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PROBABILISTIC DECISION ANALYSIS FOR SEISMIC REHABILITATION OF A REGIONAL BUILDING SYSTEM

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SUMMARY

Seismic vulnerability of building structures can be reduced with appropriate rehabilitation schemes. However, decisions on rehabilitation of structures can depend on multiple conflicting criteria such as cost, life loss, functionality, etc. In this study, a framework is developed to support decisions on seismic structural rehabilitation. Three multi-criteria decision models are considered: an equivalent cost model (ECM), multi-attribute utility theory (MAUT) and Joint Probability Decision Making (JPDM). The decision models are applied to hospital systems located in Memphis, Tennessee, and the preferred rehabilitation options are identified based on the two decision models.

INTRODUCTION

Seismic failure or damage to built systems in regions with moderate to high seismicity can exact a high toll, in lives lost, cost of damage, and other consequences of interest and concern to stakeholders. However, the seismic vulnerability of such systems can be reduced with appropriate rehabilitation schemes (Abrams [1]). Structural rehabilitation decisions can depend on multiple criteria, such as structural performance, cost, aesthetics, and functionality. These criteria often conflict with one another. There have been efforts on the decision analyses for seismic rehabilitation of building structures (e.g., Benthien [2], Thiel [3]). However, an effort to develop a decision support framework that takes into account multiple criteria including loss of life and building function loss, while utilizing comprehensive probabilistic seismic loss estimation methods for structures (either individual structure or regional systems) is sparse. In this paper, a multi-criteria decision support framework is proposed to help decision makers evaluate rehabilitation schemes, and to support regional seismic rehabilitation decisions. This approach employs three multi-criteria decision models – an equivalent cost model (ECM), multi-attribute

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utility theory (MAUT) and joint probability decision-making (JPDM) – within a flexible configuration to facilitate use by a variety of stakeholders. ECM is a decision technique in which non-monetary values are converted into equivalent monetary values. MAUT is a widely used decision theory that provides insight into preferences over a set of alternatives taking into account the decision maker's risk attitudes. JPDM is a decision model that gives an index of system performance based on the probability of achieving a pre-defined level of consequences for each attribute of the system.

To illustrate the decision support framework, structures within a regional system are divided into several classes based on their configuration, function and structural design. A seismic hazard curve is used to represent the uncertainty in the seismic hazard. This hazard curve and structural fragility curves for the system are combined to obtain the overall probabilistic distribution of structural damage within a particular time period. For the decision analyses, consequences are defined in terms of criteria selected by the decision maker. Monte Carlo simulation is used to estimate probabilistically the anticipated seismic structural damage and overall consequences to the system, both without intervention and with alternative rehabilitation schemes. The decision analyses provide summary measures of consequences, to identify the best rehabilitation scheme(s). The framework supports several forms of sensitivity analysis, including dynamic restructuring of decision criteria and rehabilitation alternatives, to provide decision makers with additional insights into the consequences of seismic rehabilitation decisions.

SYSTEM DEFINITION

Description of the Building Systems

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 [4]). Among them, six hospital buildings are selected and examined to demonstrate the decision support framework. Table 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 [5]) as loss estimation in this study follows a HAZUS approach.

Table 1 Building Description

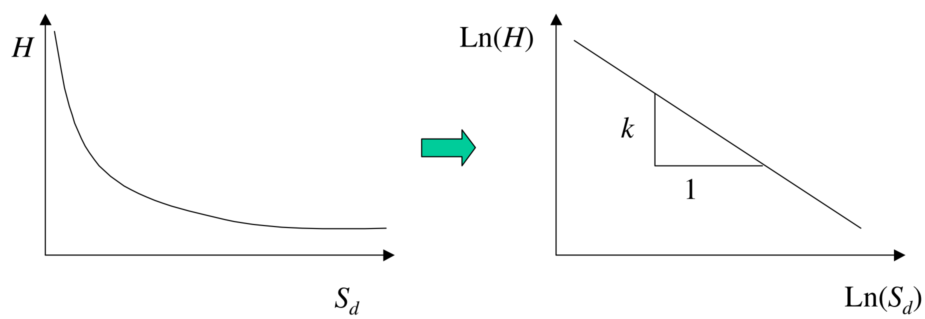
Hospital	ZIP	Structural Type	HAZUS Model Type
Methodist University Hospital	38104	Concrete Shear Wall (Mid-Rise)	C2M
Methodist North Hospital	38128	Concrete Shear Wall (Mid-Rise)	C2M
UT Bowld Hospital	38103	Concrete Shear Wall (Mid-Rise)	C2M
Methodist South Hospital	38116	Concrete Shear Wall (Mid-Rise)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

Hazard Curves

Earthquakes representative for the location of the system of concern must be defined for use in the damage analysis. Ground motion intensity is often characterized in terms of spectral displacement (S_d) or spectral acceleration (S_a). However, since earthquakes are random events, which depend on location, it is also necessary to identify the probabilistic characteristics of the earthquake intensity as well. Usually the likelihood of different earthquake levels is expressed in terms of probability of exceedance within certain time limits, for example, 10% probability of exceedance in 50 years. The relationship between the earthquake intensity and its likelihood can be represented by a hazard function H (Cornell [6], Yun [7]). The annual probability of exceedance for earthquake intensity (generally s_a or s_d) at the site can be obtained from the hazard function. According to Cornell [6], the hazard function can be approximated to lie linearly 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 by the form

$$H(s_d) = P[S_d \geq s_d] = k_0 s_d^{-k} \tag{1}$$

Parameters k_0 and k are location-specific. The hazard curve is shown schematically in Figure 1.



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

Figure 1 Hazard Curve

PROBABILISTIC EVALUATION OF DAMAGE AND LOSSES

The anticipated damage state of a building or a system of buildings can be used to estimate seismic losses. Before conducting the damage assessment, the seismic performance objective for a structure must be specified. A performance objective can be defined in terms of the structural performance level and corresponding probability that the performance level will be exceeded within a certain time limit (Yun [7]). According to SAC [8], for example, the objective performance level of a new building is that the building should have 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.

A closed form solution is available (Cornell [6]) to describe structural damage probabilistically. Three major sources of uncertainty in seismic damage assessment for structural systems are: 1) ground motion intensity; 2) structural demand; and 3) structural capacity. There are a number of ways to measure structural demand and capacity, including 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 is

$$\begin{aligned} H_D(d) = p[D \geq d] &= \sum_{all\, x_i} P[D \geq d \mid S_d = x_i] P[S_d = x_i] \\ &= \int P[D \geq d \mid S_d = x] \left| dH(x) \right| \end{aligned} \tag{2}$$

The damage probability (annual probability of exceeding certain damage level) can then be expressed as

$$P_{PL} = P[C \le D] = \sum_{all\ d_i} P[C \le D \mid D = d_i] P[D = d_i]$$
$$= \int P[C \le d] \left| dH_D(d) \right| \tag{3}$$

where C is a generic expression for structural capacity. The damage probability (annual probability of exceeding certain damage level) in Equation (3) can be approximated as

$$P_{PL} = H(S_d^{\hat{C}}) \exp\left[\frac{k^2}{2}\left(\beta^2{}_{D|S_d} + \beta^2{}_C\right)\right] \tag{4}$$

where $S_d^{\hat{C}}$ is the spectral displacement corresponding to the median capacity. 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 probabilistic distribution of seismic losses of 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 or a class of structures with the same structural type that are located relatively close to each other within a region in which the seismicity 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. To assess expected losses within a particular time period, losses are estimated for a suite of earthquake levels. The damage distribution of a structure or type of structure from a particular earthquake level can be obtained from the fragility curve for the structure. In this study, HAZUS [5] is used to estimate structural damage and losses, which requires that the buildings be classified (into one of 36 categories) based on structural type and height. Building fragility and capacity curves are used to determine building damage state probability in HAZUS. The fragility curves for a particular structural type can be obtained for different code levels (pre, low, moderate, and high code level) in force when the structures were built (assuming code compliance). HAZUS provides an extensive list of parameters that are needed to generate fragility curves (for both structural and nonstructural damage) for all 36 types of structures and for four different code levels. Based on these, fragility curves can be generated for four different damage states – slight, moderate, extensive, and complete damage. For detailed description of the damage states, see HAZUS [5].

The HAZUS loss estimation methodology is assumes that there are strong relationships between building damage and major social and economic losses (HAZUS [5]). Social losses include death and injury, loss of housing habitability, short term shelter needs, etc; economic losses include structural repair costs, nonstructural repair costs, building contents loss, business inventory loss, loss of building function, initial rehabilitation cost, etc. The decision maker chooses which losses to assess in the rehabilitation decision analysis, by selecting them as attributes of the system. Table 2 shows the losses considered in this example, where hospitals comprise the system of interest. These are the system attributes for the decision analysis. Note that only direct losses are considered, and indirect losses are not taken into account here.

The expected seismic losses are estimated for four different earthquake levels: 20%, 10%, 5%, and 2% probability of exceedance in 50 years. The loss hazard curve can then be plotted for each kind of loss. For example, Figure 1 shows the hazard curve for monetary loss for four C2M type structures among the structures listed in Table 1. The expected loss is then calculated from the area under the loss hazard curve.

Table 2 Losses Considered

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 wall partitions, panels, veneers, floors, general mechanical systems, etc.
	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.
	Death	Number of deaths.
	Injury	Number of seriously injured people

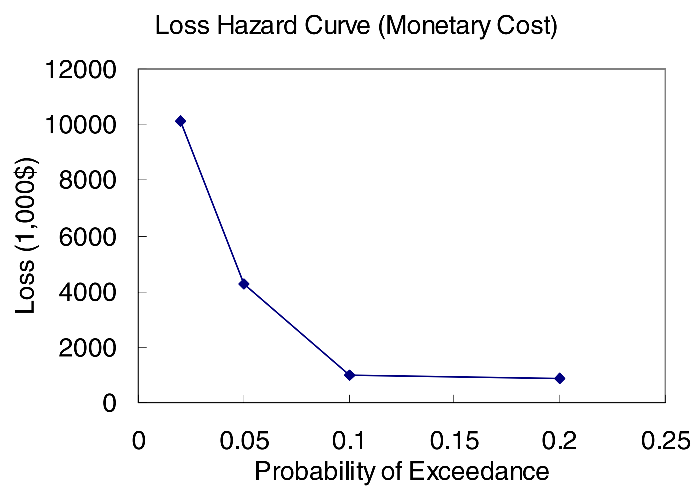


Figure 2 Monetary Loss Hazard Curve for C2M Type Structures

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) build a new building to comply with the current code level. The rehabilitation levels mentioned above are, as defined in FEMA [9], the target performance levels of the rehabilitation against an earthquake with 10% exceedance in 50 years. 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, etc. The initial rehabilitation cost for different options are obtained from FEMA documents (FEMA [10] and FEMA [11]), which provide the typical cost 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 seismic alternative. 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 code levels are shown in Table 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 of a URML type structure, as they are not available in HAZUS.

Table 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)

EQUIVALENT COST ANALYSIS

For equivalent cost analyses, consequences measured in different units are converted into a single composite measure – usually a monetary measure – by introducing conversion factors. For example, one day of construction delay can be considered equivalent to three million dollars. This cost-benefit analysis approach (Keeney [12]) is called an 'equivalent cost analysis' in this study because in decision problems regarding seismic events, that the only benefit apparent is the minimization of losses (or costs). However, there are several known problems with this method (Keeney [12]). In order to use a 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. Even when these assumptions are considered valid, many important attributes such as the value of a life are very hard (and sometimes considered impossible or immoral) to price out. Moreover, attributes may be ignored or not included in the analysis when it is hard to convert them into monetary values using market mechanisms (e.g., aesthetics). Nevertheless, the equivalent cost model is still widely used because of its simplicity in use and straightforwardness.

Among the non-monetary attributes, the value of human life is very difficult to determine and has been highly debated. Moreover, the value of human life will have a wide range of values depending on the decision context. According to FEMA [10], the typical value of a statistical life ranges from $1.1 million to $8 million per life (other authors have found different ranges). In this study, the decision analysis will not be performed with fixed values for non-monetary attributes, but instead with a range of values ($1.1m to $8m for the value of a statistical human life), to investigate the effects of the equivalent monetary values on the decision. The equivalent cost for the 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 the total floor area of 10,000 square feet is estimated to cost $100,000, the equivalent cost for 5 days of loss of function of 50,000 square feet hospital would be $2,500,000. Obviously, this rough approach for determination of equivalent cost for loss of function needs future refinement. As described in Table 3, the value of loss of function should be taken into account that the loss of function may result in additional loss of life. In this study, sensitivity analysis will be performed for the value of loss of function ranging from $0 to $500,000 for one day of loss of function of a hospital per 10,000 square feet. Table 4 shows the baseline values for the non-monetary attributes for the decision analysis. Note that the value of injury is estimated (crudely) at 30% of the value of a statistical life loss.

Table 4 Baseline Values for Non-monetary Attributes

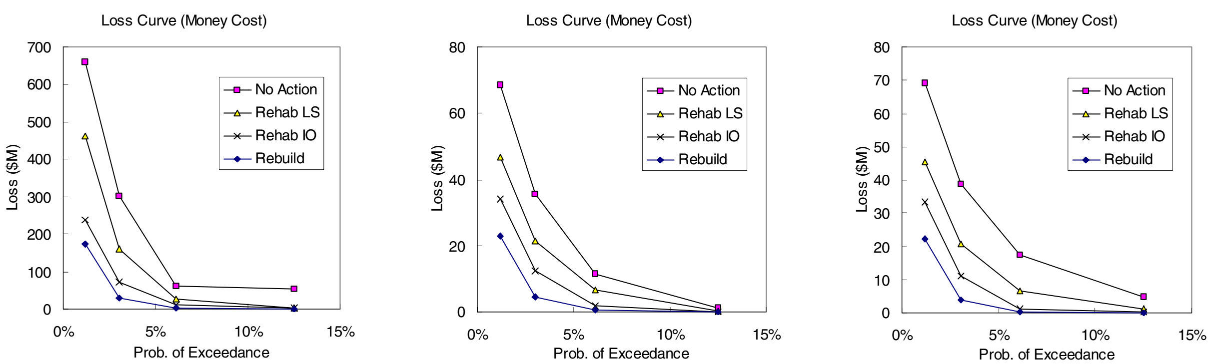
Attribute	Equivalent Cost
Value of Death	\$5,000,000 / person
Value of Injury	\$1,500,000 / person
Value of Loss of Function	\$100,000 / day to recover / 10,000 ft^2

If a temporal trade-off is considered in performing a decision analysis, future costs may be discounted to net present value, if the decision maker considers them less painful. If we have a time stream of costs ($c_0, c_1, \ldots, c_T$), the total net present value of the cost can be expressed as follows:

$$c_{npv} = \sum_{t=0}^{T} \frac{c_t}{(1+\lambda)^t} \tag{5}$$

where λ is the effective period-to-period discount rate. According to FEMA [10], several different approaches have been used to estimate the discount rate for public investments, with the resulting discount rates ranging between 3% and 10%. Determination of the time period T also depends on the decision maker. In this study, a 30-year time period and with 6% discount rate are used as baseline values, with sensitivity analyses on time periods ranging from 10 years to 50 years, and discount rates from 3% to 10%. Note that the probability of exceedance of different earthquake levels must be calibrated to be consistent with the time period.

Figure 3 shows the loss hazard curves for each type of structure with the expected equivalent losses corresponding to different earthquake levels. Note that the losses shown in this figure are the equivalent cost, where non-monetary attributes are priced out. Table 5 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 30 years of time period). This specific expected equivalent cost analysis indicates that none of the rehabilitation actions are justified.



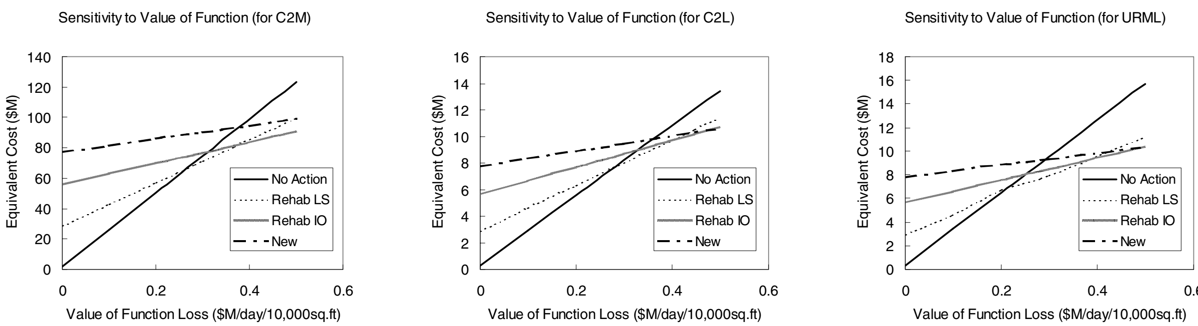
(a) C2M Structures (4 units) (b) C2L Structure (1 unit) (c) URML Structure (1 unit)

Figure 3 Loss Hazard Curves for C2M type Structures (4 units)

Figure 4 shows the sensitivity plots for different values of function loss (the sensitivity plots for other variables are not shown in this paper). Among the variables included in this decision analysis, the relative differences of the expected equivalent costs of the alternative systems are most sensitive to the change of the value of function loss. Note that the slopes (sensitivity) of the options are different and decision reverses occur when the value of function loss exceeds approximately \$200,000.

Table 5 Expected Equivalent Costs ($Million) of Different Rehabilitation Schemes

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



(a) C2M Structures (b) C2L Structure (c) URML Structure

Figure 4 Sensitivity Plot for Value of Function Loss

MULTI-ATTRIBUTE UTILITY ANALYSIS

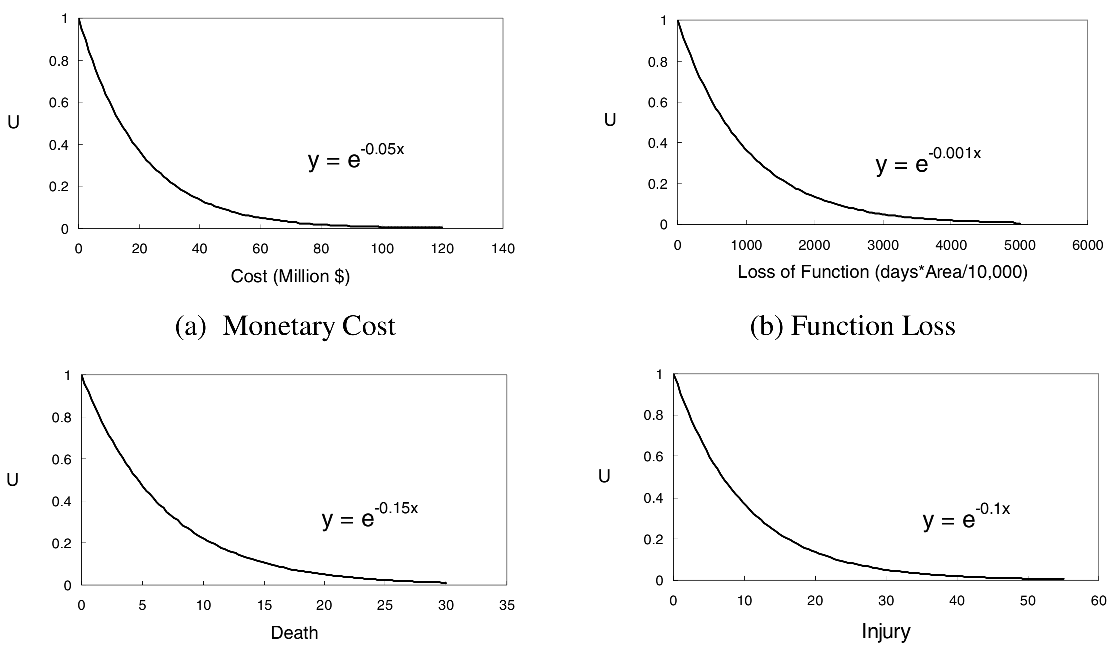
Multi-attribute utility theory (MAUT), which has been widely used in the field of decision analysis, incorporates decision makers' unique preferences for multiple attributes, thus allowing incorporation of multiple criteria into a decision. Preferences (or values) are measured in terms of utility functions, which can be linear or nonlinear. For multiple criteria decision-making problems, a multi-attribute utility function is generated as a function of a number of single utility functions, considering their relative impact on the overall value as well as their interactions. The details of the theory and the techniques for utility elicitation are well described in the literature (Keeney [12]). If uncertainty is involved in the problem, the expected utility is obtained for each alternative and the alternative with highest expected utility is the one with highest priority. To examine the effect of including risk attitudes, a set of utility functions is assumed in this study. From the fact that decision makers tend to be risk seeking (i.e., the shape of the utility function is convex) for losses (Kahneman [13]), four risk seeking utility functions are assumed as shown in Figure 5. 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). In construction of the multi-attribute utility function, the utility functions are assumed to be additive for simplicity, and the scaling factors are defined as shown in Table 6. For the purpose of comparing these results with the equivalent cost analysis, the scaling factors for the attributes are determined such that the ratios of the scaling factors are same as the ratios of the equivalent costs for the maximum values. These scaling factors are presented as baseline values and are subjected to sensitivity analysis. The multi-attribute utility function can then be formulated as

$$u(x_1, x_2, x_3, x_4) = k_1 u_1(x_1) + k_2 u_2(x_2) + k_3 u_3(x_3) + k_4 u_4(x_4) \tag{6}$$

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

Table 6 Scaling Factors of Attributes

Attributes	Min. Value	Max. Value	Scaling Factor
Monetary Cost ($M)	0	100	k_1=0.12
Function Loss ($days \cdot 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



(a) Monetary Cost

(b) Function Loss

(c) Death

(d) Injury

Figure 5 Utility Functions (Risk-Seeking) for Attributes

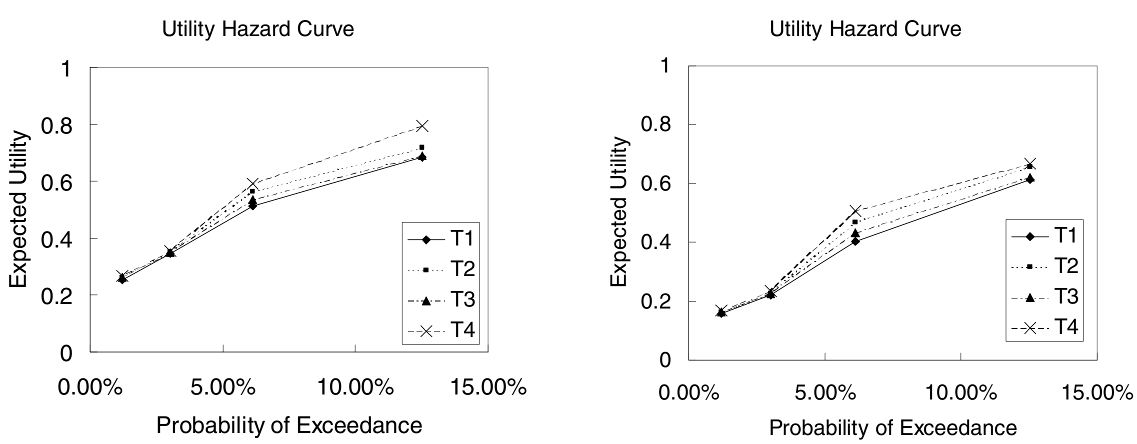
Utility functions are measured over the range of total consequences, and should be performed on the system as a whole. Accordingly, the alternative systems are defined in terms of the combinations of the alternatives for each individual structure or each type of structures. In this example, eight combinations of the alternative systems are analyzed, using two alternatives for each type of structure (here the best two options from the equivalent cost analysis). The expected utility of a rehabilitation scheme *i* can be calculated as

$$EU_i = \int_{x_1} \ldots \int_{x_4} u(x_1, x_2, x_3, x_4) f^i{}_{X_1,X_2,X_3,X_4}(x_1, x_2, x_3, x_4) dx_1 dx_2 dx_3 dx_4 \tag{7}$$

where EU_i is the expected utility of *i*th scheme and $f^i{}_{X_1,X_2,X_3,X_4}(x_1, x_2, x_3, x_4)$ is the joint probability density function for the rehabilitation alternatives corresponding to the *i*th scheme. Same as the equivalent cost analysis, the Monte-Carlo simulation is performed to obtain the expected utility of each alternative combination scheme. Table 7 shows the list of combinations of the alternative systems; expected utilities for these combinations are given as well. Note that the expected utilities are obtained for two different values of the scaling factors for loss of function, k_2. These two values of k_2 are obtained such that they are consistent with the case that the values of function loss in the equivalent cost analysis are \$100,000 and \$200,000, respectively. The utility hazard curves for selected combinations of the alternative systems are shown in Figure 6 showing the expected utilities corresponding to different earthquake levels. This analysis suggests that none of the rehabilitation actions are justified, as in the equivalent cost analysis, unless the relative importance of the function loss is very high. With a scaling factor for function loss (k_2) of 0.75, scheme T2 is preferred. It should be noted that although T4 dominates in both plots in Figure 6,T4 is less preferred than either T1 or T2 overall because T1 and T2 are preferred (because of low initial costs) over T4 when there is no earthquake, which is highly likely.

Table 7 Expected Utilities of the Combinations of the Seismic Alternative Schemes (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	0.9528	0.9424
T2	No Action	No Action	Rehab LS	0.9498	0.9434
T3	No Action	Rehab LS	No Action	0.9466	0.9395
T4	No Action	Rehab LS	Rehab LS	0.9513	0.9411
T5	Rehab LS	No Action	No Action	0.9111	0.9262
T6	Rehab LS	No Action	Rehab LS	0.9141	0.9324
T7	Rehab LS	Rehab LS	No Action	0.9094	0.9265
T8	Rehab LS	Rehab LS	Rehab LS	0.9130	0.9333

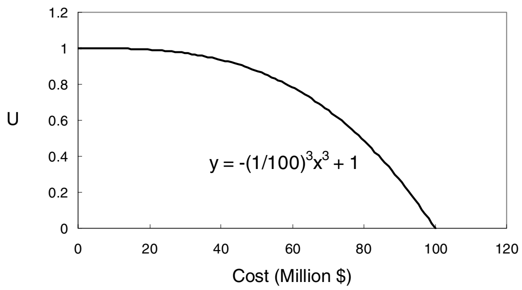


(a) with k_2=0.6

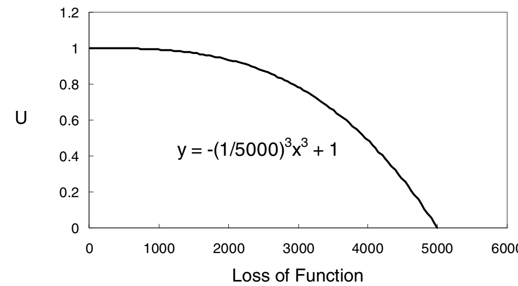
(b) with k_2=0.75

Figure 6 Utility Hazard Curves for Selected Combination Schemes

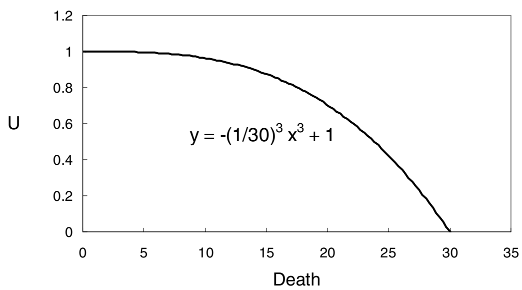
To investigate the effect of different risk attitudes, the analysis is performed with the risk-averse utility functions are shown in Figure 7. Note that the same set of scaling factors is used for the analysis. The analysis is performed in the same manner as described above. Overall expected utilities of the different rehabilitation schemes are shown in Table 8. In contrast to the results with risk-seeking utility functions, the analysis indicates that T5~T8 are preferred over T1~T4 for both sets of scaling values. Considering the fact that C2M type structures constitute the majority of the system of interest (at least in terms of square footage), the analysis shows, as one would expect, that rehabilitation actions are generally recommended when decision makers are risk averse.



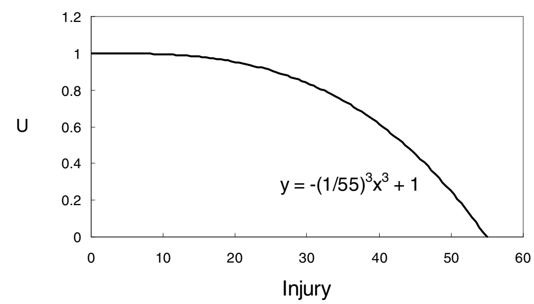
(a) Monetary Cost



(b) Loss of Function



(c) Death



(d) Injury

Figure 7 Utility Functions (Risk-Averse) for Attributes

Table 8 Expected utilities for alternative rehabilitation schemes (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	0.9925	0.9907
T2	No Action	No Action	Rehab LS	0.9925	0.9907
T3	No Action	Rehab LS	No Action	0.9925	0.9907
T4	No Action	Rehab LS	Rehab LS	0.9926	0.9908
T5	Rehab LS	No Action	No Action	0.9968	0.9962
T6	Rehab LS	No Action	Rehab LS	0.9968	0.9963
T7	Rehab LS	Rehab LS	No Action	0.9968	0.9963
T8	Rehab LS	Rehab LS	Rehab LS	0.9967	0.9962

JOINT PROBABILITY DECISION MAKING

Bandte [14] developed Joint Probabilistic Decision Making (JPDM) 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 can be obtained either mathematically or from empirical distribution functions. Using joint probability distribution functions, a unique value called Probability of Success (POS), which indicates the probability of satisfying specific decision making objectives, can be calculated to provide a barometer with which the decision can be made. The POS can be mathematically expressed as follows.

$$
\begin{aligned}
POS &= P\{\ (z_{1_{\min}} \le z_1 \le z_{1_{\max}}) \cap (z_{2_{\min}} \le z_2 \le z_{2_{\max}}) \cap \ldots \cap (z_{N_{\min}} \le z_N \le z_{N_{\max}})\ \} \\
&= \int_{z_{1\min}}^{z_{1\max}} \ldots \int_{z_{N\min}}^{z_{N\max}} f_{Z_1 Z_2 \ldots Z_N}(z_1, z_2, \ldots z_N) dz_1 dz_2 \ldots dz_N
\end{aligned} \tag{8}
$$

where, z_i is the criterion value, $f_{Z_1 Z_2 \ldots Z_N}(z_1, z_2, \ldots z_N)$ is the joint probability function of the criteria, and z_{imin} and z_{imax} are the minimum and maximum range of the objective criterion value, respectively. In JPDM the alternative with maximum probable positive consequences is preferred. Note that because JPDM requires specifying specific thresholds for success (decision criteria values), the preferred decision in JPDM may not be same as that resulting from an expected value (or expected utility) approach. Value information (i.e., success) in JPDM is expressed in terms of the criteria values. The consequential difference between ECA and MAUT is the incorporation of risk attitudes. JPDM is a categorical approach, in that the decision maker specifies at the outset what values of each decision attribute of interest (i.e., criterion values) will be considered "success" (or "acceptable"). JPDM is designed to help the decision maker maximize the joint probability of attaining success (i.e., acceptability) on all attributes of interest.

Table 9 shows the criterion values assumed for the JPDM analysis in this example. These indicate the range of the consequences the decision maker considers successful (i.e., acceptable). The Monte Carlo Simulation is used to calculate the probabilities of success (POS) of the alternative schemes and different earthquake levels. Table 10 shows the overall expected values of POS for alternative rehabilitation schemes. In this analysis, JPDM gives high priority to T6 and T8.

Table 9 Criterion Values for JPDM

Attributes	Minimum Criterion Value	Maximum Criterion Value
Monetary Cost ($M)	0	100
Function Loss ($days \cdot 10{,}000 ft^2$)	0	100
Death	0	10
Injury	0	20

Table 10 POSs of the Combinations of the Seismic Alternative Schemes

Scheme	C2M	C2L	URML	POS
T1	No Action	No Action	No Action	0.9300
T2	No Action	No Action	Rehab LS	0.9402
T3	No Action	Rehab LS	No Action	0.9334
T4	No Action	Rehab LS	Rehab LS	0.9442
T5	Rehab LS	No Action	No Action	0.9504
T6	Rehab LS	No Action	Rehab LS	0.9644
T7	Rehab LS	Rehab LS	No Action	0.9548
T8	Rehab LS	Rehab LS	Rehab LS	0.9694

CONCLUSIONS

This paper outlines a decision framework that incorporates state of the art earthquake engineering information and decision maker preferences into a flexible tool to support earthquake risk mitigation decisions. Three decision models are used to provide insight into the value of system interventions to reduce earthquake risks: 1) an equivalent cost model, 2) multi-attribute utility theory and 3) joint probability decision making. To illustrate the kinds of insights the framework can provide, it is applied to a set of hospitals in Memphis, Tennessee, to assess the relative value of structural rehabilitation options.

With the assumed baseline values of discount rate, value of function loss, value of death and injury, and time period, and the assumed set of utility functions, no rehabilitation action is justified in either the equivalent cost analysis or the utility analysis. However, sensitivity analysis suggests that the URML structure in the hospital system should be rehabilitated to life safety level if the relative importance of hospital function loss is high. If the decision maker is risk-averse, the analysis indicates rehabilitation actions are generally justified. With JPDM, two rehabilitation schemes are preferred. The results illustrate the kinds of insights the system could provide to decision makers, recognizing that any such analyses require significant assumptions, which should be probed with appropriate technical support.

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