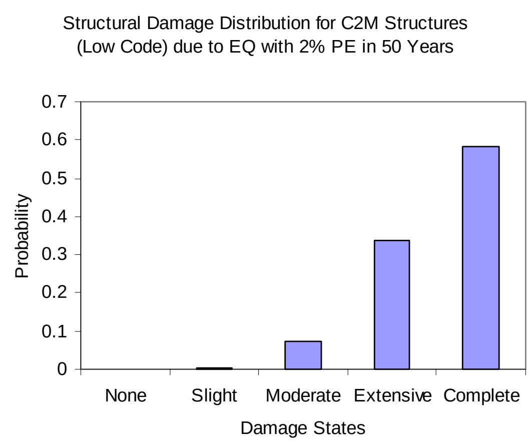
(a) Damage Distribution with 20/50 EQ



(b) Damage Distribution with 10/50 EQ



(c) Damage Distribution with 5/50 EQ



(d) Damage Distribution with 2/50 EQ

Figure 6.4 Structural Damage Distribution for Low-Code C2M Structures for Various Earthquake Levels

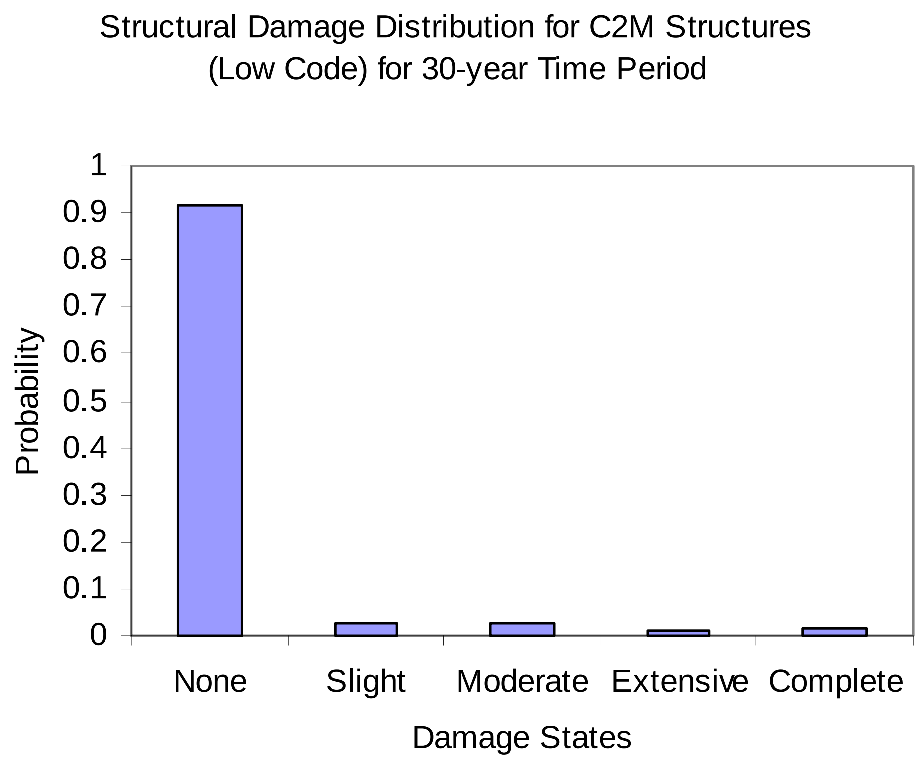


Figure 6.5 Structural Damage Distribution for Low-Code C2M Structures for a 30-Year Period

Table 6.5 Damage Probability Distribution for C2M Structures

Structural Damage						
		None	Slight	Moderate	Extensive	Complete
No Action	20/50	0.7727	0.1673	0.0568	0.0024	0.0008
	10/50	0.4023	0.3056	0.2494	0.0332	0.0095
	5/50	0.0462	0.1363	0.4226	0.2713	0.1236
	2/50	0.0004	0.0045	0.0748	0.3364	0.5839
Rehab LS	20/50	0.8710	0.1135	0.0153	0.0001	0.0000
	10/50	0.5000	0.3337	0.1583	0.0071	0.0009
	5/50	0.1018	0.2544	0.4840	0.1329	0.0269
	2/50	0.0053	0.0376	0.2914	0.4344	0.2313
Rehab IO	20/50	0.8922	0.0992	0.0086	0.0000	0.0000
	10/50	0.6513	0.2898	0.0586	0.0003	0.0000
	5/50	0.1535	0.4279	0.3877	0.0308	0.0000
	2/50	0.0495	0.1360	0.5174	0.2870	0.0101
Rebuild	20/50	0.9602	0.0384	0.0014	0.0000	0.0000
	10/50	0.7840	0.1967	0.0192	0.0001	0.0000
	5/50	0.3404	0.4861	0.1695	0.0040	0.0000
	2/50	0.0175	0.2374	0.5804	0.1545	0.0101

Drift-Sensitive Nonstructural Damage						
		None	Slight	Moderate	Extensive	Complete
No Action	20/50	0.8874	0.0881	0.0224	0.0018	0.0004
	10/50	0.5953	0.2531	0.1307	0.0159	0.0050
	5/50	0.1230	0.2502	0.4314	0.1238	0.0717
	2/50	0.0028	0.0272	0.2795	0.2638	0.4267
Rehab LS	20/50	0.9422	0.0514	0.0064	0.0000	0.0000
	10/50	0.6853	0.2272	0.0840	0.0021	0.0014
	5/50	0.2287	0.3052	0.3934	0.0465	0.0262
	2/50	0.0238	0.0916	0.4652	0.2298	0.1895
Rehab IO	20/50	0.9422	0.0508	0.0070	0.0000	0.0000
	10/50	0.7954	0.1592	0.0451	0.0003	0.0000
	5/50	0.3390	0.3237	0.3175	0.0193	0.0005
	2/50	0.0910	0.1635	0.5332	0.1768	0.0354
Rebuild	20/50	0.9630	0.0330	0.0040	0.0000	0.0000
	10/50	0.8255	0.1404	0.0338	0.0003	0.0000
	5/50	0.4542	0.3339	0.2035	0.0079	0.0005
	2/50	0.0541	0.2030	0.5539	0.1535	0.0354

Acceleration-Sensitive Nonstructural Damage						
		None	Slight	Moderate	Extensive	Complete
No Action	20/50	0.8606	0.1216	0.0172	0.0007	0.0000
	10/50	0.6735	0.2579	0.0636	0.0049	0.0001
	5/50	0.4756	0.3635	0.1418	0.0183	0.0008
	2/50	0.4756	0.3635	0.1418	0.0183	0.0008
Rehab LS	20/50	0.7473	0.2152	0.0344	0.0030	0.0001
	10/50	0.6590	0.2758	0.0587	0.0064	0.0002
	5/50	0.4144	0.3898	0.1639	0.0300	0.0019
	2/50	0.2225	0.3891	0.2925	0.0862	0.0096
Rehab IO	20/50	0.8154	0.1636	0.0200	0.0010	0.0000
	10/50	0.5602	0.3305	0.0988	0.0105	0.0000
	5/50	0.3832	0.3892	0.1934	0.0331	0.0010
	2/50	0.2144	0.3676	0.3200	0.0943	0.0037
Rebuild	20/50	0.9358	0.0602	0.0039	0.0001	0.0000
	10/50	0.7737	0.1943	0.0305	0.0015	0.0000
	5/50	0.4384	0.3786	0.1603	0.0217	0.0010
	2/50	0.2943	0.3974	0.2526	0.0520	0.0037

Table 6.6 Damage Probability Distribution for C2L Structure

Structural Damage						
		None	Slight	Moderate	Extensive	Complete
No Action	20/50	0.8181	0.1221	0.0546	0.0050	0.0001
	10/50	0.3324	0.2425	0.3013	0.1093	0.0145
	5/50	0.0663	0.1171	0.3293	0.3316	0.1557
	2/50	0.0030	0.0121	0.0867	0.2630	0.6353
Rehab LS	20/50	0.9204	0.0614	0.0167	0.0016	0.0000
	10/50	0.4226	0.2989	0.2159	0.0609	0.0018
	5/50	0.1077	0.2399	0.3817	0.2361	0.0346
	2/50	0.0094	0.0666	0.2800	0.3883	0.2557
Rehab IO	20/50	0.9683	0.0272	0.0043	0.0002	0.0000
	10/50	0.7210	0.1968	0.0749	0.0072	0.0002
	5/50	0.1999	0.3054	0.3783	0.1048	0.0115
	2/50	0.0210	0.1072	0.4339	0.3275	0.1105
Rebuild	20/50	0.9854	0.0142	0.0004	0.0000	0.0000
	10/50	0.7786	0.1991	0.0214	0.0009	0.0001
	5/50	0.2894	0.4811	0.2062	0.0203	0.0030
	2/50	0.0184	0.2149	0.5249	0.1910	0.0508

Drift-Sensitive Nonstructural Damage						
		None	Slight	Moderate	Extensive	Complete
No Action	20/50	0.8181	0.1277	0.0517	0.0024	0.0001
	10/50	0.3324	0.2616	0.3247	0.0669	0.0145
	5/50	0.0663	0.1303	0.4103	0.2374	0.1557
	2/50	0.0030	0.0140	0.1340	0.2137	0.6353
Rehab LS	20/50	0.8822	0.0878	0.0295	0.0005	0.0001
	10/50	0.4347	0.2536	0.2710	0.0319	0.0089
	5/50	0.1483	0.1913	0.4315	0.1500	0.0789
	2/50	0.0239	0.0606	0.2898	0.2784	0.3472
Rehab IO	20/50	0.9295	0.0580	0.0118	0.0006	0.0001
	10/50	0.6137	0.2448	0.1257	0.0133	0.0025
	5/50	0.1491	0.2557	0.4257	0.1187	0.0508
	2/50	0.0158	0.0748	0.3941	0.2615	0.2538
Rebuild	20/50	0.9540	0.0413	0.0046	0.0000	0.0000
	10/50	0.6566	0.2492	0.0905	0.0025	0.0013
	5/50	0.2126	0.3330	0.3918	0.0421	0.0206
	2/50	0.0143	0.0865	0.4829	0.2368	0.1795

Acceleration-Sensitive Nonstructural Damage						
		None	Slight	Moderate	Extensive	Complete
No Action	20/50	0.7805	0.1833	0.0341	0.0020	0.0000
	10/50	0.5000	0.3496	0.1326	0.0170	0.0008
	5/50	0.3676	0.3909	0.2025	0.0365	0.0025
	2/50	0.3676	0.3909	0.2025	0.0365	0.0025
Rehab LS	20/50	0.7442	0.2137	0.0386	0.0034	0.0001
	10/50	0.4953	0.3551	0.1283	0.0202	0.0012
	5/50	0.2821	0.3938	0.2523	0.0653	0.0065
	2/50	0.1540	0.3460	0.3460	0.1333	0.0207
Rehab IO	20/50	0.8189	0.1569	0.0231	0.0011	0.0000
	10/50	0.3384	0.3891	0.2245	0.0454	0.0026
	5/50	0.2385	0.3803	0.2938	0.0809	0.0065
	2/50	0.1361	0.3255	0.3679	0.1510	0.0194
Rebuild	20/50	0.9358	0.0592	0.0048	0.0002	0.0000
	10/50	0.5404	0.3319	0.1127	0.0146	0.0003
	5/50	0.3022	0.3923	0.2441	0.0583	0.0031
	2/50	0.2039	0.3732	0.3134	0.1015	0.0080

Table 6.7 Damage Probability Distribution for URML Structure

Structural Damage						
		None	Slight	Moderate	Extensive	Complete
No Action	20/50	0.5988	0.2129	0.1417	0.0402	0.0063
	10/50	0.2307	0.2510	0.3040	0.1584	0.0560
	5/50	0.0480	0.1306	0.3040	0.2874	0.2300
	2/50	0.0015	0.0145	0.0968	0.2132	0.6741
Rehab LS	20/50	0.8136	0.1323	0.0478	0.0063	0.0000
	10/50	0.4226	0.2989	0.2159	0.0609	0.0018
	5/50	0.1167	0.2473	0.3789	0.2261	0.0310
	2/50	0.0115	0.0750	0.2943	0.3879	0.2313
Rehab IO	20/50	0.9253	0.0613	0.0126	0.0007	0.0000
	10/50	0.7811	0.1611	0.0532	0.0045	0.0001
	5/50	0.2294	0.3147	0.3559	0.0909	0.0091
	2/50	0.0229	0.1125	0.4386	0.3212	0.1048
Rebuild	20/50	0.9547	0.0434	0.0018	0.0000	0.0000
	10/50	0.8189	0.1652	0.0153	0.0006	0.0001
	5/50	0.3384	0.4703	0.1737	0.0154	0.0022
	2/50	0.0202	0.2246	0.5234	0.1838	0.0479

Drift-Sensitive Nonstructural Damage						
		None	Slight	Moderate	Extensive	Complete
No Action	20/50	0.6876	0.1716	0.1198	0.0198	0.0013
	10/50	0.3358	0.2481	0.2991	0.0969	0.0201
	5/50	0.0998	0.1741	0.3808	0.2186	0.1267
	2/50	0.0065	0.0346	0.1978	0.2092	0.5519
Rehab LS	20/50	0.7736	0.1504	0.0733	0.0023	0.0004
	10/50	0.4347	0.2536	0.2710	0.0319	0.0089
	5/50	0.1576	0.1970	0.4298	0.1428	0.0727
	2/50	0.0277	0.0673	0.3067	0.2760	0.3223
Rehab IO	20/50	0.8612	0.1075	0.0293	0.0019	0.0002
	10/50	0.6794	0.2147	0.0954	0.0090	0.0015
	5/50	0.1720	0.2692	0.4097	0.1063	0.0427
	2/50	0.0171	0.0788	0.4004	0.2589	0.2447
Rebuild	20/50	0.8930	0.0914	0.0153	0.0001	0.0001
	10/50	0.7032	0.2227	0.0716	0.0017	0.0009
	5/50	0.2507	0.3440	0.3560	0.0332	0.0160
	2/50	0.0156	0.0915	0.4895	0.2312	0.1722

Acceleration-Sensitive Nonstructural Damage						
		None	Slight	Moderate	Extensive	Complete
No Action	20/50	0.5000	0.3569	0.1267	0.0158	0.0007
	10/50	0.3498	0.3964	0.2119	0.0393	0.0026
	5/50	0.1937	0.3707	0.3260	0.0988	0.0109
	2/50	0.1726	0.3588	0.3425	0.1125	0.0135
Rehab LS	20/50	0.6286	0.2889	0.0735	0.0086	0.0004
	10/50	0.4770	0.3621	0.1371	0.0224	0.0013
	5/50	0.2959	0.3948	0.2428	0.0607	0.0058
	2/50	0.1612	0.3510	0.3407	0.1278	0.0193
Rehab IO	20/50	0.6735	0.2594	0.0621	0.0050	0.0001
	10/50	0.3384	0.3891	0.2245	0.0454	0.0026
	5/50	0.2678	0.3864	0.2727	0.0682	0.0049
	2/50	0.1411	0.3298	0.3646	0.1461	0.0183
Rebuild	20/50	0.8537	0.1286	0.0169	0.0008	0.0000
	10/50	0.5688	0.3182	0.1007	0.0121	0.0002
	5/50	0.3104	0.3924	0.2387	0.0557	0.0028
	2/50	0.2148	0.3773	0.3054	0.0953	0.0072

6.4 Seismic Loss Estimation

Using the damage probability distributions listed in the previous section, various seismic losses associated with the system are estimated. As mentioned in Section 4.2 and 5.4, the HAZUS approach is utilized in this application and the losses described in Table 6.2 are estimated. Table 6.8 shows this deterministic relationship between various damage states and corresponding seismic losses. The losses are estimated for several earthquake levels (20%, 10%, 5%, and 2% of PE in 50 years) to come up with loss-hazard curves, from which expected losses are obtained.

6.4.1 Discount Effect

If a temporal trade-off (e.g., if you can spend 1.0 million dollars now for rehabilitation, how much can you spend for rehabilitation in 20 years?) is considered in performing a decision analysis, future cost has to be converted to net present values. Discounting is usually considered for the future value because the future cost is usually less painful than the present cost. If we have several disbursements (c_0, c_1, …, c_T) over time period T, the total net present value of the cost, c_{npv}, can be expressed as follows:

$$c_{npv} = \sum_{t=0}^{T} \frac{c_t}{(1+\lambda)^t} \qquad [6.2]$$

where λ is the effective period-to-period discount rate expressed as a fraction. If λ is an effective annual discount rate, then T should be measured in years. When applying this equation for calculation of the net present value of a future repair cost due to a given level of earthquake that occurs within a given time horizon, it is assumed that the probability of having that earthquake is same for each year within the time horizon. It is also assumed that the building repair cost is always same within the time horizon. That is, the expected net present value of a building repair cost, C_{Rnpv} due to a given level of scenario earthquake that occurs within a time horizon of T is:

$$c_{Rnpv} = \frac{1}{T} \sum_{t=0}^{T} \frac{c_{Rt}}{(1+\lambda)^t} \qquad [6.3]$$

where, C_{Rt} = the building repair cost at time of $t = C_{R1} = C_{R2} = \ldots = C_{RT}$. Therefore, the discount rate λ solely represents the discount effect. However, one should be cautious in using this equation because some criticism has been voiced over the last several decades (Frederick et al., 2002). Namely, the discount rate is not constant but tends to decline over time and discount rates should not be the same for all kinds of attributes. However, the discounted-cost model, which uses a constant discount rate, is still widely used because of its simplicity and elegance of the formulation.

Considerable efforts have been exerted to determine the discount rate. However, given the complexity and the diversity of the decision problem relevant to the seismic risk reduction, it is very hard to come up with a single discount rate to use. That is, different discount rates result from different approaches. According to FEMA 227 (FEMA, 1992), several different approaches have been used to estimate the discount rate for public investment and the resulting discount rate ranges from 3% to 10%. Therefore, it is important to perform sensitivity analysis using the discount rate as a variable to investigate the influence of the discount rate on the decision, varying the discount rates at least from 3% to 10%.

Table 6.8 Losses for Different Damage States (HAZUS, 1999)

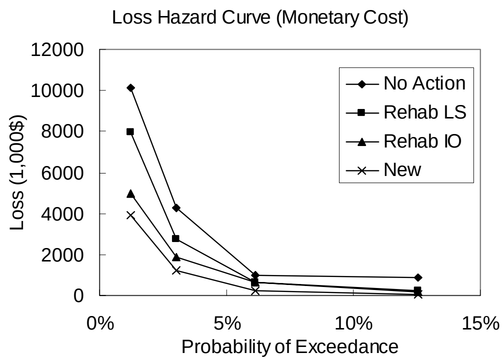
	C2M			
	Slight	Moderate	Extensive	Complete
Structural Repair Cost ($/ft^2)	0.3	1.7	8.5	17
DS Nonstr. Repair Cost ($/ft^2)	0.8	4.2	21	42
AS Nonstr. Repair Cost ($/ft^2)	1.2	6.2	18.6	62
Contents Loss ($/ft^2)	1.21	6.05	30.25	60.5
Death (fraction)	0	0	0.000015	No Collapse: 0.00015 Collapse: 0.125
Injury (fraction)	0	0.0003	0.001005	No Collapse: 0.01005 Collapse: 0.225
Recovery Time (days)	2	67.5	270	360

	C2L			
	Slight	Moderate	Extensive	Complete
Structural Repair Cost ($/ft^2)	0.3	1.7	8.5	17
DS Nonstr. Repair Cost ($/ft^2)	0.8	4.2	21	42
AS Nonstr. Repair Cost ($/ft^2)	1.2	6.2	18.6	62
Contents Loss ($/ft^2)	1.21	6.05	30.25	60.5
Death (fraction)	0	0	0.000015	No Collapse: 0.00015 Collapse: 0.125
Injury (fraction)	0	0.0003	0.001005	No Collapse: 0.01005 Collapse: 0.225
Recovery Time (days)	20	67.5	270	360

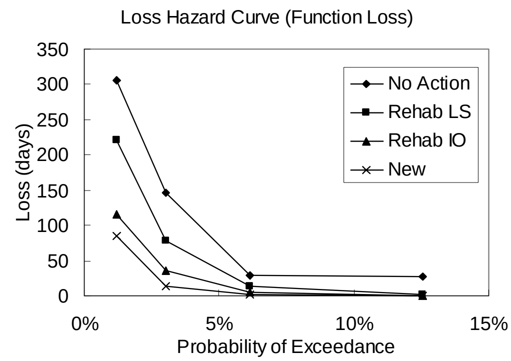
	URML			
	Slight	Moderate	Extensive	Complete
Structural Repair Cost ($/ft^2)	0.3	1.7	5.1	17
DS Nonstr. Repair Cost ($/ft^2)	0.8	4.2	21	42
AS Nonstr. Repair Cost ($/ft^2)	1.2	6.2	18.6	62
Contents Loss ($/ft^2)	1.21	6.05	30.25	60.5
Death (fraction)	0	0	0.000015	No Collapse: 0.0003 Collapse: 0.125
Injury (fraction)	0	0.0003	0.001005	No Collapse: 0.0201 Collapse: 0.225
Recovery Time (days)	2	67.5	270	360

6.4.2 Loss Hazard Curves

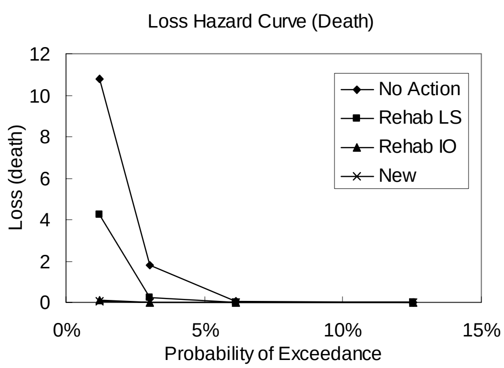
The seismic losses of the system are estimated from the damage probability distributions obtained as described in Section 6.3. Taking the damage states as random variables, the losses corresponding to various damage states are probabilistically estimated for a large number of times to estimate the losses probabilistically. Crystal Ball software (1998) is used as the simulation tool. To increase the accuracy of the analysis with smaller sample size, the Latin Hypercube sampling (Imam and Conover, 1980) with 500 intervals is used. Loss is estimated for each of the four earthquake levels and the loss-hazard curves are generated to calculate the overall expected loss. Figure 6.6 - Figure 6.8 show the loss-hazard curves for each type of structure. The points on the plots are expected losses due to the corresponding earthquake levels. For all types of structures, the “No Action” option shows the largest seismic losses for the four earthquake levels. However, this does not consider the initial costs of the alternative schemes and the probability of having no or minor earthquake.



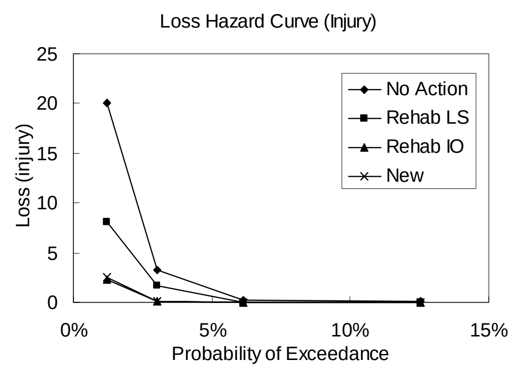
(a) Monetary Cost



(b) Function Loss

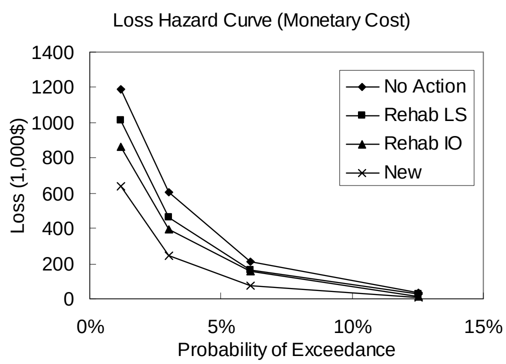


(c) Death

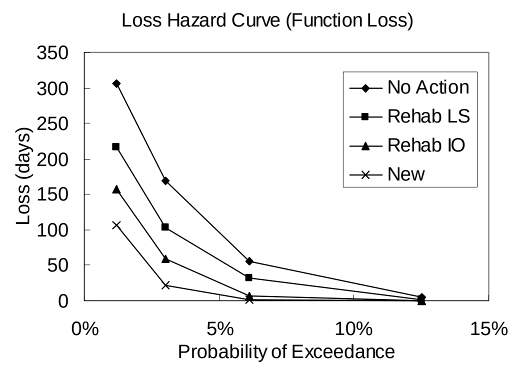


(d) Injury

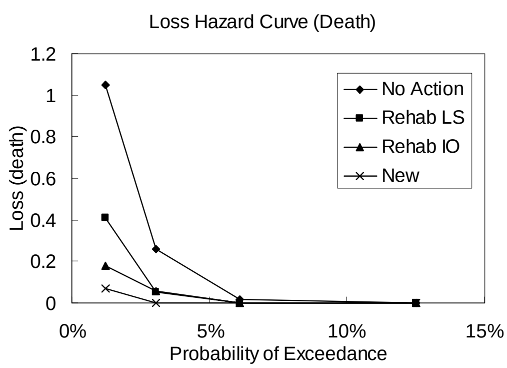
Figure 6.6 Loss-Hazard Curves for C2M Structures (4 units)



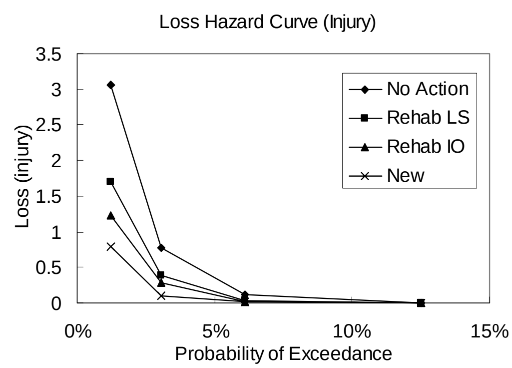
(a) Monetary Cost



(b) Function Loss

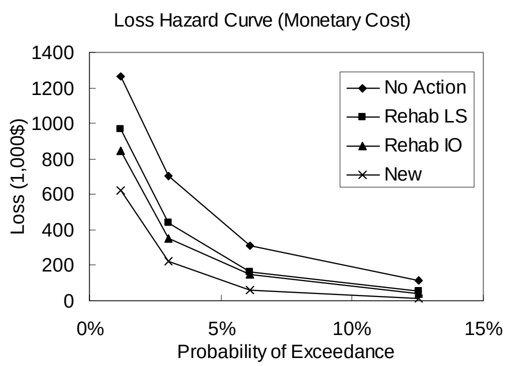


(c) Death

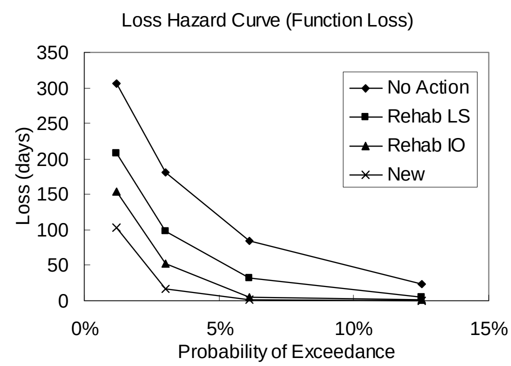


(d) Injury

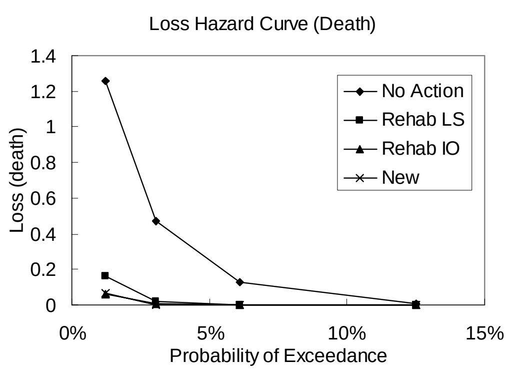
Figure 6.7 Loss-Hazard Curves for C2L Structure (1 unit)



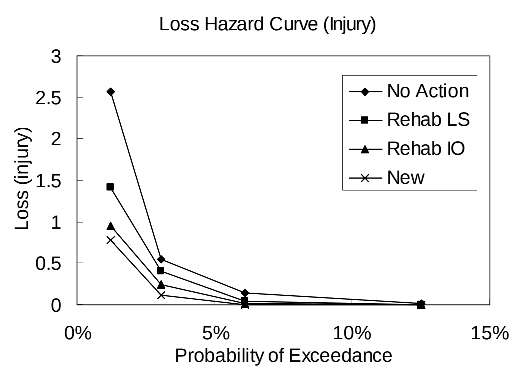
(a) Monetary Cost



(b) Function Loss



(c) Death



(d) Injury

Figure 6.8 Loss-Hazard Curves for URML Structure (1 unit)

6.5 Value Quantification for ECA

For equivalent cost analyses, consequences measured in different units are converted into a single composite measure – usually a monetary measure – by introducing conversion factors (i.e., taking trade-offs into account). However, as discussed in Chapter 3, the determination of these conversion factors for non-monetary values is not an easy task. In many public decision problems, especially decisions regarding earthquake risk, the value of human life becomes a key factor (FEMA, 1992). In decision problems on whether to rehabilitate building systems or not, for example, many times the benefit/cost analysis shows the rehabilitation of the system is not justified based on the monetary loss caused by the physical damage (without considering the value of life). However, if the value of life is taken into consideration, the decision often changes so that the rehabilitation is justified (FEMA, 1992).

It is very hard to determine the economic value of a human life. According to FEMA 227 (1992), the suggested value of life ranges from $1.1 million to $8 million per life. This approach is useful in the sense that the procedure is straightforward, and it is easy for the decision maker to understand the problem. However, assessing a monetary value to the value of life is controversial.

The determination of the equivalent monetary value of a human life is not the main concern in this thesis; detailed value elicitation (e.g., Hammond et al., 1999 and Keeney and Raiffa, 1993) is outside the scope of this study. The relative weight, scaling factor, or the equivalent monetary value of a human life used for this study is determined using common and reasonable assumptions along with references to literatures. The goal of this study is to provide flexible decision support data to aid the decision maker in updating his/her value information, eventually enabling dynamic decision-making to be performed. To accomplish this, sensitivity analysis should be performed to explore how value of human life affects the final decision.

The equivalent cost for loss of function is expressed in terms of the function recovery time (days) per 10,000 square feet. For example, if one day of loss of function of a hospital with total floor area of 10,000 square feet is estimated to be $100,000, the equivalent cost for five days of loss of function for a 50,000 square feet hospital would be $2,500,000. Note that this approach for determination of the equivalent cost of loss of function is rough and needs future refinement. As described in Table 6.2, the value of loss of function used in the analysis should take into account the fact that loss of function in a hospital setting may result in additional loss of life. In this study, sensitivity analysis will be performed using variable values for loss of function ranging from $0 to $200,000 for one day of loss of function of a hospital per 10,000 square feet. However, Table 6.9 shows the baseline values for the non-monetary attributes for the decision analysis to be used in this study. Note that the value of injury is estimated (crudely) at 30% of the value of a statistical life loss.

Table 6.9 Baseline Values for Non-monetary Attributes

Attribute	Equivalent Cost
Value of Death	$5,000,000 / person
Value of Injury	$1,500,000 / person
Value of Loss of Function	$100,000 / day to recover / 10,000 ft^2

6.6 Equivalent Cost Analysis

Using the conversion factors described in Table 6.9, the equivalent cost analysis is performed. The equivalent cost of an alternative *i* is calculated as:

$$EC_i = M_i + F_i \cdot C_F + D_i \cdot C_D + I_i \cdot C_I \qquad [6.4]$$

where, EC_i = equivalent cost for alternative *i*, and M_i, F_i, D_i, and I_i are the monetary cost, function loss expressed in terms of days to recover, number of people deceased and injured for an alternative *i*, respectively; and variables C_F, C_D, and C_I are the conversion factors for function loss, death, and injury, respectively; baseline values for these factors are listed in Table 6.9 but a range of possible values will be considered in the sensitivity analyses. Note that the discount effect is considered to obtain the net present value of the future cost using Equation 6.2. Figure 6.9 – Figure 6.11 show the loss hazard curves for each type of structure showing the expected equivalent losses corresponding to different earthquake levels. Note that the losses shown in these figures are the equivalent cost, where non-monetary attributes are priced out. From the loss-hazard curves, the expected equivalent cost of the alternatives can be obtained by calculating the area under the curves. Table 6.10 shows the expected earthquake losses for each rehabilitation scheme, which are obtained from the loss hazard curves, along with the initial costs for the rehabilitation, followed by the total expected losses (for a 30 year time). Note that these expected losses are calculated considering the probability of each level of the earthquake. The result of the expected equivalent cost analysis indicates that none of the rehabilitation actions is justified for all three types of structures; the "No Action" alternative is preferred in all cases.

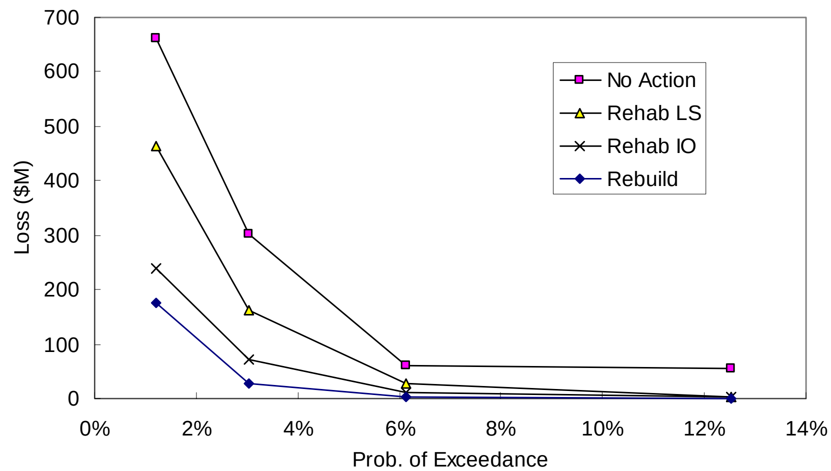


Figure 6.9 Equivalent Cost - Hazard Curves for C2M type Structures (4 units)

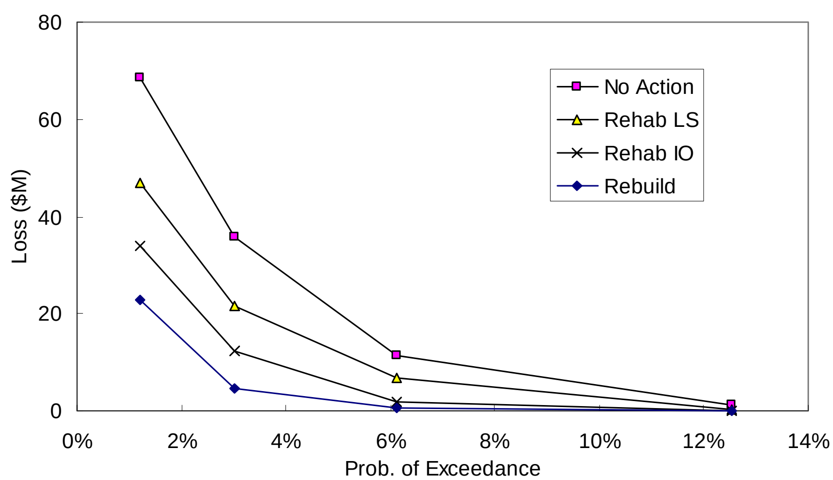


Figure 6.10 Equivalent Cost - Hazard Curves for C2L type Structure (1 unit)

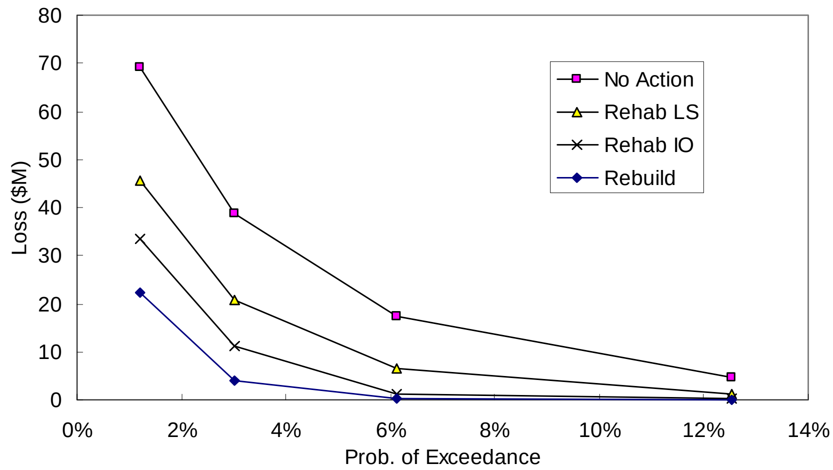


Figure 6.11 Equivalent Cost - Hazard Curves for URML type Structure (1 unit)

Table 6.10 Expected Equivalent Costs ($Million) of Different Rehabilitation Schemes

		Initial Cost (Rehab. Cost)	Expected Earthquake Loss (in 30 years)	Total Expected Cost (in 30 years)
C2M (4 units)	No Action	0	26.03	26.03
	Rehab LS	27.34	15.19	42.53
	Rehab IO	55.32	7.38	62.70
	Rebuild	76.93	4.60	82.53
C2L (1 unit)	No Action	0	2.91	2.91
	Rehab LS	2.73	1.85	4.58
	Rehab IO	5.53	1.11	6.64
	Rebuild	7.69	0.63	8.32
URML (1 unit)	No Action	0	3.40	3.40
	Rehab LS	2.73	1.82	4.55
	Rehab IO	5.53	1.05	6.58
	Rebuild	7.69	0.59	8.28

6.7 Sensitivity Analysis

Since the consequence table above (Table 6.10) is based on the pre-defined base line values (Table 6.9) which depend upon numerous assumptions and uncertainties inherent in the problem, sensitivity analysis should be performed to obtain better insight into the effect of these values on the final consequence values. As discussed in Section 3.2, sensitivity analysis can also help to identify variables or factors that should be further refined. The sensitivity analysis is performed for the variables and their corresponding ranges shown in Table 6.11.

Table 6.11 Ranges of Variables for Sensitivity Analysis

	Baseline Value	Lower Bound	Upper Bound
Value of Death ($M/person)	5.0	1.0	9.0
Value of Function ($/day to recover/10,000ft^2)	100,000	0.0	200,000
Discount Rate	6%	3%	9%
Time Horizon (years)	30 years	10 years	50 years

The sensitivity plots in Figure 6.12 - Figure 6.15 display the change in the expected equivalent cost of the various alternatives for different ranges of the key variables. It appears that the relative differences of the expected equivalent costs of the alternatives do not vary much over the entire range of the value of life (death), discount rate, and time horizon, implying no rehabilitation action is justified over the chosen range of the variables. However, the expected equivalent costs of the alternatives are relatively sensitive to changes in the value of function loss (Figure 6.13). The slopes (sensitivity) of the options are different from each other and decision reverses can be anticipated with higher values of function loss (in fact, decision reverse occurs when the value of function is \$0.2-0.3M/day to recover/10,000ft^2 for all three types of structures). This implies that the seismic rehabilitation actions could be justified when the value of loss of function is relatively high. Because the value of function can be subjectively determined depending on the decision maker as discussed in Section 6.5, it is necessary to further investigate the determination of the value of function.

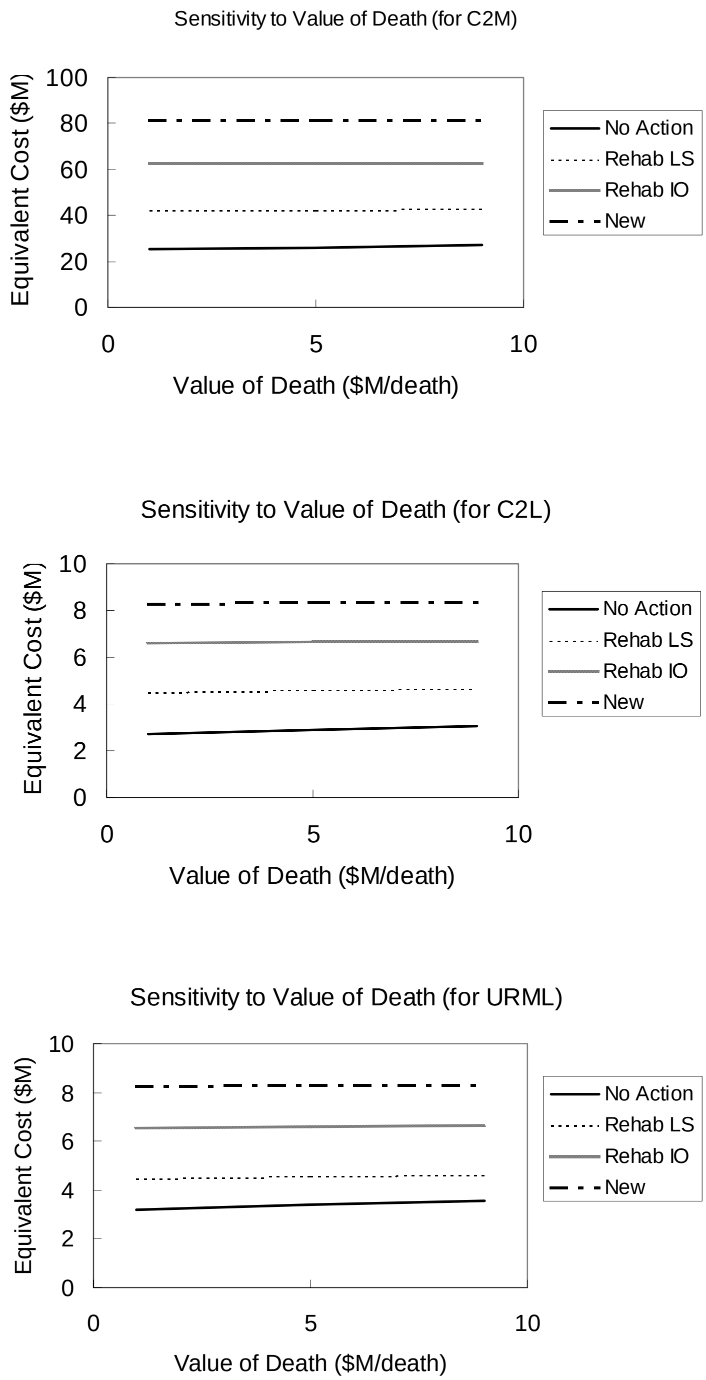


Figure 6.12 Sensitivity Plot for Value of Death

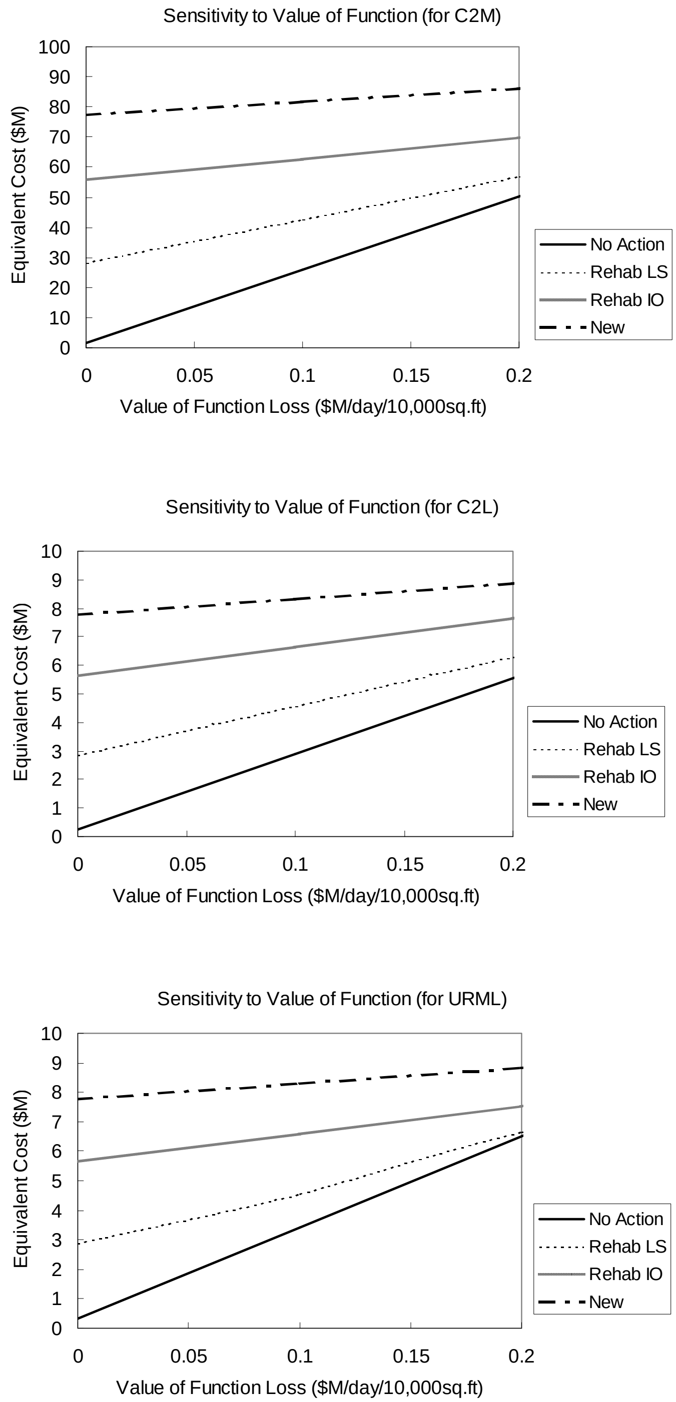


Figure 6.13 Sensitivity Plot for Value of Function

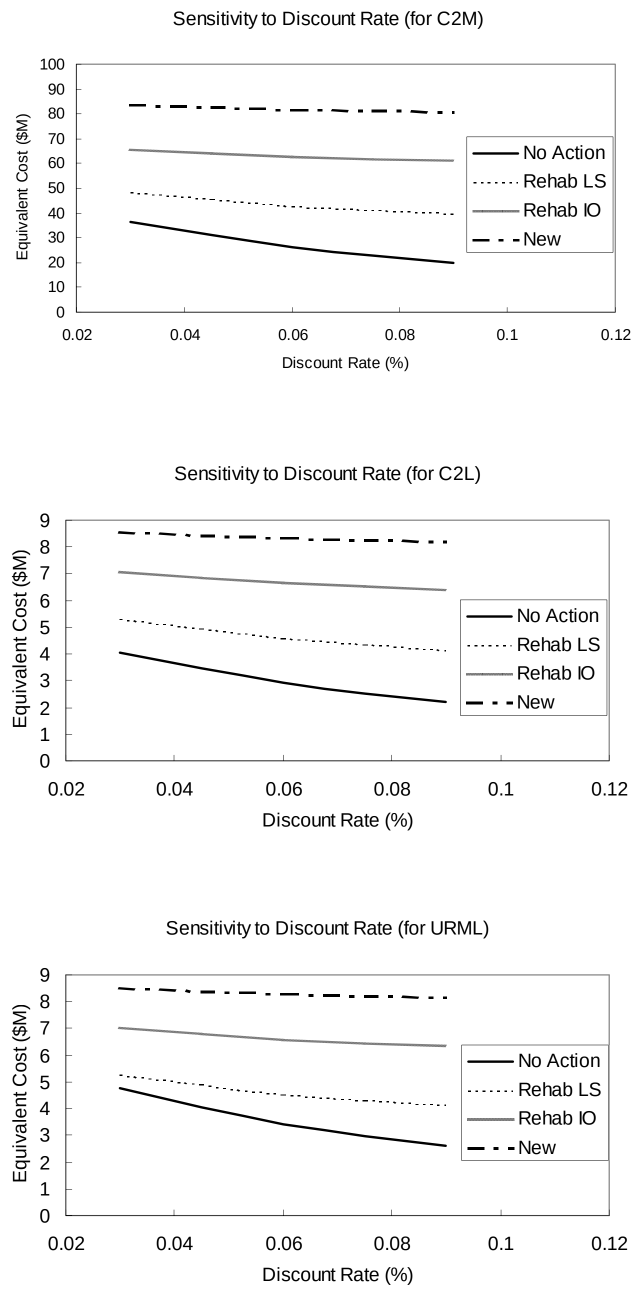


Figure 6.14 Sensitivity Plot for Discount Rate

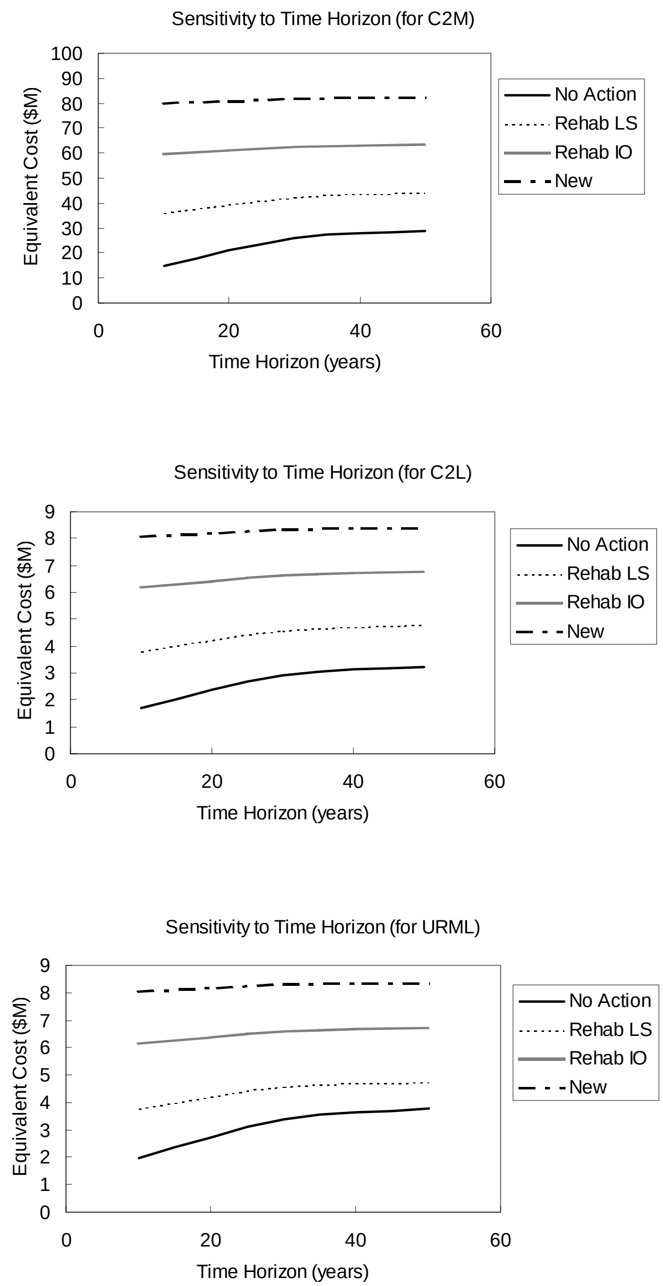


Figure 6.15 Sensitivity Plot for Time Horizon

6.8 Summary of Equivalent Cost Analysis

Equivalent cost analysis is performed for six hospital structures located in the Memphis, Tennessee area. The non-monetary values are priced out through conversion factors and the equivalent cost is calculated for each alternative as a decision index. With the baseline values for the conversion factors, discount rate, and time horizon, the analysis indicates that no rehabilitation action is justified based on equivalent cost analysis for all types of structures. This remains true with the sensitivity analyses that are performed for the value of life, discount rate, and time horizon over the possible ranges. However, the sensitivity analysis for the value of function indicates that with very high value of function, the rehabilitation actions (either 'Rehab to Life Safety Level' or 'Rehab to Immediate Occupancy Level') could be recommended for all three types (C2M, C2L, and URML) of structures based on the equivalent cost analysis.

CHAPTER 7

APPLICATION TO A HOSPITAL SYSTEM – MAUT ANALYSIS

As discussed in Chapter 3, utility analysis is one of the three main approaches for decision analysis in this study. The decision maker's values are expressed in terms of utility functions. The main difference in utility analysis compared to equivalent cost analysis is the inclusion of the risk attitudes of decision makers. Among the attributes (or losses) that are of interest in this detailed hospital example (see Chapter 6 for background information), structural/nonstructural repair cost, initial rehabilitation cost, contents loss, and business inventory loss can be aggregated and represented as 'monetary loss'. Attributes other than monetary value include life loss (death and injury) and loss of function. As emphasized in Chapter 6, quantification of value (both monetary and non-monetary) is not an easy task. Value elicitation is a complex task that requires careful interaction between the decision maker and the decision analyst. However, value elicitation is outside of the scope of this study, so two sets of common utility functions are assumed for the attributes in this example, and their results are compared to explore the effect of risk attitude. One set of utility functions is for the case in which the decision maker is risk averse, and the other is for a risk-seeking decision maker.

7.1 Utility Analysis Assuming Risk-Averse Decision Maker

In this section, the utility functions for the four attributes mentioned above (i.e., monetary loss, function loss, people's life loss and injury) are constructed assuming a risk-averse decision maker. Although the utility functions should be determined through extensive interaction with the decision maker in a value elicitation exercise, they are simply assumed to be quadratic functions shown in Figure 7.1. Each function is defined such that the utility corresponding to zero loss is 1 and the utility associated with maximum possible loss is 0. Note that loss of function is measured as days of loss of function multiplied by the size of the facility (in terms of 10,000 ft^2). For example, one day of loss of function of a hospital facility of which area is 500,000 ft^2 is measured as 50.

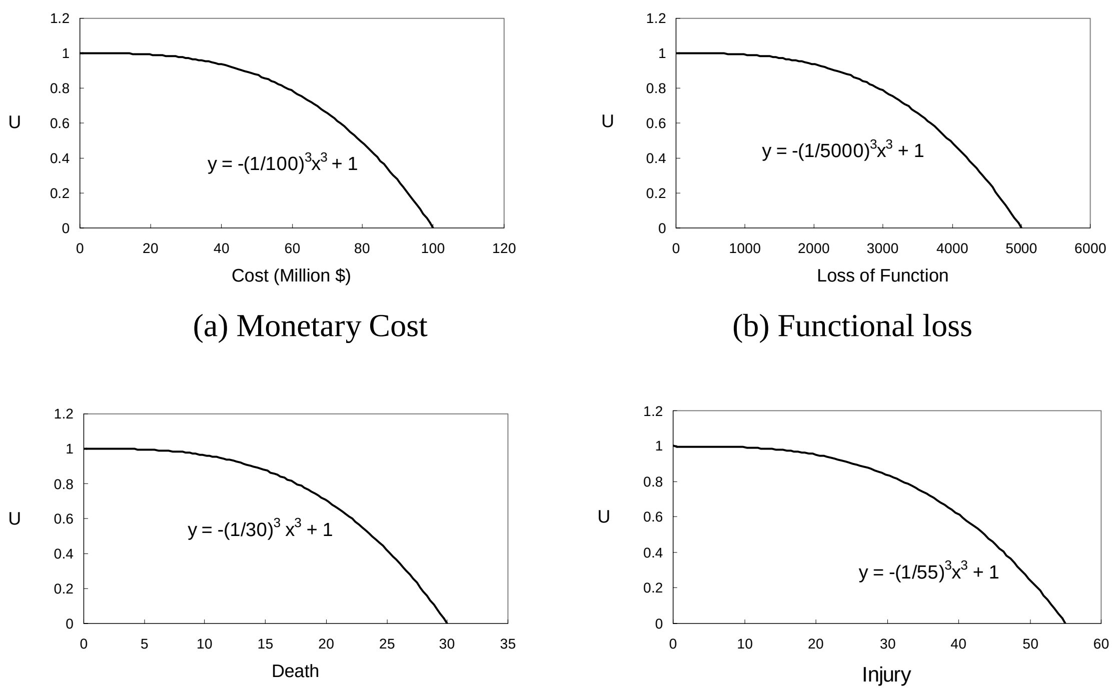
In constructing the multi-attribute utility function, the utility functions are assumed to be additive for simplicity, and scaling factors k_i are defined as shown in Table 7.1. The table also lists the minimum and the maximum value of each consequence, which are obtained from the simulation for consequence estimation in Chapter 6. For the purpose of comparing these results with the equivalent cost analysis results in Chapter 6, the scaling factors for the attributes are determined such that the ratios among the scaling factors are the same as the ratios among the equivalent costs of the maximum values. This relationship can be expressed as follows.

$$\frac{k_i}{k_j} = \frac{C_{i\max} \cdot V_i}{C_{j\max} \cdot V_j} \qquad [7.1]$$

where, k_i and k_j are scaling factors, C_{imax} and C_{jmax} are the maximum consequence, V_i and V_j are the conversion factors in ECA corresponding to the *i*th and *j*th attribute. Note that the scaling factors are summed up to 1.0, since additive utilities are assumed. These scaling factors are presented as baseline values and are subject to change in the sensitivity analysis to investigate the effects of these values. The multi-attribute utility function can then be formulated as

$$u(x_1, x_2, x_3, x_4) = k_1 u_1(x_1) + k_2 u_2(x_2) + k_3 u_3(x_3) + k_4 u_4(x_4) \qquad [7.2]$$

where $u(x_1, x_2, x_3, x_4)$ is the multi-attribute utility function, k_i's are the additive scaling factors (see Table 7.1) and $u_i(x_i)$'s are the marginal utility functions of the attributes (see Figure 7.1).



(a) Monetary Cost

(b) Functional loss

(c) Death

(d) Injury

Figure 7.1 Utility Functions (Risk-Averse) of Attributes

Table 7.1 Scaling Factors for Attributes

Attributes	Min. Value	Max. Value	Scaling Factor
Monetary Cost ($M)	0	100	$k_1 = 0.12$
Functional loss ($days \cdot A_{total} / 10{,}000\, ft^2$)	0	5,000	$k_2 = 0.60$
Death	0	30	$k_3 = 0.18$
Injury	0	55	$k_4 = 0.10$

In this example, twenty-seven combinations of the alternative systems are analyzed, using three alternatives from each type of structure (here the "Rebuild" option, which received the lowest rank in the equivalent cost analysis, is not considered). As in equivalent cost analysis, Latin Hypercube Sampling is performed with 500 intervals to obtain the expected utility of each of the twenty-seven alternative combination schemes. The analysis is performed by changing baseline values. For example, Table 7.2 shows the expected utilities of the alternatives for two different values of k_2 (scaling factor for function loss): k_2 =0.6 and k_2 =0.75. These values of k_2 are determined based on Equation 7.1 corresponding to the cases where the value of function loss is $100,000 and $200,000 in ECA, respectively. In addition to the scaling factor for function loss, the analyses are performed for different configurations of the scaling factors for life loss (k_1), discount rate (*DR*), and time horizon (*TH*) as shown in Table 7.3 - Table 7.5. In addition, the utility hazard curves for selected combinations (T1: "No Action" for all three types of structures, T14: "Rehab LS" options for all three types of structures, and T27: "Rehab IO" options for all three types of structures) of the alternative systems are shown in

Figure 7.2 - Figure 7.5 for different earthquake levels. These three schemes are selected because they represent different levels of rehabilitation.

In Table 7.2, where the expected utilities of the alternative schemes are shown for two different values of k_2, it is shown that the 'Rehabilitation to Life Safety Level' option is suggested for C2M type structures with the baseline value (k_2=0.6). Although the table indicates that schemes T10 and T11 result in the highest expected utilities, the differences in the expected utilities among alternative schemes T10 to T18 are relatively small. This implies that the impact on overall preference of the rehabilitation of C2L and URML type structures are relatively small compared to the impact of the rehabilitation of C2M type structures. On the other hand, when the scaling factor for the functional loss is set high (k_2=0.75), scheme T19 is best since it has the highest expected utility. These results show that as the value of functional loss becomes higher, so does the target performance level of the seismic rehabilitation. Table 7.3 shows the expected utilities of the alternative schemes for two different values of the scaling factor for life loss (k_1). Even with high value of k_1 (when k_1=0.25), the preferences among the alternative schemes remains the same, indicating that the value of loss of life does not make significant impact on the determination of the most preferred seismic rehabilitation scheme. However, the choice of the discount rate value does affect the decisions. In Table 7.4, if a discount rate of 9% is used, the suggested alternative schemes are shifted to T19, where the option for C2M type structures is 'Rehabilitation to Immediate Occupancy Level.' Next, additional analyses are performed for different values of time horizon, and the change of time horizon also has an impact on the final outcome. As can be seen in Table 7.5, T19 is preferred in the case where the time horizon is 50 years.

It should be noted that the expected utilities of different alternatives are so close to one another that three or four significant digits are needed for differentiation. This is in part because the probability of encountering an earthquake large enough to cause a substantial damage to the system is very low, and in part because of the incorporation of the risk aversion, as the utilities of relatively small losses are close to one. Therefore, additional data must be provided in order for the user to obtain a better insight into the seismic consequences associated with the system. This can be done by providing seismic losses corresponding to several significant levels of earthquakes, and will be demonstrated in more detail in Chapter 9.

Table 7.2 Expected Utilities for the Combinations of Seismic Alternative Schemes for Different Values of the Scaling Factor for Functional loss, k_2 (with risk-averse utility functions)

Scheme	C2M	C2L	URML	Expected Utility	
				k_2=0.6	k_2=0.75
T1	No Action	No Action	No Action	0.9946	0.9933
T2	No Action	No Action	Rehab LS	0.9947	0.9934
T3	No Action	No Action	Rehab IO	0.9947	0.9935
T4	No Action	Rehab LS	No Action	0.9946	0.9934
T5	No Action	Rehab LS	Rehab LS	0.9947	0.9934
T6	No Action	Rehab LS	Rehab IO	0.9948	0.9935
T7	No Action	Rehab IO	No Action	0.9947	0.9934
T8	No Action	Rehab IO	Rehab LS	0.9947	0.9935
T9	No Action	Rehab IO	Rehab IO	0.9948	0.9935
T10	Rehab LS	No Action	No Action	**0.9969**	0.9963
T11	Rehab LS	No Action	Rehab LS	**0.9969**	0.9964
T12	Rehab LS	No Action	Rehab IO	0.9968	0.9963
T13	Rehab LS	Rehab LS	No Action	0.9968	0.9963
T14	Rehab LS	Rehab LS	Rehab LS	0.9968	0.9964
T15	Rehab LS	Rehab LS	Rehab IO	0.9967	0.9963
T16	Rehab LS	Rehab IO	No Action	0.9968	0.9963
T17	Rehab LS	Rehab IO	Rehab LS	0.9967	0.9963
T18	Rehab LS	Rehab IO	Rehab IO	0.9966	0.9963
T19	Rehab IO	No Action	No Action	0.9964	**0.9970**
T20	Rehab IO	No Action	Rehab LS	0.9961	0.9969
T21	Rehab IO	No Action	Rehab IO	0.9957	0.9967
T22	Rehab IO	Rehab LS	No Action	0.9961	0.9969
T23	Rehab IO	Rehab LS	Rehab LS	0.9957	0.9967
T24	Rehab IO	Rehab LS	Rehab IO	0.9953	0.9965
T25	Rehab IO	Rehab IO	No Action	0.9957	0.9967
T26	Rehab IO	Rehab IO	Rehab LS	0.9953	0.9965
T27	Rehab IO	Rehab IO	Rehab IO	0.9948	0.9962

Table 7.3 Expected Utilities for the Combinations of Seismic Alternative Schemes for Different Values of the Scaling Factor for Life Loss, k_1 (with risk-averse utility functions)

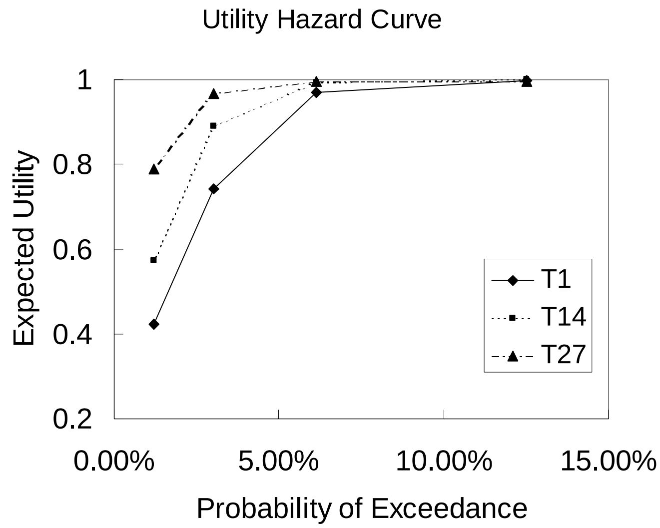
Scheme	C2M	C2L	URML	Expected Utility	
				k_1=0.18	k_1=0.25
T1	No Action	No Action	No Action	0.9946	0.9953
T2	No Action	No Action	Rehab LS	0.9947	0.9954
T3	No Action	No Action	Rehab IO	0.9947	0.9954
T4	No Action	Rehab LS	No Action	0.9946	0.9954
T5	No Action	Rehab LS	Rehab LS	0.9947	0.9954
T6	No Action	Rehab LS	Rehab IO	0.9948	0.9955
T7	No Action	Rehab IO	No Action	0.9947	0.9954
T8	No Action	Rehab IO	Rehab LS	0.9947	0.9955
T9	No Action	Rehab IO	Rehab IO	0.9948	0.9955
T10	Rehab LS	No Action	No Action	**0.9969**	**0.9973**
T11	Rehab LS	No Action	Rehab LS	**0.9969**	**0.9973**
T12	Rehab LS	No Action	Rehab IO	0.9968	0.9972
T13	Rehab LS	Rehab LS	No Action	0.9968	0.9973
T14	Rehab LS	Rehab LS	Rehab LS	0.9968	0.9972
T15	Rehab LS	Rehab LS	Rehab IO	0.9967	0.9972
T16	Rehab LS	Rehab IO	No Action	0.9968	0.9972
T17	Rehab LS	Rehab IO	Rehab LS	0.9967	0.9972
T18	Rehab LS	Rehab IO	Rehab IO	0.9966	0.9971
T19	Rehab IO	No Action	No Action	0.9964	0.9969
T20	Rehab IO	No Action	Rehab LS	0.9961	0.9967
T21	Rehab IO	No Action	Rehab IO	0.9957	0.9963
T22	Rehab IO	Rehab LS	No Action	0.9961	0.9966
T23	Rehab IO	Rehab LS	Rehab LS	0.9957	0.9963
T24	Rehab IO	Rehab LS	Rehab IO	0.9953	0.9960
T25	Rehab IO	Rehab IO	No Action	0.9957	0.9963
T26	Rehab IO	Rehab IO	Rehab LS	0.9953	0.9960
T27	Rehab IO	Rehab IO	Rehab IO	0.9948	0.9956

Table 7.4 Expected Utilities for the Combinations of Seismic Alternative Schemes for Different Values of the Discount Rate, *DR* (with risk-averse utility functions)

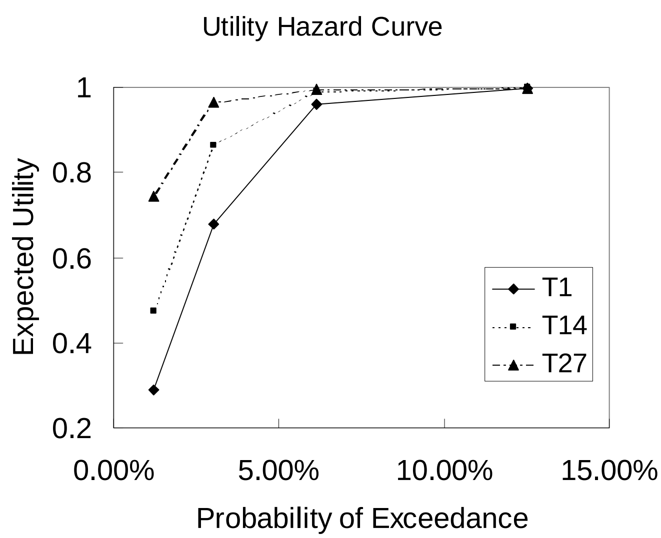
Scheme	C2M	C2L	URML	Expected Utility	
				DR=0.06	*DR*=0.09
T1	No Action	No Action	No Action	0.9946	0.9955
T2	No Action	No Action	Rehab LS	0.9947	0.9956
T3	No Action	No Action	Rehab IO	0.9947	0.9958
T4	No Action	Rehab LS	No Action	0.9946	0.9956
T5	No Action	Rehab LS	Rehab LS	0.9947	0.9958
T6	No Action	Rehab LS	Rehab IO	0.9948	0.9959
T7	No Action	Rehab IO	No Action	0.9947	0.9957
T8	No Action	Rehab IO	Rehab LS	0.9947	0.9959
T9	No Action	Rehab IO	Rehab IO	0.9948	0.9960
T10	Rehab LS	No Action	No Action	**0.9969**	0.9975
T11	Rehab LS	No Action	Rehab LS	**0.9969**	0.9976
T12	Rehab LS	No Action	Rehab IO	0.9968	0.9977
T13	Rehab LS	Rehab LS	No Action	0.9968	0.9976
T14	Rehab LS	Rehab LS	Rehab LS	0.9968	0.9977
T15	Rehab LS	Rehab LS	Rehab IO	0.9967	0.9977
T16	Rehab LS	Rehab IO	No Action	0.9968	0.9976
T17	Rehab LS	Rehab IO	Rehab LS	0.9967	0.9977
T18	Rehab LS	Rehab IO	Rehab IO	0.9966	0.9977
T19	Rehab IO	No Action	No Action	0.9964	**0.9981**
T20	Rehab IO	No Action	Rehab LS	0.9961	0.9980
T21	Rehab IO	No Action	Rehab IO	0.9957	0.9978
T22	Rehab IO	Rehab LS	No Action	0.9961	0.9980
T23	Rehab IO	Rehab LS	Rehab LS	0.9957	0.9978
T24	Rehab IO	Rehab LS	Rehab IO	0.9953	0.9977
T25	Rehab IO	Rehab IO	No Action	0.9957	0.9978
T26	Rehab IO	Rehab IO	Rehab LS	0.9953	0.9977
T27	Rehab IO	Rehab IO	Rehab IO	0.9948	0.9975

Table 7.5 Expected Utilities for the Combinations of Seismic Alternative Schemes for Different Values of the Time Horizon, *TH*
(with risk-averse utility functions)

Scheme	C2M	C2L	URML	Expected Utility	
				TH=30	*TH*=50
T1	No Action	No Action	No Action	0.9946	0.9935
T2	No Action	No Action	Rehab LS	0.9947	0.9938
T3	No Action	No Action	Rehab IO	0.9947	0.9940
T4	No Action	Rehab LS	No Action	0.9946	0.9937
T5	No Action	Rehab LS	Rehab LS	0.9947	0.9939
T6	No Action	Rehab LS	Rehab IO	0.9948	0.9941
T7	No Action	Rehab IO	No Action	0.9947	0.9939
T8	No Action	Rehab IO	Rehab LS	0.9947	0.9941
T9	No Action	Rehab IO	Rehab IO	0.9948	0.9943
T10	Rehab LS	No Action	No Action	**0.9969**	0.9967
T11	Rehab LS	No Action	Rehab LS	**0.9969**	0.9969
T12	Rehab LS	No Action	Rehab IO	0.9968	0.9970
T13	Rehab LS	Rehab LS	No Action	0.9968	0.9969
T14	Rehab LS	Rehab LS	Rehab LS	0.9968	0.9971
T15	Rehab LS	Rehab LS	Rehab IO	0.9967	0.9971
T16	Rehab LS	Rehab IO	No Action	0.9968	0.9970
T17	Rehab LS	Rehab IO	Rehab LS	0.9967	0.9971
T18	Rehab LS	Rehab IO	Rehab IO	0.9966	0.9971
T19	Rehab IO	No Action	No Action	0.9964	**0.9982**
T20	Rehab IO	No Action	Rehab LS	0.9961	0.9981
T21	Rehab IO	No Action	Rehab IO	0.9957	0.9981
T22	Rehab IO	Rehab LS	No Action	0.9961	0.9981
T23	Rehab IO	Rehab LS	Rehab LS	0.9957	0.9981
T24	Rehab IO	Rehab LS	Rehab IO	0.9953	0.9980
T25	Rehab IO	Rehab IO	No Action	0.9957	0.9981
T26	Rehab IO	Rehab IO	Rehab LS	0.9953	0.9980
T27	Rehab IO	Rehab IO	Rehab IO	0.9948	0.9979

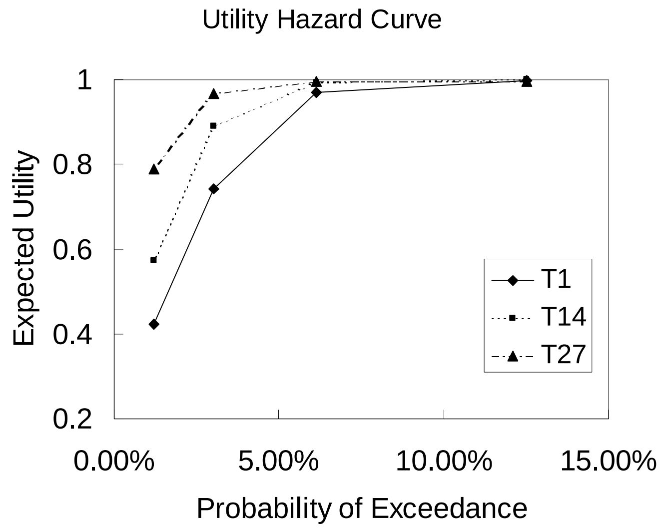


(a) with k_2=0.6

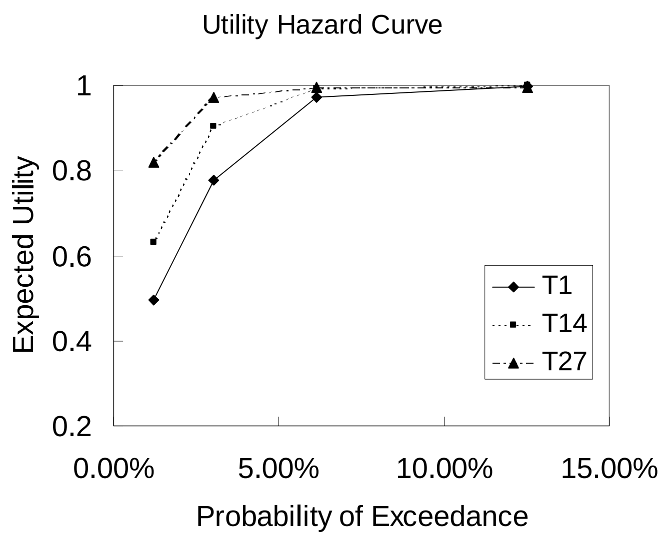


(b) with k_2=0.75

Figure 7.2 Comparison of Utility Hazard Curves for Selected Combination Schemes for Different Values of k_2 (with risk-averse utility functions)

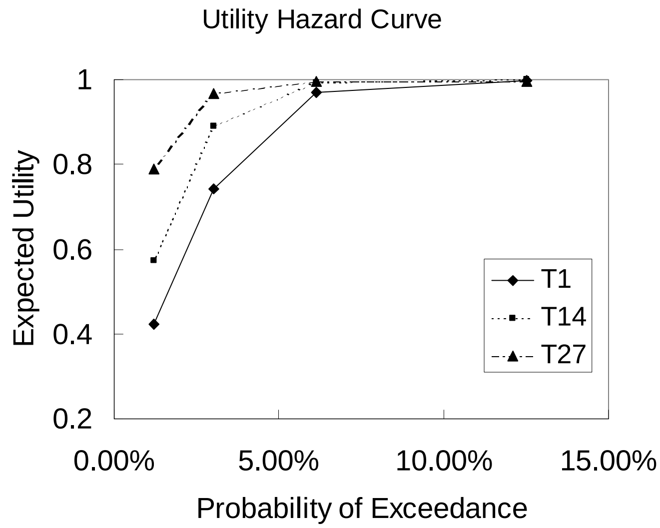


(a) with k_1=0.18

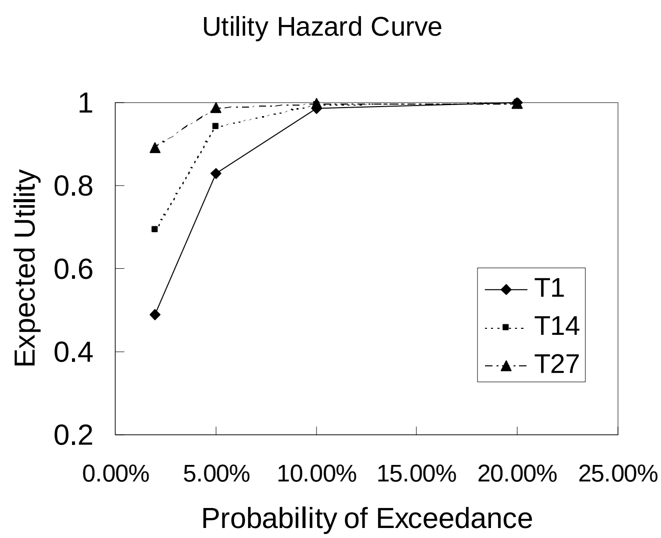


(b) with k_1=0.25

Figure 7.3 Comparison of Utility Hazard Curves for Selected Combination Schemes for Different Values of k_1 (with risk-averse utility functions)

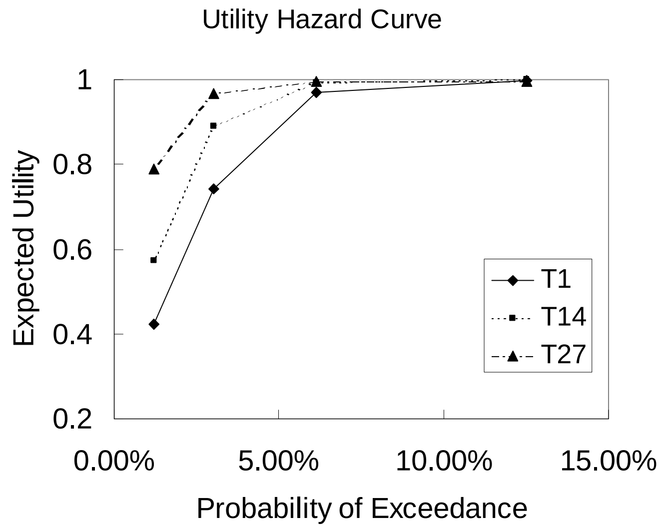


(a) with *DR*=0.06

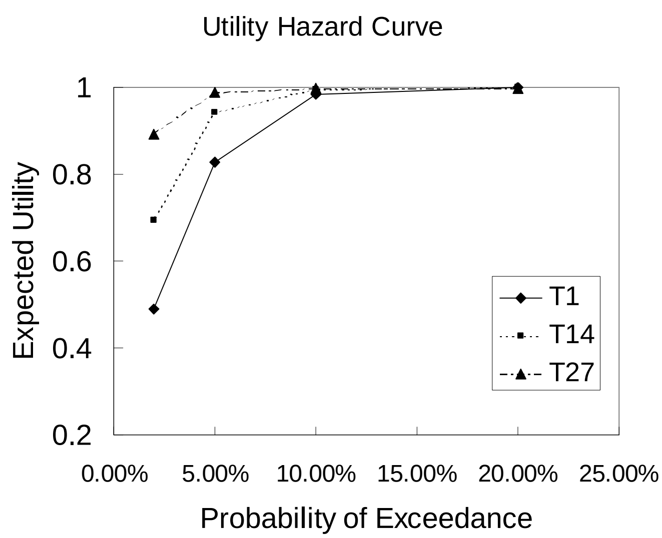


(b) with *DR*=0.09

Figure 7.4 Comparison of Utility Hazard Curves for Selected Combination Schemes for Different Values of Discount Rate, *DR*
(with risk-averse utility functions)



(a) with *TH*=30 yrs

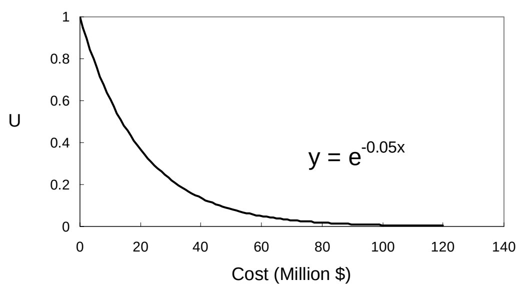


(b) with *TH*=50 yrs

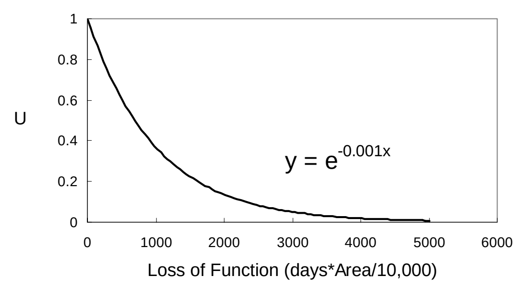
Figure 7.5 Comparison of Utility Hazard Curves for Selected Combination Schemes for Different Values of Time Horizon, *TH*
(with risk-averse utility functions)

7.2 Utility Analysis Assuming Risk-Seeking Decision Maker

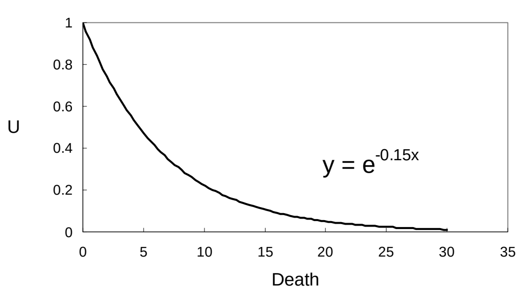
In the previous section, the utility analysis is performed for the system with the assumption that the decision maker is risk averse. In this section, the analysis is performed assuming risk-seeking utility functions to investigate the effect of different risk attitudes. Note that the analysis in this section is for illustrative purpose, as a risk-seeking decision maker might be unrealistic for this case. Four risk-seeking utility functions are assumed as shown in Figure 7.6. Note that the scaling factors for the attributes are the same as those listed in Table 7.1.



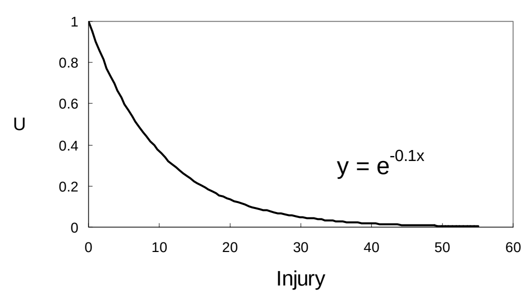
(a) Monetary Cost



(b) Functional loss



(c) Death



(d) Injury

Figure 7.6 Marginal Utility Functions (Risk-Seeking) for Attributes

Table 7.6 - Table 7.9 show the consequence tables for different configurations of the variables listed in Table 6.11. In Table 7.6, where the expected utilities of the alternative schemes are shown for two different values of k_2, the expected utilities of schemes T1 through T9 are relatively high for both values of k_2. Note that the options for C2M structures are "No Action" for these schemes. Considering the fact that C2M structures take most part of the hospital system, the analysis implies that overall no rehabilitation actions are suggested. More specifically, scheme T1 ("No Action" for all the structures) is the preferred option for the case in which k_2 is 0.6, and scheme T2 ('Rehabilitation to Life Safety Level' option for URML structure, and "No Action" for the rest) is preferred for the case in which k_2 is 0.75.

In addition to the scaling factor for functional loss k_2, analyses are also performed for different configurations of the scaling factors for life loss, discount rate, and time period. Table 7.7 - Table 7.9 show the resulting consequence tables for different configurations of the variables mentioned above. Note that the scaling factor for life loss (k_1) of 0.25 corresponds to the case in which the value of life is $8,000,000 in the equivalent cost analysis (see Chapter 6) based on Equation 7.1. The analysis results show that the values of k_1, discount rate, and time horizon do not have significant impacts on the overall rank of the preferences. More specifically, with a high value of discount rate or time horizon, the analysis shows scheme T2 is most preferred, suggesting low level of rehabilitation for URML type structure only. However, considering the differences in expected utilities of T1 and T2 are not significant for most cases, and the scale of suggested rehabilitation in T2 is minor, it can be concluded that any rehabilitation action is hardly justified for the system with risk-seeking utilities.

Same as in the previous section, the utility-hazard curves of selected rehabilitation schemes (T1, T14 and T27) for different configuration of the variables mentioned above are shown in Figure 7.7 - Figure 7.10. The expected utilities of the alternative schemes are obtained from the utility-hazard curves by calculating the area under the curves. Note that the curves shown in Figure 7.7 - Figure 7.10 are plotted up to an earthquake level of 20% of PE in 50 years. The case of having a minor or no earthquake, where utilities are estimated based on the initial cost, must be considered in order to calculate the expected utilities of the alternative schemes.

Unlike the case with the risk-averse utility functions, the differences in the expected utilities of the different alternatives are clearer with the risk-seeking utility functions. This is because the losses due to minor earthquakes, which have moderate probability of occurring result in relatively low utilities.

Table 7.6 Expected Utilities for the Combinations of Seismic Alternative Schemes for Different Values of the Scaling Factor for Functional loss, k_2 (with risk-seeking utility functions)

Scheme	C2M	C2L	URML	Expected Utility	
				$k_2 = 0.6$	$k_2 = 0.75$
T1	No Action	No Action	No Action	**0.9659**	0.9584
T2	No Action	No Action	Rehab LS	0.9646	**0.9615**
T3	No Action	No Action	Rehab IO	0.9593	0.9595
T4	No Action	Rehab LS	No Action	0.9603	0.9561
T5	No Action	Rehab LS	Rehab LS	0.9600	0.9602
T6	No Action	Rehab LS	Rehab IO	0.9553	0.9586
T7	No Action	Rehab IO	No Action	0.9538	0.9527
T8	No Action	Rehab IO	Rehab LS	0.9543	0.9574
T9	No Action	Rehab IO	Rehab IO	0.9503	0.9564
T10	Rehab LS	No Action	No Action	0.9111	0.9262
T11	Rehab LS	No Action	Rehab LS	0.9141	0.9324
T12	Rehab LS	No Action	Rehab IO	0.9130	0.9334
T13	Rehab LS	Rehab LS	No Action	0.9094	0.9265
T14	Rehab LS	Rehab LS	Rehab LS	0.9133	0.9336
T15	Rehab LS	Rehab LS	Rehab IO	0.9126	0.9349
T16	Rehab LS	Rehab IO	No Action	0.9067	0.9255
T17	Rehab LS	Rehab IO	Rehab LS	0.9111	0.9331
T18	Rehab LS	Rehab IO	Rehab IO	0.9111	0.9350
T19	Rehab IO	No Action	No Action	0.8821	0.9088
T20	Rehab IO	No Action	Rehab LS	0.8872	0.9164
T21	Rehab IO	No Action	Rehab IO	0.8882	0.9187
T22	Rehab IO	Rehab LS	No Action	0.8824	0.9103
T23	Rehab IO	Rehab LS	Rehab LS	0.8884	0.9190
T24	Rehab IO	Rehab LS	Rehab IO	0.8895	0.9215
T25	Rehab IO	Rehab IO	No Action	0.8818	0.9109
T26	Rehab IO	Rehab IO	Rehab LS	0.8882	0.9198
T27	Rehab IO	Rehab IO	Rehab IO	0.8900	0.9230

Table 7.7 Expected Utilities for the Combinations of Seismic Alternative Schemes for Different Values of the Scaling Factor for Life Loss, k_1 (with risk-seeking utility functions)

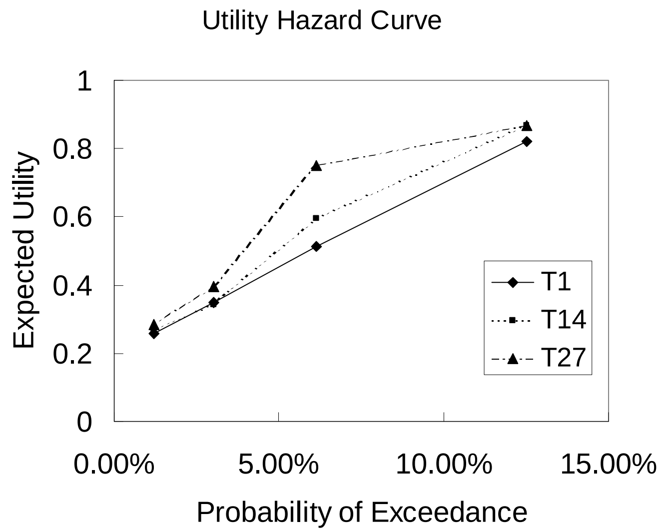
Scheme	C2M	C2L	URML	Expected Utility	
				k_1=0.18	k_1=0.25
T1	No Action	No Action	No Action	**0.9659**	**0.9705**
T2	No Action	No Action	Rehab LS	0.9646	0.9694
T3	No Action	No Action	Rehab IO	0.9593	0.9650
T4	No Action	Rehab LS	No Action	0.9603	0.9658
T5	No Action	Rehab LS	Rehab LS	0.9600	0.9656
T6	No Action	Rehab LS	Rehab IO	0.9553	0.9615
T7	No Action	Rehab IO	No Action	0.9538	0.9602
T8	No Action	Rehab IO	Rehab LS	0.9543	0.9607
T9	No Action	Rehab IO	Rehab IO	0.9503	0.9573
T10	Rehab LS	No Action	No Action	0.9111	0.9237
T11	Rehab LS	No Action	Rehab LS	0.9141	0.9263
T12	Rehab LS	No Action	Rehab IO	0.9130	0.9254
T13	Rehab LS	Rehab LS	No Action	0.9094	0.9222
T14	Rehab LS	Rehab LS	Rehab LS	0.9133	0.9256
T15	Rehab LS	Rehab LS	Rehab IO	0.9126	0.9250
T16	Rehab LS	Rehab IO	No Action	0.9067	0.9200
T17	Rehab LS	Rehab IO	Rehab LS	0.9111	0.9238
T18	Rehab LS	Rehab IO	Rehab IO	0.9111	0.9238
T19	Rehab IO	No Action	No Action	0.8821	0.8988
T20	Rehab IO	No Action	Rehab LS	0.8872	0.9033
T21	Rehab IO	No Action	Rehab IO	0.8882	0.9041
T22	Rehab IO	Rehab LS	No Action	0.8824	0.8991
T23	Rehab IO	Rehab LS	Rehab LS	0.8884	0.9043
T24	Rehab IO	Rehab LS	Rehab IO	0.8895	0.9053
T25	Rehab IO	Rehab IO	No Action	0.8818	0.8987
T26	Rehab IO	Rehab IO	Rehab LS	0.8882	0.9042
T27	Rehab IO	Rehab IO	Rehab IO	0.8900	0.9057

Table 7.8 Expected Utilities for the Combinations of Seismic Alternative Schemes for Different Values of the Discount Rate, *DR* (with risk-seeking utility functions)

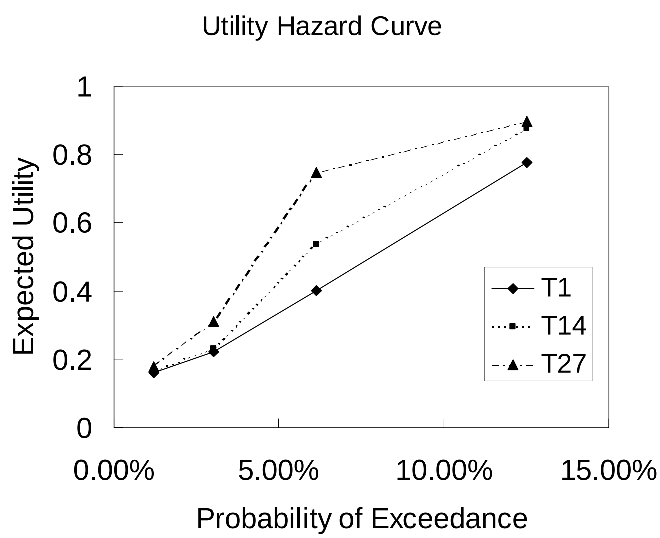
Scheme	C2M	C2L	URML	Expected Utility	
				DR=0.06	*DR*=0.09
T1	No Action	No Action	No Action	**0.9659**	0.9680
T2	No Action	No Action	Rehab LS	0.9646	**0.9682**
T3	No Action	No Action	Rehab IO	0.9593	0.9643
T4	No Action	Rehab LS	No Action	0.9603	0.9640
T5	No Action	Rehab LS	Rehab LS	0.9600	0.9649
T6	No Action	Rehab LS	Rehab IO	0.9553	0.9614
T7	No Action	Rehab IO	No Action	0.9538	0.9591
T8	No Action	Rehab IO	Rehab LS	0.9543	0.9606
T9	No Action	Rehab IO	Rehab IO	0.9503	0.9576
T10	Rehab LS	No Action	No Action	0.9111	0.9236
T11	Rehab LS	No Action	Rehab LS	0.9141	0.9267
T12	Rehab LS	No Action	Rehab IO	0.9130	0.9257
T13	Rehab LS	Rehab LS	No Action	0.9094	0.9221
T14	Rehab LS	Rehab LS	Rehab LS	0.9133	0.9259
T15	Rehab LS	Rehab LS	Rehab IO	0.9126	0.9252
T16	Rehab LS	Rehab IO	No Action	0.9067	0.9198
T17	Rehab LS	Rehab IO	Rehab LS	0.9111	0.9239
T18	Rehab LS	Rehab IO	Rehab IO	0.9111	0.9237
T19	Rehab IO	No Action	No Action	0.8821	0.8957
T20	Rehab IO	No Action	Rehab LS	0.8872	0.9003
T21	Rehab IO	No Action	Rehab IO	0.8882	0.9009
T22	Rehab IO	Rehab LS	No Action	0.8824	0.8957
T23	Rehab IO	Rehab LS	Rehab LS	0.8884	0.9012
T24	Rehab IO	Rehab LS	Rehab IO	0.8895	0.9019
T25	Rehab IO	Rehab IO	No Action	0.8818	0.8950
T26	Rehab IO	Rehab IO	Rehab LS	0.8882	0.9007
T27	Rehab IO	Rehab IO	Rehab IO	0.8900	0.9020

Table 7.9 Expected Utilities for the Combinations of Seismic Alternative Schemes for Different Values of the Time Horizon, *TH* (with risk-seeking utility functions)

Scheme	C2M	C2L	URML	Expected Utility	
				TH=30	*TH*=50
T1	No Action	No Action	No Action	**0.9659**	0.9491
T2	No Action	No Action	Rehab LS	0.9646	**0.9533**
T3	No Action	No Action	Rehab IO	0.9593	0.9511
T4	No Action	Rehab LS	No Action	0.9603	0.9469
T5	No Action	Rehab LS	Rehab LS	0.9600	0.9520
T6	No Action	Rehab LS	Rehab IO	0.9553	0.9501
T7	No Action	Rehab IO	No Action	0.9538	0.9431
T8	No Action	Rehab IO	Rehab LS	0.9543	0.9489
T9	No Action	Rehab IO	Rehab IO	0.9503	0.9476
T10	Rehab LS	No Action	No Action	0.9111	0.9111
T11	Rehab LS	No Action	Rehab LS	0.9141	0.9179
T12	Rehab LS	No Action	Rehab IO	0.9130	0.9185
T13	Rehab LS	Rehab LS	No Action	0.9094	0.9109
T14	Rehab LS	Rehab LS	Rehab LS	0.9133	0.9188
T15	Rehab LS	Rehab LS	Rehab IO	0.9126	0.9197
T16	Rehab LS	Rehab IO	No Action	0.9067	0.9095
T17	Rehab LS	Rehab IO	Rehab LS	0.9111	0.9178
T18	Rehab LS	Rehab IO	Rehab IO	0.9111	0.9194
T19	Rehab IO	No Action	No Action	0.8821	0.8850
T20	Rehab IO	No Action	Rehab LS	0.8872	0.8933
T21	Rehab IO	No Action	Rehab IO	0.8882	0.8954
T22	Rehab IO	Rehab LS	No Action	0.8824	0.8863
T23	Rehab IO	Rehab LS	Rehab LS	0.8884	0.8959
T24	Rehab IO	Rehab LS	Rehab IO	0.8895	0.8981
T25	Rehab IO	Rehab IO	No Action	0.8818	0.8864
T26	Rehab IO	Rehab IO	Rehab LS	0.8882	0.8963
T27	Rehab IO	Rehab IO	Rehab IO	0.8900	0.8995

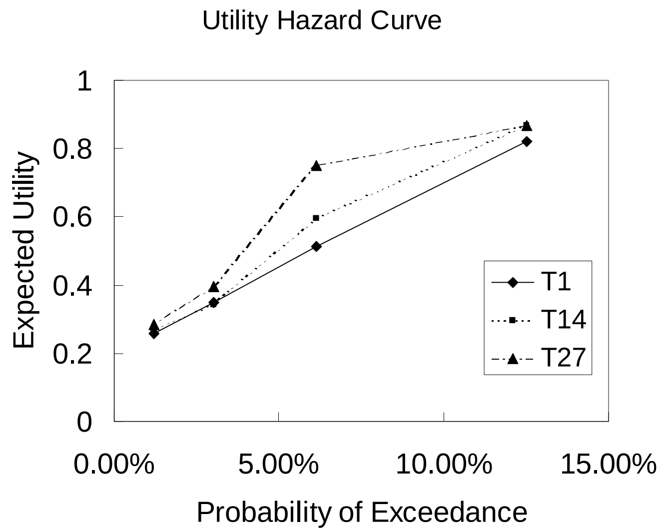


(a) with k_2=0.6

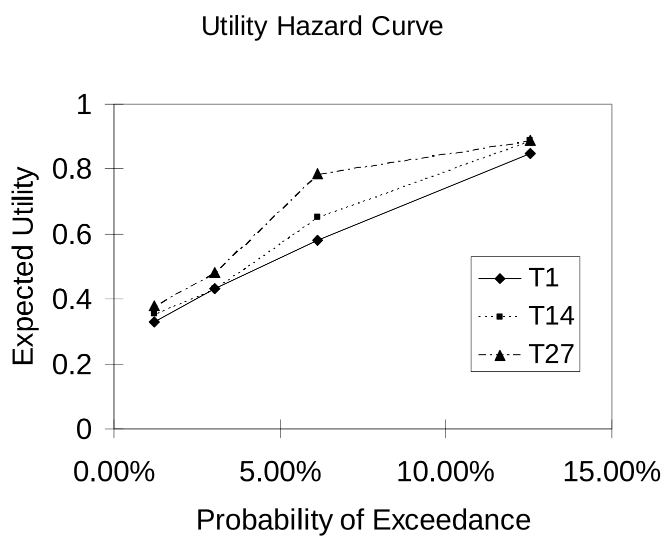


(b) with k_2=0.75

Figure 7.7 Comparison of Utility Hazard Curves for Selected Combination Schemes for Different Values of k_2 (with risk-seeking utility functions)

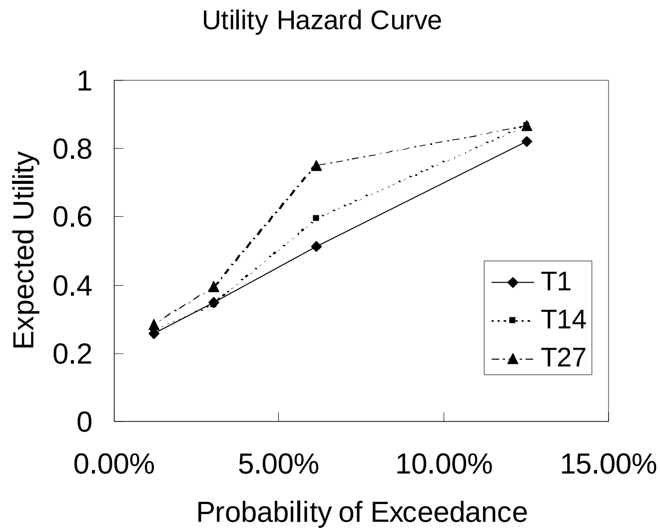


(a) with k_1=0.18

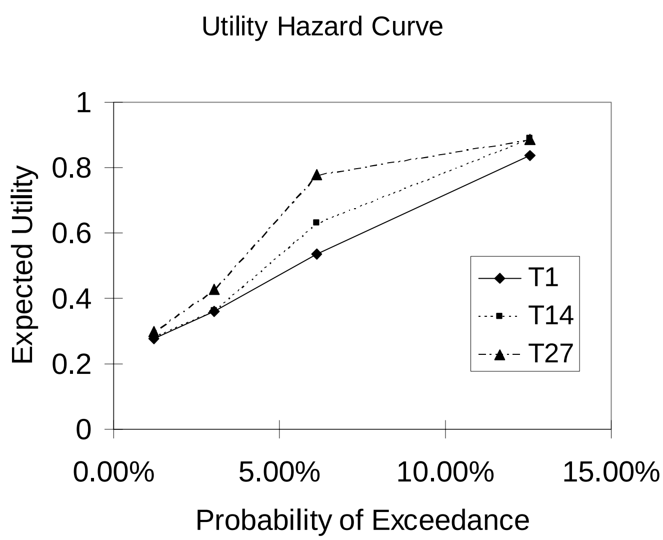


(b) with k_1=0.25

Figure 7.8 Comparison of Utility Hazard Curves for Selected Combination Schemes for Different Values of k_1 (with risk-seeking utility functions)

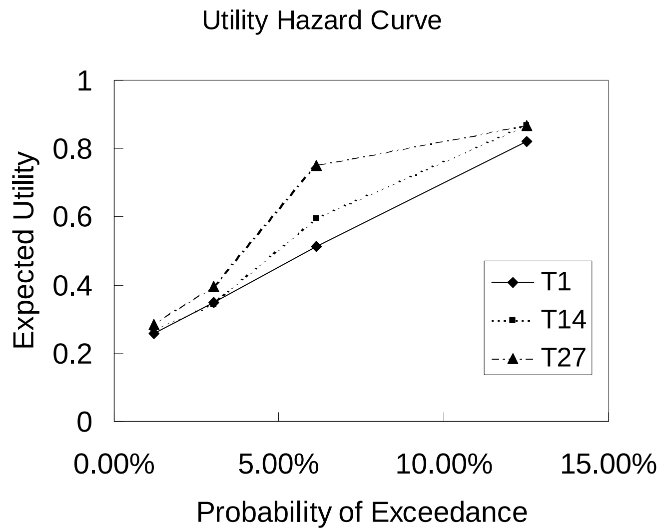


(a) with *DR*=0.06

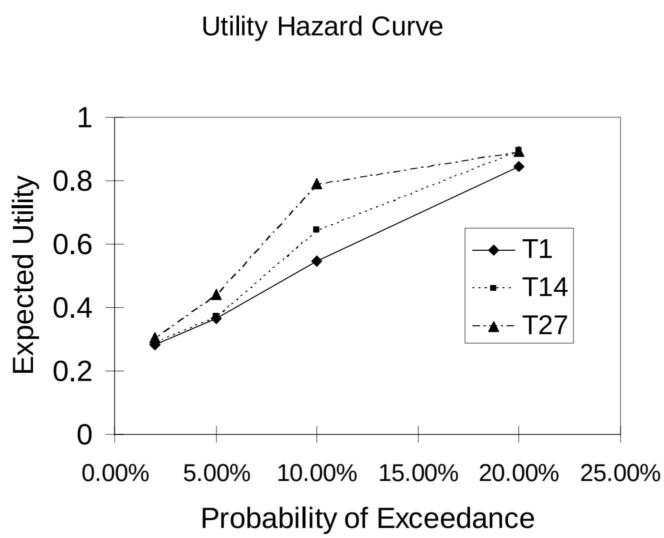


(b) with *DR*=0.09

Figure 7.9 Comparison of Utility Hazard Curves for Selected Combination Schemes for Different Values of *DR* (with risk-seeking utility functions)



(a) with *TH*=30 yrs



(b) with *TH*=50 yrs

Figure 7.10 Comparison of Utility Hazard Curves for Selected Combination Schemes for Different Values of *TH* (with risk-seeking utility functions)

7.3 Summary of MAUT Analysis

Multi-attribute utility analysis is performed for the test-bed hospital systems described in the previous chapter. The effect of the decision maker's risk attitude is incorporated by utilizing utility functions. To investigate the effect of risk attitude, the analysis is performed for two different sets of utility functions: risk-averse utility functions and risk-seeking utility functions.

With risk-averse utility functions

The analysis is performed first for risk-averse utility functions. With baseline values (k_2=0.6, k_1=0.18, *DR*=0.06, and *TH*=30 yrs), the analysis suggests scheme T10 ('Rehabilitation to Life Safety Level' option for C2M structures, and "No Action" for the C2L and URML). However, for high values of k_2, *DR*, or *TH*, the analysis shows highest expected utility for scheme T19, suggesting that C2M structures should be rehabilitated to the immediate occupancy level.

With risk-seeking utility functions

The second analysis using risk-seeking utility functions is performed to investigate the effect of this alternate risk attitude. With baseline values of the scaling factors for functional loss (k_2=0.6), life loss (k_1=0.18), discount rate (*DR*=0.06), and time horizon (*TH*=30 yrs), the analysis shows that no rehabilitation is suggested for all structures within the system. The analysis is also performed for values of the above variables which differ from the assumed baseline case. For each case where a high value is used for k_2 (0.75), *DR* (0.09), or *TH* (50 yrs), the analysis indicates that scheme T2 ('Rehabilitation to Life Safety Level' option for URML structure, and "No Action" for

C2M and C2L) is suggested. However, considering the fact that URML structures comprise only a small portion of the overall inventory of structures in the test bed, and that the suggested performance level for rehabilitation of URML structures is relatively low, it can be reasonably concluded that no rehabilitation action is justified for the test-bed hospital system in the case in which risk-seeking utility functions are assumed.

CHAPTER 8

APPLICATION TO A HOSPITAL SYSTEM – JPDM ANALYSIS

In this chapter, the Joint Probability Decision-making (JPDM) technique is applied to the test-bed hospital system for identification of the preferred seismic rehabilitation options. Same as for the ECA analysis and MAUT analysis in the previous chapter, the main attributes that are considered here in the decision analysis using JPDM include monetary loss, functional loss, and life loss (death and injury).

In the analysis described here, reasonable criterion values are assumed. The relative weights among the attributes are the same as the scaling factors used in the MAUT analysis. Note that the shortcomings of JPDM discussed in Chapter 3 are not applicable to this example. As discussed in Chapter 3, the shortcoming of JPDM occurs when a relatively high weight makes the criterion value less than the minimum value of the consequence when the consequence has a nonzero minimum value. However, the relative weight for monetary loss in this example is relatively low (even considering the range of the relative weight in sensitivity analysis) so the original JPDM can be applied without causing the problem discussed in Chapter 3.

8.1 JPDM Analysis

As shown in Chapter 3, the area of interest (acceptable consequences) must be defined within the consequence space and the area of interest is expressed in terms of the criterion values. In this example, the criterion values are assumed as shown in Table 8.1. Note that the functional loss is measured in a way described in Section 7.1. The criterion values and relative weights listed in Table 8.1 are the baseline values, and analyses with different ranges for these values will be performed to investigate the effect of these values on the final results.

Table 8.1 Baseline Criterion Values of the Attributes

Attributes	Lower Bound Criterion Value	Upper Bound Criterion Value	Relative Weight
Monetary Cost ($M)	L_m=0 (-∞)	U_m=15	w_m=0.12
Functional loss ($days \cdot A_{total}$ /10,000 ft^2)	L_f=0 (-∞)	U_f=700	w_f=0.60
Death	L_d=0 (-∞)	U_d=5	w_d=0.18
Injury	L_i=0 (-∞)	U_i=10	w_i=0.10

First, the analyses are performed for different upper criterion values for monetary loss. It should be noted that the criterion value defined by the user is not the criterion value used for the analysis. The criterion values are internally recalculated based on the relative weights assigned to them based on Equation 3.13. If the adjusted criterion value for monetary loss is less than the initial cost of an alternative scheme, it can be anticipated that the POS of the scheme will be zero. The initial cost of each alternative scheme is shown in Table 8.2.

Table 8.2 Initial Cost Required for the Alternative Schemes

Scheme	C2M	C2L	URML	Initial Cost ($M)
T1	No Action	No Action	No Action	0.00
T2	No Action	No Action	Rehab LS	2.73
T3	No Action	No Action	Rehab IO	5.53
T4	No Action	Rehab LS	No Action	2.73
T5	No Action	Rehab LS	Rehab LS	5.47
T6	No Action	Rehab LS	Rehab IO	8.27
T7	No Action	Rehab IO	No Action	5.53
T8	No Action	Rehab IO	Rehab LS	8.27
T9	No Action	Rehab IO	Rehab IO	11.06
T10	Rehab LS	No Action	No Action	27.34
T11	Rehab LS	No Action	Rehab LS	30.07
T12	Rehab LS	No Action	Rehab IO	32.87
T13	Rehab LS	Rehab LS	No Action	30.07
T14	Rehab LS	Rehab LS	Rehab LS	32.81
T15	Rehab LS	Rehab LS	Rehab IO	35.61
T16	Rehab LS	Rehab IO	No Action	32.87
T17	Rehab LS	Rehab IO	Rehab LS	35.61
T18	Rehab LS	Rehab IO	Rehab IO	38.40
T19	Rehab IO	No Action	No Action	55.32
T20	Rehab IO	No Action	Rehab LS	58.05
T21	Rehab IO	No Action	Rehab IO	60.85
T22	Rehab IO	Rehab LS	No Action	58.05
T23	Rehab IO	Rehab LS	Rehab LS	60.78
T24	Rehab IO	Rehab LS	Rehab IO	63.58
T25	Rehab IO	Rehab IO	No Action	60.85
T26	Rehab IO	Rehab IO	Rehab LS	63.58
T27	Rehab IO	Rehab IO	Rehab IO	66.38

Table 8.3 shows the POS's of the alternative schemes for different upper criterion values for the monetary loss. For each criterion value, alternative schemes of which initial cost is less than the upper criterion value are considered. Note that the criterion values shown in Table 8.3 are the initial criterion values before they are adjusted by the relative weight. Alternative schemes with initial costs larger than the criterion value must not be considered, and they are grayed out in the table. One of these schemes may have

the highest POS (denoted with italic fonts in the table), as the criterion values are adjusted based on relative weights. As mentioned earlier, the baseline value for w_m is determined such that it is same as the scaling factor in MAUT analysis, which is 0.12 for monetary loss. The adjusted criterion value based on the relative weight based on Equation 3.13 is as follows:

$$U_m' = \frac{U_m}{w_m \cdot N} = \frac{\$15M}{0.12 \times 4} = \$31.25M \qquad [8.1]$$

where, U_m'= weighted criterion value for monetary loss, U_m= initial criterion value for monetary loss, w_m= relative weight for monetary loss, and N = number of attributes. However, alternative schemes that have initial costs larger than the original criterion value ($15M) must be ruled out from the beginning of the analysis because the decision maker would not be able to afford the cost for rehabilitation. In Table 8.3, it is observed that a highest level of rehabilitation that the decision maker can initially afford is always suggested. This could have been expected because once the decision maker can afford the initial cost, the alternative scheme with highest expected performance would be preferred. Note that the suggested alternative schemes in ECA and MAUT are different because these approaches do not explicitly account for the budget limit.

The analysis is performed for different relative weights for monetary loss (w_m) as well. To compare the results obtained using a relative weight w_m of 0.12, another analysis is performed using w_m = 0.064. This corresponds to the case in ECA where the equivalent cost of life loss and functional loss are double their original values. In this case, the weighted criterion value will increase, and can be calculated as follows:

$$U_m' = \frac{U_m}{w_m \cdot N} = \frac{\$15M}{0.064 \times 4} = \$58.59M \qquad [8.2]$$

Table 8.4 shows the POS's of the alternative schemes for the two different relative weights for monetary loss (0.12 and 0.064) referenced above. Note that the relative weights for other criteria are also updated such that the summation of the relative weights becomes unity. The analysis results show that the preference moves to scheme T18 when w_m= 0.064 is used. However, schemes T10 to T27 must be ruled out because the initial costs for these schemes are larger than the original criterion value of \$15M. Therefore, T9 is also preferred here.

Next, the analyses are performed for different values for functional loss. First, different upper criterion values (200 and 700 $days \cdot A_{total} / 10{,}000\, ft^2$) for functional loss are applied and the resulting POS values are shown in Table 8.5. Here, the upper criterion value does not seem to have a great impact on the relative performance among the alternatives, indicating that scheme T9 is most preferable for both criterion values. In fact, this result could have been anticipated. That is, alternatives that have higher rehabilitation level are expected to work better than other alternatives in reducing functional loss.

Different configurations of the relative weight for functional loss, w_f, are then applied and the results are shown in Table 8.6. The two values of w_f used in these analyses are 0.6 (baseline) and 0.75. When w_f = 0.75, the analysis indicates that scheme T18 has the highest POS and therefore is preferred. However, again, schemes from T10 to T27 are not feasible as mentioned earlier. As a result, T9 is preferred within the feasible schemes.

Different values of the time horizon (TH) and the discount rate (DR) are investigated next and results are listed in Table 8.7 and Table 8.8. It is apparent that changes in these variables do not cause a substantial change in the most preferred option (T9).

Table 8.3 POS of the Combinations of the Seismic Alternative Schemes for Different Upper Criterion Values for the Monetary Loss (U_m)

Scheme	C2M	C2L	URML	POS				
				U_m=15 (baseline)	U_m =20	U_m =25	U_m =30	U_m =35
T1	No Action	No Action	No Action	0.9664	0.9664	0.9664	0.9664	0.9664
T2	No Action	No Action	Rehab LS	0.9727	0.9727	0.9727	0.9727	0.9727
T3	No Action	No Action	Rehab IO	0.9740	0.9740	0.9740	0.9740	0.9740
T4	No Action	Rehab LS	No Action	0.9680	0.9680	0.9680	0.9680	0.9680
T5	No Action	Rehab LS	Rehab LS	0.9745	0.9745	0.9745	0.9745	0.9745
T6	No Action	Rehab LS	Rehab IO	0.9753	0.9753	0.9753	0.9753	0.9753
T7	No Action	Rehab IO	No Action	0.9689	0.9689	0.9689	0.9689	0.9689
T8	No Action	Rehab IO	Rehab LS	0.9754	0.9754	0.9754	0.9754	0.9754
T9	No Action	Rehab IO	Rehab IO	**0.9765**	**0.9765**	**0.9765**	0.9765	0.9765
T10	Rehab LS	No Action	No Action	0.9699	0.9725	0.9727	0.9727	0.9728
T11	Rehab LS	No Action	Rehab LS	0.9699	0.9789	0.9791	**0.9791**	0.9791
T12	Rehab LS	No Action	Rehab IO	0.0000	0.9803	0.9806	0.9806	0.9807
T13	Rehab LS	Rehab LS	No Action	0.9647	0.9739	0.9742	0.9742	0.9742
T14	Rehab LS	Rehab LS	Rehab LS	0.0000	0.9808	0.9811	0.9811	**0.9811**
T15	Rehab LS	Rehab LS	Rehab IO	0.0000	***0.9819***	0.9825	0.9826	0.9826
T16	Rehab LS	Rehab IO	No Action	0.0000	0.9752	0.9755	0.9755	0.9756
T17	Rehab LS	Rehab IO	Rehab LS	0.0000	0.9816	0.9822	0.9823	0.9823
T18	Rehab LS	Rehab IO	Rehab IO	0.0000	0.9784	***0.9835***	***0.9841***	0.9841
T19	Rehab IO	No Action	No Action	0.0000	0.0000	0.0000	0.9744	0.9747
T20	Rehab IO	No Action	Rehab LS	0.0000	0.0000	0.0000	0.9804	0.9813
T21	Rehab IO	No Action	Rehab IO	0.0000	0.0000	0.0000	0.9766	0.9834
T22	Rehab IO	Rehab LS	No Action	0.0000	0.0000	0.0000	0.9753	0.9763
T23	Rehab IO	Rehab LS	Rehab LS	0.0000	0.0000	0.0000	0.9774	0.9840
T24	Rehab IO	Rehab LS	Rehab IO	0.0000	0.0000	0.0000	0.0000	0.9857
T25	Rehab IO	Rehab IO	No Action	0.0000	0.0000	0.0000	0.9716	0.9778
T26	Rehab IO	Rehab IO	Rehab LS	0.0000	0.0000	0.0000	0.0000	0.9854
T27	Rehab IO	Rehab IO	Rehab IO	0.0000	0.0000	0.0000	0.0000	***0.9874***

Table 8.4 POS of the Combinations of the Seismic Alternative Schemes for Different Relative Weights for the Monetary Loss (w_m)

Scheme	C2M	C2L	URML	POS	
				w_m=0.064	w_m=0.12 (baseline)
T1	No Action	No Action	No Action	0.9664	0.9664
T2	No Action	No Action	Rehab LS	0.9727	0.9727
T3	No Action	No Action	Rehab IO	0.9740	0.9740
T4	No Action	Rehab LS	No Action	0.9680	0.9680
T5	No Action	Rehab LS	Rehab LS	0.9745	0.9745
T6	No Action	Rehab LS	Rehab IO	0.9753	0.9753
T7	No Action	Rehab IO	No Action	0.9689	0.9689
T8	No Action	Rehab IO	Rehab LS	0.9754	0.9754
T9	No Action	Rehab IO	Rehab IO	**0.9765**	**0.9765**
T10	Rehab LS	No Action	No Action	0.9727	0.9699
T11	Rehab LS	No Action	Rehab LS	0.9791	0.9699
T12	Rehab LS	No Action	Rehab IO	0.9806	0.0000
T13	Rehab LS	Rehab LS	No Action	0.9742	0.9647
T14	Rehab LS	Rehab LS	Rehab LS	0.9811	0.0000
T15	Rehab LS	Rehab LS	Rehab IO	0.9826	0.0000
T16	Rehab LS	Rehab IO	No Action	0.9755	0.0000
T17	Rehab LS	Rehab IO	Rehab LS	0.9823	0.0000
T18	Rehab LS	Rehab IO	Rehab IO	***0.9841***	0.0000
T19	Rehab IO	No Action	No Action	0.9717	0.0000
T20	Rehab IO	No Action	Rehab LS	0.9536	0.0000
T21	Rehab IO	No Action	Rehab IO	0.0000	0.0000
T22	Rehab IO	Rehab LS	No Action	0.9499	0.0000
T23	Rehab IO	Rehab LS	Rehab LS	0.0000	0.0000
T24	Rehab IO	Rehab LS	Rehab IO	0.0000	0.0000
T25	Rehab IO	Rehab IO	No Action	0.0000	0.0000
T26	Rehab IO	Rehab IO	Rehab LS	0.0000	0.0000
T27	Rehab IO	Rehab IO	Rehab IO	0.0000	0.0000

Table 8.5 POS of the Combinations of the Seismic Alternative Schemes for Different Upper Criterion Values for the Functional loss (U_f)

Scheme	C2M	C2L	URML	POS	
				U_f=200 ($days \cdot A_{total} / 10{,}000\, ft^2$)	U_f=700 (baseline)
T1	No Action	No Action	No Action	0.9460	0.9664
T2	No Action	No Action	Rehab LS	0.9594	0.9727
T3	No Action	No Action	Rehab IO	0.9636	0.9740
T4	No Action	Rehab LS	No Action	0.9502	0.9680
T5	No Action	Rehab LS	Rehab LS	0.9649	0.9745
T6	No Action	Rehab LS	Rehab IO	0.9694	0.9753
T7	No Action	Rehab IO	No Action	0.9519	0.9689
T8	No Action	Rehab IO	Rehab LS	0.9674	0.9754
T9	No Action	Rehab IO	Rehab IO	**0.9725**	**0.9765**
T10	Rehab LS	No Action	No Action	0.9486	0.9699
T11	Rehab LS	No Action	Rehab LS	0.9586	0.9699
T12	Rehab LS	No Action	Rehab IO	0.0000	0.0000
T13	Rehab LS	Rehab LS	No Action	0.9487	0.9647
T14	Rehab LS	Rehab LS	Rehab LS	0.0000	0.0000
T15	Rehab LS	Rehab LS	Rehab IO	0.0000	0.0000
T16	Rehab LS	Rehab IO	No Action	0.0000	0.0000
T17	Rehab LS	Rehab IO	Rehab LS	0.0000	0.0000
T18	Rehab LS	Rehab IO	Rehab IO	0.0000	0.0000
T19	Rehab IO	No Action	No Action	0.0000	0.0000
T20	Rehab IO	No Action	Rehab LS	0.0000	0.0000
T21	Rehab IO	No Action	Rehab IO	0.0000	0.0000
T22	Rehab IO	Rehab LS	No Action	0.0000	0.0000
T23	Rehab IO	Rehab LS	Rehab LS	0.0000	0.0000
T24	Rehab IO	Rehab LS	Rehab IO	0.0000	0.0000
T25	Rehab IO	Rehab IO	No Action	0.0000	0.0000
T26	Rehab IO	Rehab IO	Rehab LS	0.0000	0.0000
T27	Rehab IO	Rehab IO	Rehab IO	0.0000	0.0000

Table 8.6 POS of the Combinations of the Seismic Alternative Schemes for Different Relative Weight for Functional loss (w_f)

Scheme	C2M	C2L	URML	POS	
				w_f=0.60 (baseline)	w_f=0.75
T1	No Action	No Action	No Action	0.9664	0.9654
T2	No Action	No Action	Rehab LS	0.9727	0.9722
T3	No Action	No Action	Rehab IO	0.9740	0.9738
T4	No Action	Rehab LS	No Action	0.9680	0.9673
T5	No Action	Rehab LS	Rehab LS	0.9745	0.9741
T6	No Action	Rehab LS	Rehab IO	0.9753	0.9753
T7	No Action	Rehab IO	No Action	0.9689	0.9687
T8	No Action	Rehab IO	Rehab LS	0.9754	0.9753
T9	No Action	Rehab IO	Rehab IO	**0.9765**	**0.9765**
T10	Rehab LS	No Action	No Action	0.9699	0.9714
T11	Rehab LS	No Action	Rehab LS	0.9699	0.9782
T12	Rehab LS	No Action	Rehab IO	0.0000	0.9804
T13	Rehab LS	Rehab LS	No Action	0.9647	0.9732
T14	Rehab LS	Rehab LS	Rehab LS	0.0000	0.9804
T15	Rehab LS	Rehab LS	Rehab IO	0.0000	0.9820
T16	Rehab LS	Rehab IO	No Action	0.0000	0.9751
T17	Rehab LS	Rehab IO	Rehab LS	0.0000	0.9815
T18	Rehab LS	Rehab IO	Rehab IO	0.0000	***0.9835***
T19	Rehab IO	No Action	No Action	0.0000	0.0000
T20	Rehab IO	No Action	Rehab LS	0.0000	0.0000
T21	Rehab IO	No Action	Rehab IO	0.0000	0.0000
T22	Rehab IO	Rehab LS	No Action	0.0000	0.0000
T23	Rehab IO	Rehab LS	Rehab LS	0.0000	0.0000
T24	Rehab IO	Rehab LS	Rehab IO	0.0000	0.0000
T25	Rehab IO	Rehab IO	No Action	0.0000	0.0000
T26	Rehab IO	Rehab IO	Rehab LS	0.0000	0.0000
T27	Rehab IO	Rehab IO	Rehab IO	0.0000	0.0000

Table 8.7 POS of the Combinations of Seismic Alternative Schemes for Different Time Horizons (TH)

Scheme	C2M	C2L	URML	POS	
				TH=30 yrs (baseline)	*TH*=50 yrs
T1	No Action	No Action	No Action	0.9664	0.9459
T2	No Action	No Action	Rehab LS	0.9727	0.9556
T3	No Action	No Action	Rehab IO	0.9740	0.9572
T4	No Action	Rehab LS	No Action	0.9680	0.9481
T5	No Action	Rehab LS	Rehab LS	0.9745	0.9583
T6	No Action	Rehab LS	Rehab IO	0.9753	0.9596
T7	No Action	Rehab IO	No Action	0.9689	0.9490
T8	No Action	Rehab IO	Rehab LS	0.9754	0.9596
T9	No Action	Rehab IO	Rehab IO	**0.9765**	**0.9613**
T10	Rehab LS	No Action	No Action	0.9699	0.9551
T11	Rehab LS	No Action	Rehab LS	0.9699	0.9550
T12	Rehab LS	No Action	Rehab IO	0.0000	0.0000
T13	Rehab LS	Rehab LS	No Action	0.9647	0.9477
T14	Rehab LS	Rehab LS	Rehab LS	0.0000	0.0000
T15	Rehab LS	Rehab LS	Rehab IO	0.0000	0.0000
T16	Rehab LS	Rehab IO	No Action	0.0000	0.0000
T17	Rehab LS	Rehab IO	Rehab LS	0.0000	0.0000
T18	Rehab LS	Rehab IO	Rehab IO	0.0000	0.0000
T19	Rehab IO	No Action	No Action	0.0000	0.0000
T20	Rehab IO	No Action	Rehab LS	0.0000	0.0000
T21	Rehab IO	No Action	Rehab IO	0.0000	0.0000
T22	Rehab IO	Rehab LS	No Action	0.0000	0.0000
T23	Rehab IO	Rehab LS	Rehab LS	0.0000	0.0000
T24	Rehab IO	Rehab LS	Rehab IO	0.0000	0.0000
T25	Rehab IO	Rehab IO	No Action	0.0000	0.0000
T26	Rehab IO	Rehab IO	Rehab LS	0.0000	0.0000
T27	Rehab IO	Rehab IO	Rehab IO	0.0000	0.0000

Table 8.8 POS of the Combinations of Seismic Alternative Schemes for Different Discount Rates (DR)

Scheme	C2M	C2L	URML	POS		
				DR=3%	*DR*=6% (baseline)	*DR*=9%
T1	No Action	No Action	No Action	0.9654	0.9664	0.9673
T2	No Action	No Action	Rehab LS	0.9722	0.9727	0.9734
T3	No Action	No Action	Rehab IO	0.9738	0.9740	0.9743
T4	No Action	Rehab LS	No Action	0.9672	0.9680	0.9686
T5	No Action	Rehab LS	Rehab LS	0.9741	0.9745	0.9750
T6	No Action	Rehab LS	Rehab IO	0.9752	0.9753	0.9758
T7	No Action	Rehab IO	No Action	0.9687	0.9689	0.9692
T8	No Action	Rehab IO	Rehab LS	0.9753	0.9754	0.9757
T9	No Action	Rehab IO	Rehab IO	**0.9764**	**0.9765**	**0.9767**
T10	Rehab LS	No Action	No Action	0.9666	0.9699	0.9727
T11	Rehab LS	No Action	Rehab LS	0.9578	0.9699	0.9721
T12	Rehab LS	No Action	Rehab IO	0.0000	0.0000	0.0000
T13	Rehab LS	Rehab LS	No Action	0.9532	0.9647	0.9672
T14	Rehab LS	Rehab LS	Rehab LS	0.0000	0.0000	0.0000
T15	Rehab LS	Rehab LS	Rehab IO	0.0000	0.0000	0.0000
T16	Rehab LS	Rehab IO	No Action	0.0000	0.0000	0.0000
T17	Rehab LS	Rehab IO	Rehab LS	0.0000	0.0000	0.0000
T18	Rehab LS	Rehab IO	Rehab IO	0.0000	0.0000	0.0000
T19	Rehab IO	No Action	No Action	0.0000	0.0000	0.0000
T20	Rehab IO	No Action	Rehab LS	0.0000	0.0000	0.0000
T21	Rehab IO	No Action	Rehab IO	0.0000	0.0000	0.0000
T22	Rehab IO	Rehab LS	No Action	0.0000	0.0000	0.0000
T23	Rehab IO	Rehab LS	Rehab LS	0.0000	0.0000	0.0000
T24	Rehab IO	Rehab LS	Rehab IO	0.0000	0.0000	0.0000
T25	Rehab IO	Rehab IO	No Action	0.0000	0.0000	0.0000
T26	Rehab IO	Rehab IO	Rehab LS	0.0000	0.0000	0.0000
T27	Rehab IO	Rehab IO	Rehab IO	0.0000	0.0000	0.0000

8.2 Summary of JPDM Analysis

JPDM is applied to the hospital system for identification of the preferred rehabilitation scheme for a range of different decision variables. The analysis shows that T9 ("No Action" for C2M structures, "Rehab IO" for the others) is suggested for the base line value for the criterion values and relative weights shown in Table 8.1, discount rate (*DR*=0.6), and time horizon (*TH*=30 years). The analysis shows that the decision is most sensitive to determination of criterion value for monetary cost. In other words, the decision is most sensitive to what the decision maker can afford. Once the criterion value for monetary cost is defined, JPDM selects an alternative scheme with highest level of rehabilitation given that only schemes with initial costs less than the criterion value are considered. This is because monetary cost is the only attribute of which consequence increases as rehabilitation level becomes higher in this example, whereas all other attributes – function loss and life loss – are decreasing with higher rehabilitation level.

8.3 Comparison of the Results from Three Decision Models

Equivalent cost analysis (ECA) in this example indicates that a rehabilitation is hardly justified for the hospital located in the Memphis, Tennessee area. Sensitivity analysis conducted on the equivalent analysis shows that minor level of rehabilitation is suggested only when the value of function loss is determined very high. In other words, the social importance of the system is the main factor that could justify seismic rehabilitation. However, this analysis does not account for the fact that the high consequence that might occur is so substantial that the decision maker might not be able to sustain the consequence. As a result, the pain from the seismic consequence might be much higher than the consequence expressed with the numeric values in the ECA. To account for this effect, MAUT analysis is performed with risk attitudes incorporated. From an assumption that the decision maker is risk averse, which is generally true for policy maker or tax payers (Baker and Miller, 2000), minor to moderate level of rehabilitation is suggested for the hospital system. Sensitivity analysis indicates that even higher level of rehabilitation might be needed with higher value of function loss, higher discount rate, or longer time period than the baseline value.

Considering the fact that that seismic consequences could be disastrous to the society especially when a large earthquake hits a populated area, and that hospital systems are essential facilities of which activities is highly important for the society in case of an earthquake, it would be a rational assumption that the decision maker is risk-averse. However, from the fact that the suggested decisions from MAUT analysis might be different from the decisions from the equivalent cost analysis, and that structural rehabilitation generally requires substantial amount of money, two suggestions can be made for further refinement of the decision analysis. First, the decision maker must be well identified and the decision maker's value must be carefully elicited. Note that the risk attitudes may affect the decisions significantly. Second, it appears that the decisions in both ECA and MAUT analyses are relatively sensitive to determination of value of function. As the value of function is roughly determined as shown in Chapter 6, further investigation is needed for quantification of function loss.

The results from JPDM analysis are relatively straightforward, as it suggests the highest level of rehabilitation as long as the budget allows. This is mainly because the example is set up such that the monetary cost is the only trade-off against the system performance, which is generally true for decision problems in seismic rehabilitation.

Nonetheless, a single round of JPDM analysis is for the case where certain amount of budget for seismic rehabilitation is ensured. In reality, however, the budget is determined after detailed review of all aspects of the corresponding actions and their consequences. Therefore, thorough investigation of seismic consequences of alternative schemes is suggested in order to determine the budget.

CHAPTER 9

CRITICAL EVALUATION OF DECISION SUPPORT SYSTEM

In the previous chapters, the decision analysis procedure for seismic rehabilitation of structures was discussed. The generation and management of the data needed for the specific decision problem were demonstrated. Three MCDM models were utilized and the application of each of the models was illustrated by performing decision analyses on the hospital systems. The integrated usage of the decision support system (DSS), however, was not discussed and evaluated. Yet, the previous chapters show various aspects of the decision support system rather independently. In this chapter, the overall decision support framework developed in this study is critically evaluated. The components of decision support system in general are briefly identified, and the decision support framework developed in this study is evaluated for each component. The decision support framework is then evaluated based on the attributes of decision support system that are desirable to the end-users. In doing so, the characteristics of the three MCDM models are also reviewed and the guidelines for selection of the decision model that is appropriate for a given decision maker is provided. The use of the decision support framework, including the selection of the decision model, is then demonstrated using several hypothetical scenarios with different decision makers and value sets.

9.1 Evaluation of Main Components of Decision Support System

According to Bonczek et al. (1981), a decision support system consists of a language system, knowledge system, and problem processing system. A language system provides user interface methods. A decision support system takes requests from a user via a language system. Pull-down menu systems and/or dialog boxes in decision support software are examples of a language system. A knowledge system contains a database needed for the decision support in different ways. These data can be stored in the form of spread sheets, equations, rules, or texts (Holsapple and Whinston, 1987). The data stored in a knowledge system is manipulated in a problem processing system as requested by the user. The interaction of these three systems is illustrated in Figure 9.1.

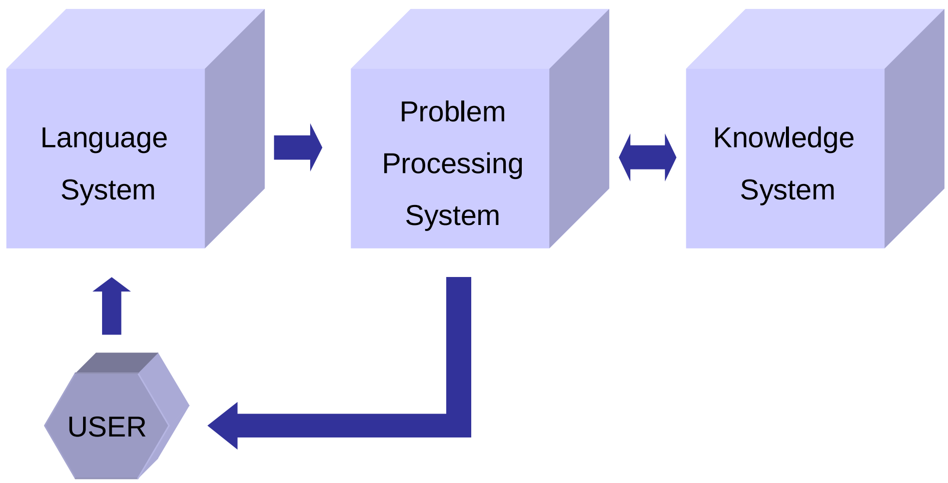


Figure 9.1 Components of Decision Support System (based on Bonczek et al., 1981)

As mentioned in Chapter 1, the language system is not of interest in this study: this study focuses mainly on the generation and manipulation of data for decision supports in seismic rehabilitation of structures. The knowledge system and problem processing system of the decision support framework developed in this study are evaluated and its capabilities and limitations are identified. However, it should be noted that both the knowledge system and problem processing system constrain and are constrained by the language system.

The Knowledge System

The knowledge system of the decision support framework developed in this study contains data needed for a decision support in seismic rehabilitation of structures. The contents of the knowledge system can be divided into two parts: seismic loss estimation data and models, and MCDM models. The seismic loss estimation data includes probabilistic characteristics of seismic hazards (hazard curves), seismic response spectra, capacity spectra and seismic fragility curves of structures, social and economic factors (e.g., number of occupancy in a given time, building replacement value, building repair value, value of contents, and income rate) associated with the structures, and seismic loss estimation methods. As discussed in Chapter 4, the probabilistic characteristic of seismic hazard corresponding to a given region is defined using the USGS hazard map, and response spectra for given probability levels are generated using the FEMA method. This method provides flexibility in selecting a probability level of seismic hazard. That is, the system could provide the response spectrum of any probability levels a user requests (e.g., 15% of PE in 30 years) using the data, rules and equations that are embedded in the system. However, generating response spectra is not the only method for representing seismic hazard. Some users, such as engineers, might want a suite of time history data of ground motions for seismic inputs, especially when more accurate damage assessment of a structure is needed. In order for the decision support system to have the capability of providing a suite of time history ground motions for a given location, an algorithm that generates synthetic ground motions based on site-specific information such as source and path would have to be implemented.

Seismic damage of structures is assessed using fragility curves of the structures in the decision support system developed in this study. The fragility curves are generated using the HAZUS method, and the data can be stored within the decision support system in the form of tabulated data. This method of generating fragility curves allows quick response time because no significant calculation or analysis is needed. However, these curves represent seismic fragility of a class of structures, and possible variation in configuration and construction practice that might occur within a class of structures is not taken into account. Similar to the case with seismic hazard input, some users such as engineers may want to use more refined fragility curves for a given structure. In order to obtain refined fragility curves of a structure, additional structural analyses (e.g., a suite of time-history analyses for different levels of earthquake) must be performed. This procedure generally requires considerable time and effort. Moreover, this procedure cannot be done without the assistance of structural engineers. The effectiveness could be increased if a structural analysis engine for the additional structural analyses is integrated into the DSS.

Seismic losses are estimated from probabilistic damage assessment of structures using HAZUS data. However, the kinds of seismic losses estimated in HAZUS are limited, such that the DSS would not satisfy a user who wanted to include a type of seismic loss or other decision attribute that HAZUS does not provide (e.g., aesthetics). This problem can be resolved by making the decision support system flexible such that it can incorporate additional external modules for calculation of seismic losses as well as accompanying research for corresponding attributes. This kind of idea is essential for evolutionary DSS, which will be discussed immediately following this section.

In the DSS developed, only generic alternatives are considered as discussed in Chapter 6, where the alternatives are defined in terms of different objective performance levels. In many cases, however, the user (such as building owners, practitioners or engineers) might want to know the detailed scheme and see the actual output of a seismic intervention in advance, as that could affect the practical function or aesthetics of the structures. Moreover, the remodeling cost may vary depending on the specifics of the intervention schemes. For example, installation of passive energy dissipating (PED) devices inside the structure might be appropriate for a warehouse because a temporary space could be used during the time of construction. On the other hand, the same scheme might not be appropriate for facilities of which temporary movement is not easy (e.g., hospitals and lifeline systems). In this case, other intervention schemes that could be effectively applied must be sought (e.g., base isolation). To do that, seismic intervention schemes that can be effectively applied to a given structure must be identified in advance. A graphical image of the anticipated appearance of the structure could help, too. It should be noted that if detailed intervention schemes are utilized in the DSS, the seismic performance and cost information corresponding to the schemes must be identified as well for better estimation of seismic losses.

Three MCDM models are currently included in the knowledge system of the DSS. As discussed in Chapter 3, these models are considered to be effectively applied to decision problems with multiple criteria and uncertainty. However, application of multiple MCDM for a given decision problem may confuse the user. According to Sen and Yang (1998), “no single MCDM method could be regarded as absolutely superior to others in every decision situation or by every decision maker.” In other words, every MCDM model has its own strengths and weaknesses. Therefore, a guideline is needed for selection of a decision model that is appropriate to a user for a given decision problem considering the characteristics of the MCDM models. The MCDM models utilized in this study have different methods for measuring value and preference. Therefore, users can select a MCDM model based on the following criteria:

1) Value measure: how the value of a marginal attribute is measured

2) Preference measure: how the preference among multiple attributes is measured

ECA measures the value of an attribute in terms of equivalent monetary value. Therefore, the preferences among multiple attributes are represented in terms of conversion factors used for determining equivalent monetary values of the attributes. MAUT quantifies value of an attribute in terms of utility, taking into account risk attitudes. The preferences among attributes are then represented in terms of scaling factors. JPDM measures values in terms of constraints, which are thresholds for acceptable consequences. The preference information in JPDM is represented in terms of relative weights. Considering these characteristics of the MCDM models in measuring value and preference, an appropriate MCDM model can be selected for a given decision problem and user, following the procedure illustrated in Figure 9.2.

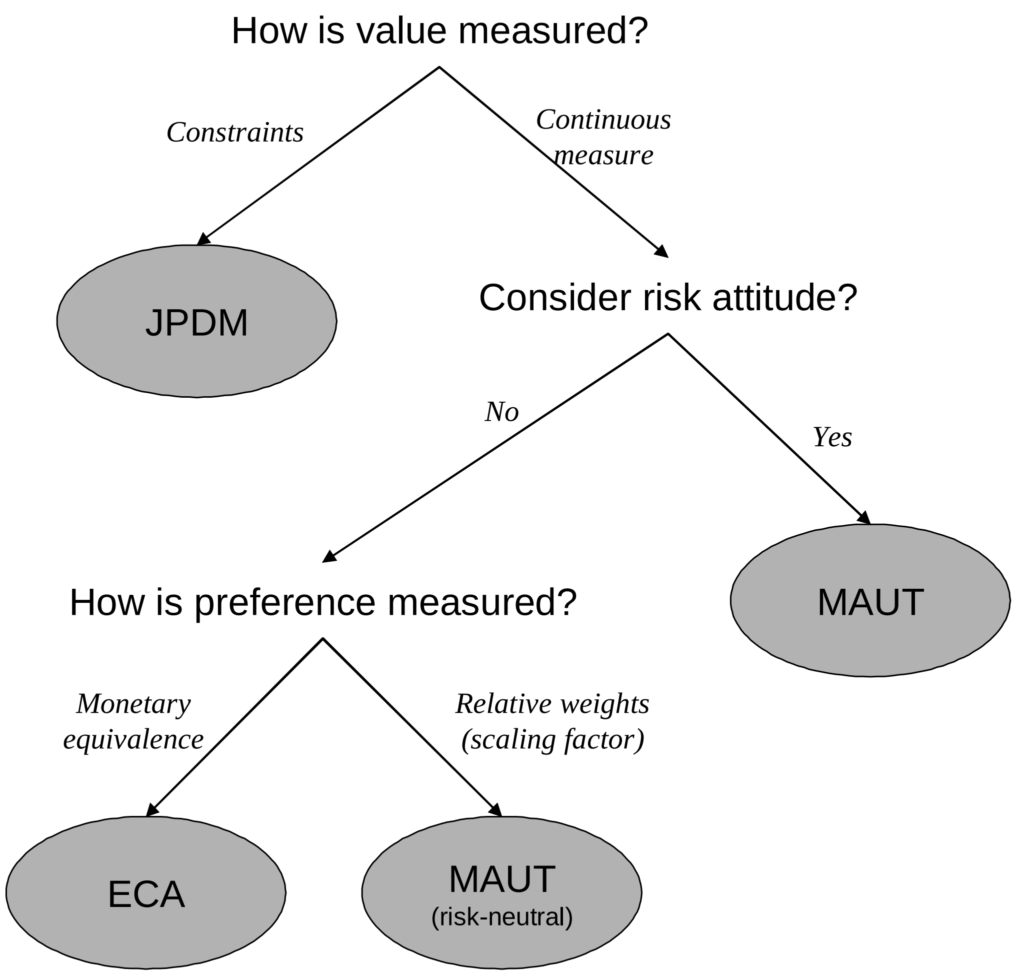
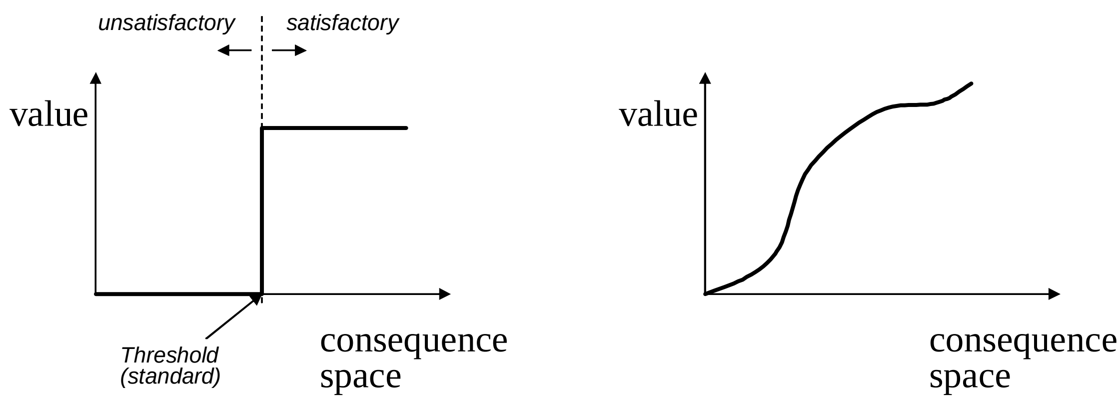


Figure 9.2 MCDM Model Selection Procedure

The first question that should be asked of the user is how the value should be measured. In other words, how the decision criteria of the user are described must be identified. In some cases, the user determines a threshold for each decision criteria and wants to find an alternative that satisfies the criteria. This way of measuring value can be often used when budget is limited or when some standards must be satisfied either from legal or policy making point of view. JPDM should be selected in this case, as JPDM calculates the overall preference by probability of satisfying the user's requirements defined by criterion values. On the contrary, there are cases where the user wants to measure his/her value as a continuous function in the corresponding consequence space. In this case, JPDM is not appropriate and other models should be considered. The difference in these ways of measuring value is illustrated in Figure 9.3.



(a) Value by constraints

(b) Value by continuous function

Figure 9.3 Two Approaches for Measuring Value

If the user wants to measure his/her value in terms of continuous functions, the next step is to ask if risk attitudes should be considered. MAUT is selected if risk attitudes must be considered. The last question is then asked on how the preference is measured. If monetary equivalence is used for quantifying values and relative preferences, ECA should be selected. If the preference is represented in terms of relative weights among attributes, MAUT is selected. Note that in this case the selected MAUT must use risk-neutral utility functions, as incorporation of risk-attitude is ruled out in the previous question. Hypothetical examples of selection of MCDM models are presented in Section 9.3.

The Problem Processing System

In the problem processing system of the decision support system developed, the data and models mentioned above are manipulated such that the decision support system can provide information users request in an effective manner. Monte-Carlo simulations, generation of consequence tables, sensitivity analyses, and plot generations are those that are performed by the problem processing system in the DSS. The output of the problem processing system is a direct input to the user for making a decision. Therefore, the problem processing system should be designed such that it can provide the outputs the user requests in an effective manner.

Because the DSS in this study is intended for rehabilitation of structures against seismic events, which have low probability and high consequence, showing the overall decision index (e.g., expected value, expected utility, or probability of success) itself is not good enough for the user to have a sufficient insight into the problem. In fact, the differences of these overall decision indices among different alternatives are generally small, as illustrated in Chapters 6, 7, and 8. This is because the probability of having earthquakes that are large enough to result in high seismic consequences is relatively low. The level of seismic consequence is strongly dependent on the level of an earthquake that occurs, and the level of earthquakes is probabilistically distributed. Therefore, it would be effective if the DSS provides seismic consequences based on several meaningful levels of earthquake. For example, the DSS could provide seismic consequences of the system of interest based on 2/50, 5/50, and 10/50 earthquakes. Note that the choice of the level of earthquake should be flexible such that the user can choose other levels of earthquakes as well. Table 9.1 illustrates an example of the consequence table that shows seismic consequences based on different earthquake levels, along with the overall decision index. This consequence table is constructed based on the results of the MAUT analysis (with risk-averse utility functions), with the baseline case presented in Chapter 7, for selected alternative schemes. This kind of consequence table provides better understanding of differences in alternative schemes because it shows performance of the alternative systems for different levels of earthquake.

Table 9.1 Consequence Table for Selected Alternative Schemes

EQ level	2/50			5/50			10/50			Overall Expected Utility
	Monetary Loss ($M)	Function Loss (days*Area (10,000ft^2))	Number of Deaths	Monetary Loss ($M)	Function Loss (days*Area (10,000ft^2))	Number of Deaths	Monetary Loss ($M)	Function Loss (days*Area (10,000ft^2))	Number of Deaths	
Scheme #1	19.88	7239.23	7.37	8.65	3570.53	1.12	2.24	855.94	0.18	0.9946
	EU = 0.4234			EU = 0.7428			EU = 0.9736			
Scheme #10	43.78	5545.86	3.13	33.67	2231.28	0.55	29.07	542.88	0.13	0.9969
	EU = 0.5654			EU = 0.8811			EU = 0.9928			
Scheme #27	77.05	2606.80	0.30	70.59	914.70	0.02	67.86	114.97	0.00	0.9948
	EU= 0.7378			EU = 0.9321			EU = 0.9614			

9.2 Evaluation Based on Desirable Attributes of Decision Support System

According to Ghiaseddin (1987), desirable characteristics of a decision support system (DSS) from the viewpoint of end users are: 1) easy data management, 2) easy method to use analytical models, 3) personalized DSS, 4) supporting wide range of decision-making activities, 5) an evolving DSS, 6) learning, 7) security and integrity, 8) transferability, and 9) other requirements such as reliable system, forward looking, timely support and reasonable cost. Based on these attributes of decision support system, the decision support framework developed in this study is evaluated. Among these attributes, 7, 8, and 9 are what have to be considered in development of the software as an end product, so are not discussed here. The decision support framework in this study is evaluated in light of the attributes 1 to 6.

Easy data management

Users want to manage the data in an easy manner. They do not want to go through complicated procedures, such as programming or data structuring in order to manage data. As discussed in the previous section, the data stored in the DSS in this study are mainly for seismic loss estimation. The data can be promptly managed, as the HAZUS seismic loss estimation data are in tabulated form. However, if there is a need to perform additional external structural analyses in order to obtain more refined fragility, the data management becomes more time-consuming. Additional information regarding the detailed configuration of the system of interest is needed, and a structural engineer would have to perform the structural analyses. As mentioned in the previous section, increased effectiveness could be expected if a structural analysis engine for the additional structural analyses is integrated into the DSS.

Easy method to use analytical models and *Personalized DSS*

Users want to use the analytical models incorporated in a DSS in an easy manner. Similarly, users want the DSS to be used in their own style as well. As discussed in the previous section, three MCDM models are utilized in the DSS in this study. ECA allows easy manipulation of the model, as the conversion factors for determination of monetary equivalence are the only parameters that the user must manipulate. For JPDM, the user must define criterion values for all the decision criteria and relative weights among the decision attributes. The dynamic manipulation of inputs to either ECA or JPDM is relatively straightforward in a sense that the user can understand without difficulty what those inputs mean. On the contrary, the user must construct the utility functions and scaling factors in order to utilize MAUT. The procedures for constructing these inputs are not straightforward and require decision analysts in general, as discussed in Chapter 3. Dynamic manipulation of these inputs requires accordingly significant time and efforts, as redefining the utility functions is a complex procedure. Therefore, users must go through the model-selection procedure presented in the previous section in order to select a decision model that is suitable for them.

Supporting wide range of decision-making activities

It should be possible to use a DSS effectively for both one-time and recurring decision problems. In general, a DSS is tailored to a certain type of decision problem. The DSS developed in this study can be used for either one-time or recurring decision problems, depending on the nature of a problem. For example, a building owner may want to use the DSS for investigation of seismic safety of his/her own system for only one time, whereas a government agency or a policy maker may have to use the DSS recursively for different systems in different locations. For recurring problems, the user's major concern about the DSS would be efficiency. For a one-time problem, however, the user would be more concerned about reliability rather than efficiency (Ghiaseddin, 1987). For recurring problems in seismic rehabilitation of structures, quick estimation of seismic losses and easy identification of alternatives are essential. In this case, the DSS demonstrated in Chapters 6, 7, and 8 can be used effectively because no additional analysis that requires significant time and efforts is needed. For a problem for which the user wants detailed loss estimation and refined identification of alternatives, additional structural analyses and customized loss estimation must be incorporated into the DSS, as discussed in the previous section.

Evolving DSS and *Learning*

It would be beneficial if the DSS grows as it conducts analyses and learns from the past experience to advance its functionality. This statement applies more so to the case of recurring decision problems. As mentioned in Section 9.1, for example, external modules developed for incorporation of the users' requests from different decision problems can be collected and incorporated into the DSS. That way, newly accumulated knowledge can be used again for similar future problems without going through time consuming processes again. Another benefit could be obtained by incorporating a self-learning process into the DSS. For example, the classes of a large number structures distributed over a region could be identified without visiting the building sites, by analyzing available information such as the building usage type and year constructed.

As mentioned in Chapter 1, some efforts have been made to support seismic intervention decisions for various structural systems, but research on development of a decision support framework that can be customized to meet the needs of a wide range of decision makers while allowing a flexible choice of decision models is scarce. For example, HAZUS (1999) is widely used for estimation of anticipated seismic losses of structural systems. It affords easy data management and visualization of various kinds of seismic losses over a region. Fragility curves, damage states of structural systems, and resulting seismic losses can be estimated effectively without any additional significant analysis. In addition, the functionality of HAZUS is evolving with time, as it is continuously upgraded. However HAZUS does not have the capability to represent, analyze and compare the effects of various seismic interventions. Another example of related DSS research is the decision analysis framework developed by Benthien and Winterfeldt (2002). This effort goes a step further than HAZUS as a DSS, as multiple alternative intervention schemes are incorporated into the analysis, although it also uses the HAZUS engine for seismic loss estimation from structural damage. However, this effort focused on the decision analysis itself for a specific structural type, using a fixed decision model based on financial cost.

In contrast, the DSS in this study allows quick access to and manipulation of seismic loss data associated with a variety of structural systems. Three MCDM models are utilized, allowing the decision maker flexibility in the choice of decision models. It can incorporate multiple attributes and alternatives associated with seismic rehabilitation of structural systems, and the quick estimation of seismic losses and identification of generic alternatives make the DSS effective for recurring problems. However, additional efforts and modules are needed for more refined seismic loss estimation and detailed identification of alternatives, as the DSS proposed herein incorporates existing loss estimation techniques from HAZUS, with known deficiencies, and only generic intervention alternatives. The effectiveness of these would then also require evaluation.

9.3 Hypothetical Applications of the DSS

Applications of the three MCDM models are demonstrated in Chapters 6, 7, and 8. However, the application of the integrated DSS has not yet been presented. In this section, the DSS is examined with the hospital problem described in Chapter 6, but with several different hypothetical decision makers. They are the owner of the hospital system and a local FEMA agency. Two cases are considered with the hospital owner: 1) when the owner is a large foundation that has enough capital to sustain the maximum loss of the hospital system of interest, and 2) when the owner is a local owner who wants to avoid huge maximum seismic loss. Note that unlike in the previous chapters, the detailed procedures for computation and simulation are not described but rather the overall usage of the DSS is discussed.

Hospital owner – large foundation

The first hypothetical decision maker is the owner of the hospital, of which the property scale is large. The MCDM model is selected first following the guide presented in Section 9.1. Concerning the first question regarding the value-measuring method, the user would most likely want to measure the value in the continuous space. As mentioned in Chapter 3, a decision maker who has enough capital to sustain the maximum loss tends to be risk-neutral. Therefore, it is assumed that there is no need to include risk attitudes. Finally, the foundation would presumably pursue profit, so it would be more realistic to represent the preference in terms of monetary equivalence. As a result, ECA is selected as the MCDM model.

It is assumed that the decision maker is most concerned about the overall monetary loss, including the loss of income due to the disruption of the hospital's continuing function, but less concerned about the hospital service provided to the community. The loss of income is estimated to be $1,210 per day to recover the function per 10,000 $ft^{2,}$ which is based on HAZUS. The attributes and corresponding conversion factors for monetary equivalence are determined accordingly, as listed in Table 9.2. It is also assumed that the time horizon and discount rate are 30 years and 0.6%, respectively. Furthermore, a set of generic alternatives that is same as in Chapter 6 to 8 are considered.

Table 9.2 Equivalent Costs of Various Seismic Losses

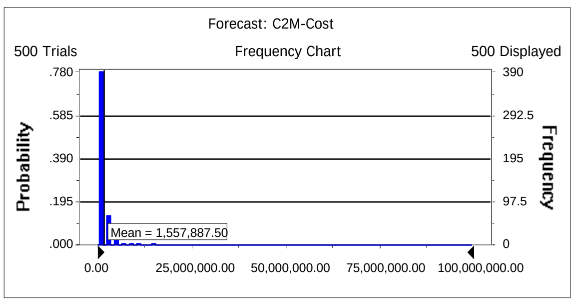
Attribute	Equivalent Cost
Value of Death	$5,000,000 / person
Value of Injury	$1,500,000 / person
Loss of Income	$1,210 / day to recover / 10,000 ft^2
Initial Rehab. Cost Str./NonStr. repair cost Contents Loss	Determined same as Chapter 6

Simulations are performed to obtain the expected costs of the alternative schemes corresponding to different levels of scenario earthquake. The consequence table is then obtained, as shown in Table 9.3, as a result of the analysis. It is shown that although high consequence is expected with "No Action" options for a high level of earthquakes, the overall expected cost of "No Action" is the least among the alternatives for all three types of structures. This is because large amounts of initial rehabilitation costs are needed for other options and the probability of having large earthquakes is low. In addition, it should be noted again that the value of the continuing function of the hospital to the community is not considered by the decision maker.

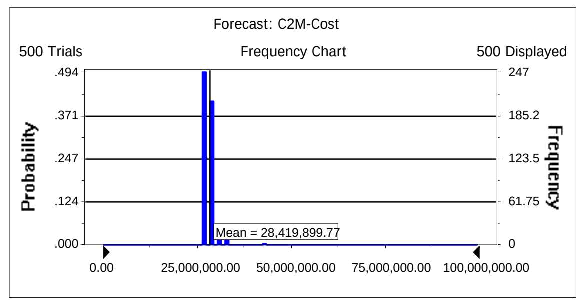
Table 9.3 Consequence Table Showing Expected Equivalent Cost (unit: $M)

	EQ Level / Alternatives	Initial Rehab Cost	With 2/50 EQ	With 5/50 EQ	With 10/50 EQ	Overall Expected Cost
C2M	No Action	0.0	57.39	13.61	1.94	1.68
	Rehab LS	27.34	29.61	6.59	1.07	28.19
	Rehab IO	55.32	9.81	3.09	1.00	55.65
	Rebuild	76.93	7.73	2.18	0.43	77.17
C2L	No Action	0.0	8.34	2.64	0.54	0.27
	Rehab LS	2.73	4.44	1.34	0.29	2.88
	Rehab IO	5.53	3.04	0.89	0.26	5.63
	Rebuild	7.69	2.09	0.47	0.12	7.75
URML	No Action	0.0	8.78	3.05	1.00	0.32
	Rehab LS	2.73	4.61	1.36	0.29	2.88
	Rehab IO	5.53	3.17	0.86	0.24	5.63
	Rebuild	7.69	2.00	0.48	0.11	7.75

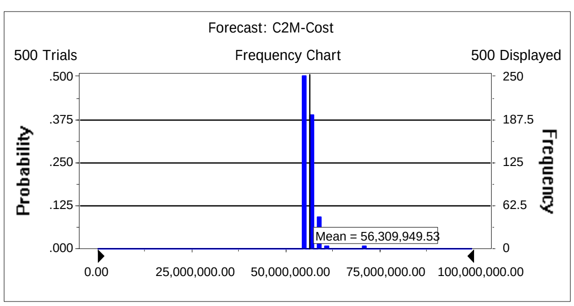
Along with the consequence table, the PDF of each seismic loss could be provided for better understanding of the anticipated seismic consequences. Figure 9.4 to Figure 9.6 show the frequency plots of the monetary losses of the four alternatives corresponding to each earthquake levels. From the plots it is observed that the dispersion of the PDFs become larger with a high level of earthquake. Note that similar plots can be generated for other seismic losses as well.



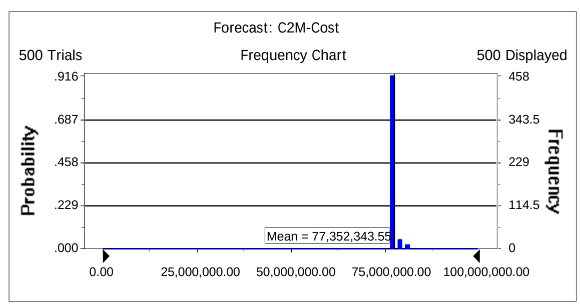
(a) “No Action”



(b) “Rehab LS”

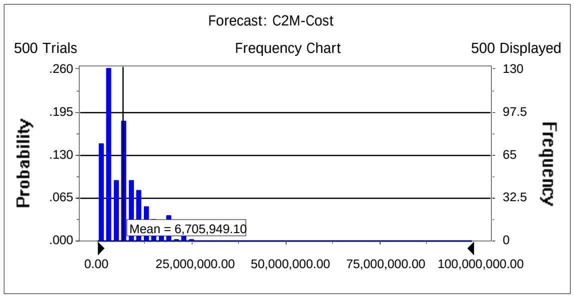


(c) “Rehab IO”

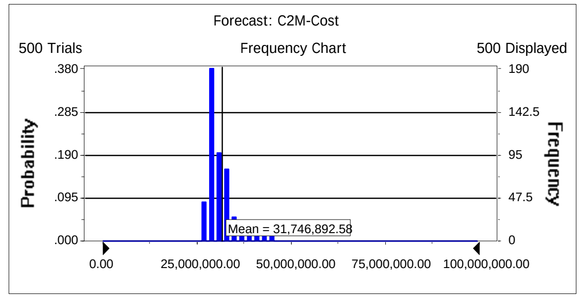


(d) “Rebuild”

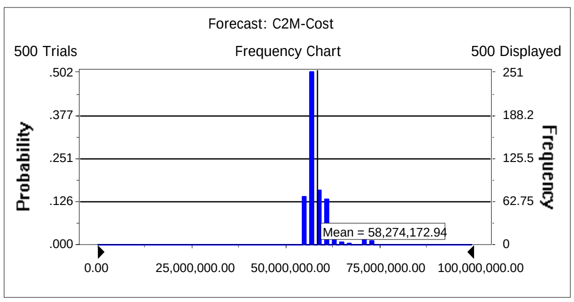
Figure 9.4 Frequency Plot of Monetary Loss ($) for C2M Structures due to 10/50 EQ



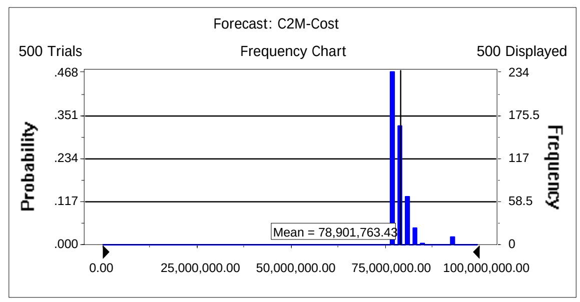
(a) “No Action”



(b) “Rehab LS”

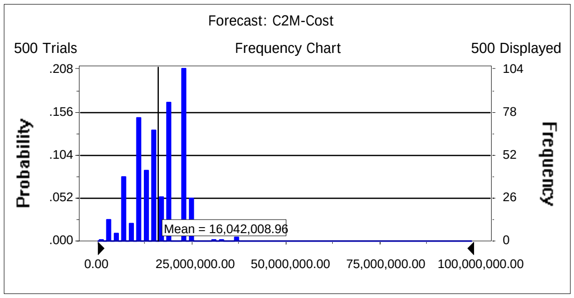


(c) “Rehab IO”

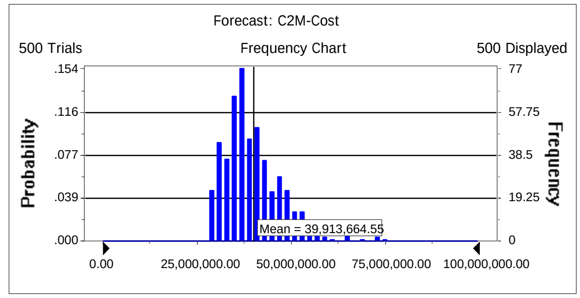


(d) “Rebuild”

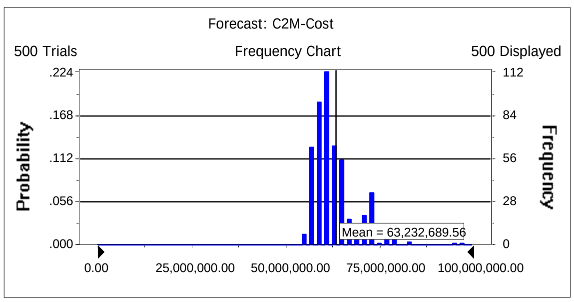
Figure 9.5 Frequency Plot of Monetary Loss ($) for C2M Structures due to 5/50 EQ



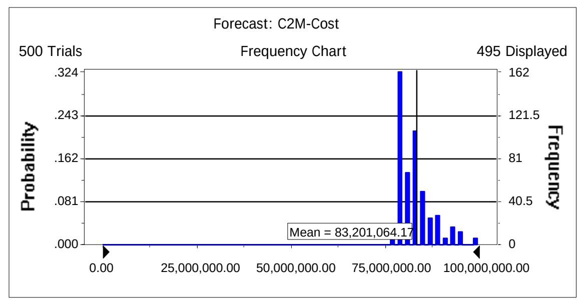
(a) "No Action"



(b) "Rehab LS"



(c) "Rehab IO"



(d) "Rebuild"

Figure 9.6 Frequency Plot of Monetary Loss ($) for C2M Structures due to 2/50 EQ

Hospital owner – local owner

The second hypothetical decision maker is a local hospital owner. It is assumed that the hospital system constitutes large portion of the decision maker's asset, so the total loss of the hospital would have to be avoided. That is, the decision maker cannot afford the extensive loss that could occur to the hospital system, so he is willing to prevent possible significant losses at some expense. In this case, the decision maker tends to be risk-averse and it would be appropriate to select MAUT so that the effect of the risk attitude of the decision maker is considered. The decision attributes for the decision maker would be same as in the previous case, except the inclusion of risk attitude. The risk-averse utility functions shown in Figure 7.1 are used. As in the previous case, the effect of disruption of the hospital to the community (i.e., loss of functionality) is not considered. The scaling factors for the monetary loss, death, and injury are then determined as 0.45, 0.25, and 0.30, respectively.

Simulations are then performed to obtain the consequence table, as shown in Table 9.4. The table shows the expected utility of each alternative scheme corresponding to each level of earthquake. In the last column, the overall expected utilities considering the probability of each level of earthquake are listed. This table can also be represented by a plot, as shown in Figure 9.7, for better understanding of the trend of the expected utilities, depending on the level of rehabilitation. The plot shows that higher level of rehabilitation decreases the expected utility of the decision maker, implying that the seismic rehabilitation of the system is less advantageous to the decision maker.

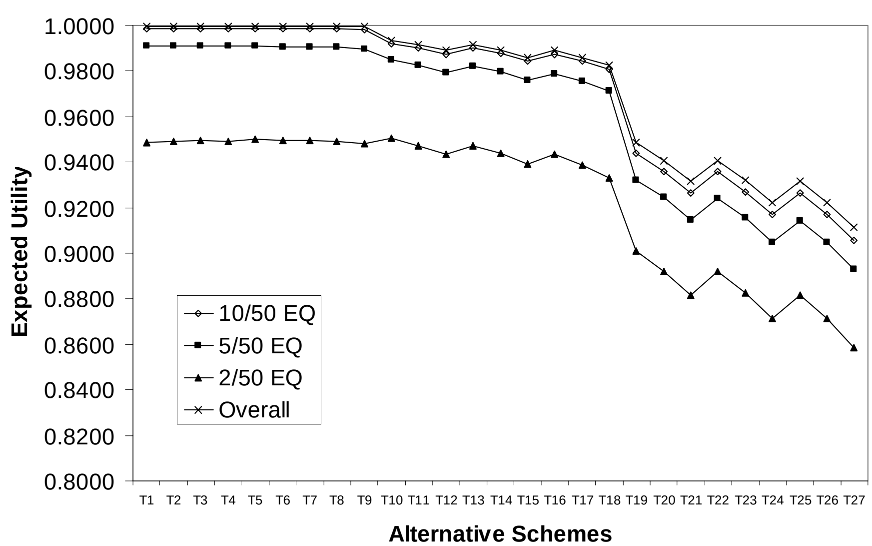


Figure 9.7 Expected Utilities of Alternative Schemes

Table 9.4 Consequence Table Showing Expected Utilities

Scheme	2/50	5/50	10/50	Overall Expected Utility
T1	0.9487	0.9910	0.9984	0.9997
T2	0.9491	0.9912	0.9987	0.9997
T3	0.9494	0.9909	0.9986	0.9997
T4	0.9492	0.9911	0.9985	0.9997
T5	0.9499	0.9912	0.9987	0.9997
T6	0.9495	0.9907	0.9985	0.9996
T7	0.9493	0.9906	0.9984	0.9997
T8	0.9492	0.9906	0.9984	0.9995
T9	0.9479	0.9898	0.9981	0.9993
T10	0.9506	0.9847	0.9921	0.9936
T11	0.9471	0.9825	0.9902	0.9915
T12	0.9434	0.9791	0.9875	0.9890
T13	0.9474	0.9823	0.9900	0.9915
T14	0.9437	0.9795	0.9877	0.9891
T15	0.9391	0.9757	0.9845	0.9861
T16	0.9435	0.9788	0.9873	0.9890
T17	0.9389	0.9757	0.9845	0.9861
T18	0.9330	0.9713	0.9807	0.9826
T19	0.9008	0.9323	0.9438	0.9486
T20	0.8919	0.9243	0.9359	0.9406
T21	0.8817	0.9144	0.9265	0.9317
T22	0.8920	0.9242	0.9357	0.9406
T23	0.8826	0.9154	0.9271	0.9319
T24	0.8713	0.9047	0.9169	0.9221
T25	0.8818	0.9142	0.9263	0.9317
T26	0.8712	0.9046	0.9169	0.9221
T27	0.8584	0.8930	0.9057	0.9114

A local FEMA agency

A local FEMA agency as a decision maker would have several unique characteristics that would distinguish it from the hospital owner. First, the agency would be more concerned about the public safety rather than the profit of the hospital. Second, the decision would be made more likely based on regulations and legal standards. Third, often times the budget allocated to the seismic rehabilitation of the system would be explicitly limited. Therefore, the selection of the MCDM model must be made keeping in mind the characteristics mentioned above. The agency would not be much concerned about the level of hospital system's functionality as long as the expected functionality satisfies the required regulations. In other words, the decision maker's value is better represented in terms of constraints, rather than continuous functions. Therefore, JPDM is considered appropriate for the decision problem, based on the selection process depicted in Figure 9.2.

Unlike the attributes considered in Chapter 8, the monetary cost – especially the repair cost and loss of income – is less likely to be considered. However, the initial cost should be considered because of the limited budget, and the budget allocated for rehabilitation of this hospital system is $50M. Note that the hospital's continuing function should be considered in this case, as the public safety is a major concern of the decision maker. It is assumed that the criterion values are determined based on the regulations that the FEMA agency tries to satisfy, and the resulting criterion values are listed in Table 9.5. It is also assumed that the regulation is based on a scenario earthquake, of which probability of exceedance is 5% in 50 years. The regulation also says that the probability of satisfying the standards must be over 90%. Since the regulation is expressed explicitly as such, the decision maker does not want to adjust the criterion values based on the relative weights. Therefore, equal weights are used for the three attributes to use the initially-defined criterion values without adjustment.

Table 9.5 Criterion Values of the Attributes

Attributes	Lower Bound Criterion Value	Upper Bound Criterion Value	Relative Weight
Functional loss ($days \cdot A_{total} / 10{,}000\, ft^2$)	L_f=0 (-∞)	U_f=700	w_f=0.33
Death	L_d=0 (-∞)	U_d=5	w_d=0.33
Injury	L_i=0 (-∞)	U_i=10	w_i=0.33

The simulation is performed to obtain the POS of each alternative scheme based on the scenario earthquake. Table 9.6 shows the consequence table along with the required initial cost for each alternative scheme. The table shows that none of the feasible alternative schemes satisfies the requirement, as all the POSs of the feasible alternatives are less than 0.9. T19 to T27 satisfy the requirements, but the required initial costs exceed the limited budget of $50M. In this case, problem should be reconfigured by reinvestigating the value or the alternatives. Since the constraints are defined based on the regulation, it is practically impossible to update the criterion values or to reallocate the budget. On the contrary, it would be possible to reconsider the alternatives. In this particular problem, the alternatives are defined per class of structures. That is, the levels of rehabilitation of all four C2M structures are always same. However, the level of rehabilitation of each C2M structure can be determined different from each other to adjust the required initial cost. Since the initial cost corresponding to T19 exceeds the budget limit but not by much, a new alternative scheme can be made by changing the rehabilitation level of the C2M structures of T19. The new alternative scheme is named "Tnew", where one of the C2M structures is determined "Rehab LS", while other three structures are assigned 'Rehab IO.' The C2L and URML structures remain the same at "No Action". In this case, the required initial cost drops down to $48.33M. The simulation is performed for this new alternative scheme and the result is shown in Table 9.7, along with the consequences of T18 and T19 for comparison. Table 9.7 shows that "Tnew" satisfies the required regulation, showing the probability of success larger than 90%, yet satisfying the budget limit as well.

Table 9.6 POS of the Alternative Schemes for Scenario Earthquake (5/50)

Scheme	Required Initial Cost ($M)	C2M	C2L	URML	POS
T1	0.00	No Action	No Action	No Action	0.563
T2	2.73	No Action	No Action	Rehab LS	0.577
T3	5.53	No Action	No Action	Rehab IO	0.580
T4	2.73	No Action	Rehab LS	No Action	0.575
T5	5.47	No Action	Rehab LS	Rehab LS	0.588
T6	8.27	No Action	Rehab LS	Rehab IO	0.592
T7	5.53	No Action	Rehab IO	No Action	0.573
T8	8.27	No Action	Rehab IO	Rehab LS	0.587
T9	11.06	No Action	Rehab IO	Rehab IO	0.591
T10	27.34	Rehab LS	No Action	No Action	0.803
T11	30.07	Rehab LS	No Action	Rehab LS	0.820
T12	32.87	Rehab LS	No Action	Rehab IO	0.822
T13	30.07	Rehab LS	Rehab LS	No Action	0.815
T14	32.81	Rehab LS	Rehab LS	Rehab LS	0.831
T15	35.61	Rehab LS	Rehab LS	Rehab IO	0.833
T16	32.87	Rehab LS	Rehab IO	No Action	0.814
T17	35.61	Rehab LS	Rehab IO	Rehab LS	0.829
T18	38.40	Rehab LS	Rehab IO	Rehab IO	0.830
T19	55.32	Rehab IO	No Action	No Action	0.929
T20	58.05	Rehab IO	No Action	Rehab LS	0.947
T21	60.85	Rehab IO	No Action	Rehab IO	0.949
T22	58.05	Rehab IO	Rehab LS	No Action	0.942
T23	60.78	Rehab IO	Rehab LS	Rehab LS	0.959
T24	63.58	Rehab IO	Rehab LS	Rehab IO	0.961
T25	60.85	Rehab IO	Rehab IO	No Action	0.941
T26	63.58	Rehab IO	Rehab IO	Rehab LS	0.957
T27	66.38	Rehab IO	Rehab IO	Rehab IO	0.960

Table 9.7 POS of the New Alternative Schemes for Scenario Earthquake (5/50)

Scheme	Required Initial Cost ($M)	C2M	C2L	URML	POS
T18	38.40	Rehab LS	Rehab IO	Rehab IO	0.830
T19	55.32	Rehab IO	No Action	No Action	0.929
Tnew	48.33	Rehab IO (3 units) Rehab LS (1 unit)	No Action	No Action	0.903

In fact, other approaches are also possible for reconfiguration of the alternatives. For example, rehabilitation levels can be determined to different objective performance levels. In this case, the cost required for the rehabilitation must be obtained and the fragility curves corresponding to the newly defined rehabilitation levels must be generated.

CHAPTER 10

CONCLUSIONS

An earthquake is a catastrophic event that can result in substantial losses of various kinds, including economic and social losses. The potential seismic losses, however, can be reduced with appropriate intervention actions. Among the many kinds of seismic intervention actions, seismic rehabilitation of structures is considered to be one of the more effective ways to reduce the potential seismic losses to structural systems.

Decisions on implementing seismic rehabilitation schemes usually cannot be based on structural performance and/or direct structural cost alone. In fact, they usually involve a large number of other factors associated with the problem such as life and secondary economic losses. In addition, the high degree of uncertainty that exists in both the formulation and solution of the decision problem must be considered as well. Past research has made some efforts for making decisions about seismic intervention of structural systems. However, these are focused on the decision analysis process itself based on a given decision model and are not focused on a flexible decision support methodology where a range of decision maker's values can be appropriately considered. Unfortunately, research on development of a decision support framework that can be customized to a wide range of decision makers allowing for a flexible choice of decision models is very limited. This study develops a decision support framework for seismic rehabilitation of structural systems incorporating uncertainties inherent in both the system and the seismic hazard. The decision support framework is developed such that it allows prompt response to a wide range of requests from the users, and flexibility in selection of the multi-criteria decision making (MCDM) models that is appropriate to a given decision problem on seismic rehabilitation of structures.

A decision procedure for seismic rehabilitation is provided and consists of: system definition; identification of attributes and alternatives; damage assessment; loss estimation; multi-criteria decision-making; and finally dynamic iteration. Techniques and procedures for generation of data (either deterministic or probabilistic) and for manipulating the data that are needed in each step of the decision process are identified. The classes of structures of interest are identified and the seismic consequences and rehabilitation cost associated with these structures are estimated based on HAZUS and FEMA methods. The probability distributions of the damage states of structural systems due to a given level of earthquake are obtained using fragility curves generated from HAZUS data, and both economic and social losses are estimated for a number of attributes of concern to the user. Alternative seismic rehabilitation schemes are represented generically in terms of the objective performance level, and seismic consequences of each alternative can be obtained for comparison. The procedures and methodology for estimation of seismic losses in the decision support framework allows prompt review and comparison of the seismic consequences of different alternative rehabilitation schemes; neither significant computation nor external structural analyses are required. The decision support framework is also able to provide seismic consequences for various structural systems due to any given level of earthquake. If the user wants to obtain more refined fragility curves for a specific structural system considering its unique configuration, however, additional structural analyses for the refined damage assessment are needed, which would require additional time and effort.

Three MCDM models that have been shown to be effective for formulation and solution of decision problems under uncertainty are employed and their applicability for use in decision analysis applied to seismic rehabilitation is investigated. These models are the Equivalent Cost Analysis (ECA) model, Multi-Attribute Utility Theory (MAUT), and Joint Probability Decision Making (JPDM). Utilization of these MCDM models in the decision support framework enables more flexible decision support because the user can select a MCDM model that is appropriate to a given decision problem and to his/her decision criteria. Guidelines for selection of the most appropriate model are also provided. ECA can be effectively used if the user is most concerned about the profit associated with the system of interest, and if the user has sufficient resources to be able to sustain the maximum possible losses to the system of interest. MAUT is more appropriate when the user's values are dependent upon the amount of the consequences. MAUT can also be used when the user does not feel comfortable with the idea of converting the value of significant non-monetary attributes (e.g., loss of life) into a monetary value. Compared to ECA and MAUT, JPDM is a relatively new decision concept that explicitly incorporates the effect of the probability distribution of consequences. When the decision criteria are most appropriately represented in terms of constraints, JPDM is more appropriate. JPDM also allows prompt and intuitive reconfiguration of the user's values by changing criterion values.

The decision support framework developed in this study is applied to a test bed system that consists of six hospitals located in the Memphis, Tennessee area to demonstrate the functionality of the decision support framework. Assuming a single decision maker, hypothetical sets of the decision maker's values are determined with reasonable assumptions. The structures are grouped into classes using the HAZUS structural model type: four C2M buildings, one C2L building, and one URML building. A number of social and economic losses are considered as the decision attributes. The economic losses include: initial rehabilitation/replacement cost, structural/nonstructural repair cost, loss of contents, and relocation cost. The social losses include: loss of functionality, death and serious injury. Four generic seismic rehabilitation alternative schemes are considered for each structural type: 1) no action; 2) rehabilitation to life safety level; 3) rehabilitation to immediate occupancy level; and 4) construction of a new building which complies with the latest code level. The damage assessment and loss estimation procedures used in HAZUS are performed on the structures. The analysis is carried out for each of the three different decision models and the Monte Carlo simulation approach is utilized for probabilistic estimation of the consequences and calculation of the decision indices. Sensitivity analyses are performed to investigate the impact of selected variables associated with the decision maker's values and other uncertain economic factors – e.g., value of life, value of functionality, discount rate and time horizon.

In this example, equivalent cost analysis (ECA) indicates that a rehabilitation is not justified for this hospital system located in the Memphis, Tennessee area, with the hypothetical value sets. Sensitivity analysis conducted on the equivalent cost analysis shows that a minor level of rehabilitation is suggested only when the value of function loss is determined to be very high. MAUT analysis using risk-averse utility functions, which is generally true for policy makers and tax payers, indicates that a minor to moderate level of rehabilitation is suggested for the hospital system. Moreover, sensitivity analysis indicates that an even higher level of rehabilitation might be needed for a higher value of function loss, higher discount rate, or longer time period than the baseline values of these variables. In contrast, JPDM analysis in this example suggests the highest level of rehabilitation as long as the budget allows. JPDM also demonstrates the effect of reconfiguration of alternatives by assigning different rehabilitation schemes for structures within a same class.

Recommendations for Further Study

Possible areas for future study of the decision support framework developed in this study can be divided into three parts. First, investigation and application of the decision support framework to actual decision problems on seismic rehabilitation is suggested. In the application presented in this study, a set of typical decision attributes are selected and the values are hypothetically quantified using reasonable assumptions. A guideline for selection of MCDM models is also provided assuming several hypothetical decision makers. However, a more detailed investigation which includes practical decision procedures regarding seismic rehabilitation of structural systems is suggested. Important issues should be identified and explored such as: who are the decision makers and which MCDM model is best suited to their needs and objectives; what range of decision makers are typically involved; what kinds of attributes are considered most significant; and how is the final decision actually made. In this way, the decision framework can be refined and tailored to the specific decision problem on seismic rehabilitation. It should also be noted that the decision maker's values must be systematically elicited through extensive interaction between the decision maker and the decision analyst in an actual application of the decision support framework.

The second area for future research involves establishment of a comprehensive and accurate method for seismic loss estimation. This is needed because the quality of a decision analysis depends on the quality of the consequence estimation approach. Although much past effort has been expended on the assessment of seismic damage of structures, the methods for conversion of the damage into social and economic losses are relatively crude and are in need of additional refinement. HAZUS provides a comprehensive procedure for seismic loss estimation, but much of the required input information is based on expert opinions and assumptions. Moreover, the effect of uncertainty in the HAZUS seismic loss estimation method must be investigated as well, as the current method assumes a deterministic relationship between the structural damage states and the corresponding seismic losses. However, more accurate loss estimation generally results in less efficiency. For example, additional structural analyses for generation of refined fragility curves requires a substantial increase in time and effort. Therefore, efficiency must be considered in the development of revised loss estimation methods. Along the same line, more refined alternatives for seismic rehabilitation should be considered as well. Effective methods should be established in order to obtain the required costs, appropriate damage distributions, and estimated seismic losses associated with the refined alternatives.

A final recommendation for future study is that interdependencies among systems should be considered in decision making involving complex systems. In the decision analyses performed in this study, each system and its loss is measured independently, without consideration of the appropriate correlation with and dependency upon other associated systems. Here it must be recognized that disruption of one system can substantially affect the performance of others and this should be included in the system evaluation and consequent decision making involving possible rehabilitation measures. For example, collapse of a bridge on a roadway near a hospital structure might limit access to the hospital and therefore lower the actual functionality of the hospital. Another example is that disruption of the electrical or water systems can decrease the operability of the hospital system. In general, seismic losses might be underestimated without consideration of these kinds of system interdependencies. It is therefore essential that seismic losses of a system be estimated considering other systems that are connected to it, either physically or functionally.

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