A Hybrid Decision Analysis Technique for Cost/Risk/Benefit Analysis

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Abstract

With limited funding, decision-makers often face the dilemma of selecting an optimal decision from a set of sound alternatives. They are faced with choosing the most cost/risk-effective safety improvement options from a large list of alternatives with funding limitations. They must also consider several implementation options along with the potential impact to the community.

The Multiattribute Utility Theory (MAU) and the Analytical Hierarchical Process (AHP) have been commonly used to evaluate multiple-attribute decision alternatives. Each of these decision analysis tools has its pros and cons. For instance, MAU has been considered to be more comprehensive but the utility functions are difficult to develop, while AHP is easy to apply but is generally regarded to be crude and unsophisticated.

This paper presents a risk-based decision technique that combines the advantages of MAU and AHP to prioritize decision alternatives based on a set of risk-based evaluation criteria and a formal cost/risk/benefit analysis structure. To further aid the decision-maker, this risk-based prioritization process is automated into a decision analysis tool. It has been found to be an effective decision-making tool to aid in the prioritization of decision alternatives where multiple attributes are involved.

Introduction

Decision-making is a complex process that often involves the evaluation and prioritization of tangible and intangible factors. A formal decision analysis requires the development of decision attributes and the determination of how each attribute contributes to the overall decision-making process. Since the decision-making process depends on the state-of-knowledge of the decision-makers, the process is inherently iterative in nature and the relative cost-risk effectiveness of the decision alternatives must be assessed.

There are many quantitative and qualitative approaches to aid in the selection of the most optimal alternative (ref. 1) in a decision analysis. The most common approaches, from least structured to most structured, are (ref. 1):

- voting, scoring, binning systems, e.g., the "hazard totem pole" (ref. 2);
- quantitative aggregations of scores and weights, sometimes termed "rate and weight," e.g., Analytical Hierarchy Process (AHP) (ref. 3);
- matrix approaches, e.g., the priority planning grid (ref. 4); and
- multiattribute decision analysis approaches, e.g., Multiattribute Utility (MAU) theory (ref. 5).

Cost/Benefit Ratio

In order to prioritize the relative importance of decision alternatives, a quantitative prioritization analysis approach is often used in conjunction with a formal cost/benefit analysis to measure the cost-effectiveness of the alternatives.

The cost of a decision alternative usually includes the cost to capital and life-cycle costs of the activities associated with the alternative. The benefit of a decision is the improvement of life quality of the decision-maker. It can be measured by varying methods for each of the decision analysis approaches described above.

Benefits for the binning system and quantitative aggregation approaches are usually measured by assigning a score to the level of improvement provided by the decision alternative. Under the binning system and quantitative aggregation approaches, the ratio between benefits and costs of improvement is only relative. That is, it is not possible to express the incremental gain in quantity of improvement between alternatives in an absolute sense, but it is possible to rank-order the cost-effectiveness of one activity relative to another. Lacking of a formal quantitative structure, these approaches are often considered to be too subjective and easily tempered.

Benefits for the matrix and multiattribute decision analysis approaches are measured by explicitly calculating improvement of life quality to the decision-maker (ref. 1). An absolute measure of cost-effectiveness can be provided by both the matrix and multiattribute decision analysis approaches if the benefit can be measured by monetary gains or losses. This provides a basis upon which management can allocate resources to mitigate risk.

Risk-Based Decision Analysis

One common methodology to assess the benefit of decision alternatives concerning safety improvements or risk reduction activities is to estimate the monetary value of the consequence should an identified hazard become a reality, or the amount saved if the concern is eliminated or the consequence is minimized. This monetary value can be multiplied by the predicted probability to yield a measure of risk. This measure of risk can be calculated for the baseline condition (status-quo) and for conditions following the proposed decision alternatives. The difference in measured risk then becomes the net improvement (which can be positive or negative) attributable to the proposed alternative.

Multiple types of consequences (e.g., public and worker health and safety, public perception, etc.) are often of concern for many risk-based prioritization efforts. This requires that management's trade-offs among the different types of consequences are reflected in the prioritization approaches. The ordering of different combinations of bins is used by the binning approach to qualitatively handle the trade-offs among types of consequences (e.g., the risk totem). Each consequence scale is weighed as part of a linear combination by the quantitative aggregation approach. Utility theory is commonly used by both the matrix and decision analysis approaches described earlier to model and measure the relative trade-offs among types of consequences (ref. 1).

The general equation form of a risk-benefit-to-cost ratio for the i^{th} alternative is as follows:

$$R/C_i = \frac{Risk_{i,\,baseline} - Risk_{i,\,improved}}{Cost_i} \qquad (1)$$

where:

i = i^{th} alternative
R/C_i = benefit-to-cost ratio of alternative i
$Risk_{i,\,baseline}$ = baseline risk of alternative i
$Risk_{i,\,improved}$ = residual risk following improvement of alternative i
$Cost_i$ = cost of alternative i

The baseline risk referred to in Equation 1 is the existing risk corresponding to the alternative being assessed. This refers to the risk before any improvements in the alternative are executed. The improved risk is the residual risk after an alternative is executed. And the cost in Equation 1 is the corresponding cost of the alternative being assessed. Typically, risk reduction activities can be termed cost effective if their benefit-to-cost ratios exceed 1.0 (ref. 1).

Hybrid Multiattribute Decision Analysis

When a decision is associated with multiple attributes and alternatives, there are several methods to prioritize the decision alternatives and assess the cost/risk-benefit ratio. The multiattribute utility theory (MAU) and the analytical hierarchy process (AHP) are two of the more acceptable formalized approaches. These two methods possess the ability to evaluate highly complex problems that involve the integration of both subjective and quantitative criteria.

This paper presents a hybrid decision analysis technique (ref. 6) that utilizes the advantages of both MAU and AHP in a decision analysis. Briefly, an iterative version of MAU is the primary decision analysis tool for prioritizing the alternatives. However, within the prioritization process, a simplified version of AHP is applied to define the relative weights (for the utility functions) of the critical set of decision-making attributes. To illustrate the application of this technique, this paper will use an example involving the operating agency of a transit system that needs to select a set of life safety improvement projects from a pool of 100 possible options with limited funding. The technique prioritizes the decision alternatives comparing the costs of each alternative to its economic benefit of reducing safety risks. The results can also provide a basis for determining where to stop spending on the alternatives. Only those projects with benefits at least as attractive as the cost should be supported in their current form. Where cost exceeds benefits, there is incentive to re-examine the way in which those benefits are achieved. Also, the prioritization allows budgets to be allocated over the entire business cycle so that the decision-maker can consider how to manage risks over a multi-year planning process.

Figure 1 illustrates the general methodology of the hybrid decision analysis technique. The approach is to first identify the decision objective, evaluation criteria (attributes), and the detailed scales for evaluating performance against those criteria. An equation for measuring the overall benefit based on MAU is then developed. This final step requires that weights be applied to each attribute to quantify the relative value (i.e., the utility value) of making improvements according to each attribute (e.g., reducing public safety risk versus complying with regulations). Ideally, the utility functions are developed from the decision-makers' preferences and trade-offs of the attributes. In this paper, these relative weights are obtained using AHP.

Multiattribute Utility Theory: The MAU is used as the primary tool in the hybrid decision analysis technique. MAU provides a logical and consistent framework for solving prioritization problems. The theory ensures that prioritization decisions are based on documented value judgments and technical assessments, and that an "auditable" logic is created to support the choices made by the decision-makers (ref. 5, 7, 8). Besides being based on a theoretically sound methodology, the MAU-based prioritization process has been repeatedly proven and successfully used in practice to model the unique characteristics of complicated prioritization problems.

The benefit of an alternative with respect to each decision-making criterion is first determined. Then an indifference or trade-off analysis is used to determine the scaling or weighting factors that compare the importance of decision criteria. A common scale, called utility, is used to measure the benefits of different criteria. Finally, the utilities are aggregated using an additive utility model to determine an alternative's overall utility.

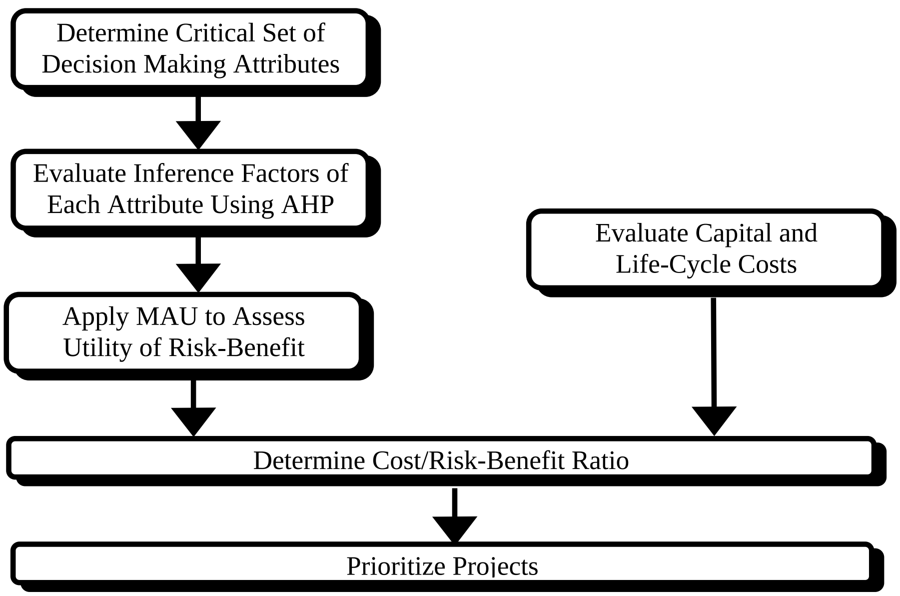

Figure 1 - Overview of the Analysis Methodology

The basic form of the risk-based prioritization model developed for this paper is as follows:

$$U_i = \sum_j A_j \tag{2}$$

where:

$$A_j = f(L_j, S_j, W_j, C_j) \tag{3}$$

and:

i = alternative i
j = attribute j
W_j = relative weight of attribute j
A_j = utility for attribute j of alternative i
L_j = likelihood inference factor affecting attribute j
S_j = severity inference factor affecting attribute j
C_j = utility conversion factor (i.e., "willingness to pay") of attribute j
U_i = total utility of alternative i

Each of these terms is described below.

Alternative i: The alternative i is the particular decision alternative (e.g., life improvement projects) being considered.

Attribute j: Attribute j is one of the attributes evaluated for each alternative. The determination of the attributes (i.e., objectives) is an iterative process beginning with the selection of various possible attributes which are then evaluated for their contribution to the assessment process. If an attribute is shown not to have any significant weight in the selection process, it will be discarded. Each of the attributes is evaluated against the others for impact and relative weight. An approach to obtaining agreement is to include all suggested attributes in an initial structure. Attributes can then be eliminated if they are duplicates, inappropriate proposed attributes, or insignificant attributes. In addition, highly dominant attributes (i.e., their impact is much larger than the others) can be eliminated since they affect all alternatives and would act as background noise to the decision analysis. Similarly, indifferent attributes can be eliminated since they do not impact the final choice of one over another.

The attributes included in Equation 2 are those determined to be highly relevant to the decision-making process for that particular alternative.

Relative Weight of Attribute *j*: The relative weight *W* of each attribute is the importance of a particular attribute when compared to the other attributes. Relative weights are best obtained by using AHP because of its general acceptance as a relative ranking decision analysis tool.

Analytical Hierarchy Process: AHP uses simple pairwise comparisons to form a matrix of numbers which describes the relative importance of each of the attributes. This matrix is termed a square, reciprocal matrix. Using the square matrix form is important in that it allows the use of matrix operations to obtain the priority ordering of the attributes (i.e., the principal eigenvector), or the relative weights. In addition, it provides a measure of the consistency of judgment (i.e., the principal eigenvalue).

Each element in the matrix is a pairwise comparison of the row attribute to the column attribute. Once the matrix of comparisons has been filled out, matrix calculations can yield the principal eigenvector and the principal eigenvalue. However, by performing some basic arithmetic manipulations and a normalization, an approximation to the principal eigenvector can be found. This vector, also known as the vector of priorities (i.e., relative weights), ranks the attributes in order of importance. After further manipulation to the vector of priorities, an approximation to the principal eigenvalue can be obtained. This can then be used to determine the deviation from consistency (i.e., how consistently the matrix of comparisons was filled out) (ref. 3).

In order to obtain a matrix that is not heavily influenced by one person's subjective views, several people can be selected to fill out a matrix utilizing a pairwise comparison of the attributes. The individual matrices are combined with equal weight to assess the overall average relative weights that are used as final rankings and weights.

The weights and scales are most easily applied to the utility analysis using dollar amounts. They are developed through an estimate of management's "willingness to pay" dollar quantities. For example, what amount is management willing to pay to avoid one statistical public death? The answer may be around $2.8 million (ref. 9). Similar "willingness to pay" information can be obtained for the other attributes and used to develop an equation for measuring the overall benefit of proposed improvement alternatives.

Utility for Attribute *j* of Alternative *i*: For each alternative, the utility value for each attribute affecting that alternative is first assessed. The basis of MAU is to aggregate these single attribute utilities into a measure of overall utility for each alternative.

Likelihood and Severity Inference Factors Affecting Attribute *j*: The attributes discussed above can be described with classes that affect each of the attributes. These classes are called inference factors. Each attribute is affected by a set of attribute-specific inference factors. The inference factors help to quantify the attributes and assign quantitative value to qualitative elements.

In most cases, each attribute can be described by two inference factors: the attribute-specific severity and the likelihood of event. Each inference factor is further divided into internal scales. This identifies the degree to which each inference factor applies in a certain situation. All alternatives are evaluated using a common set of inference factors for the attributes. The scales are assigned to facilitate a straightforward classification of the alternatives within each inference factor.

Utility Conversion Factor of Attribute *j*: The utility conversion factor *C* is the factor that converts each attribute into a dollar figure that is used as the common scale (utility value) for different attributes. This ultimately allows the comparison of risk to cost for each project. Each attribute is evaluated for the amount that has been estimated that management is willing to pay to avoid the consequence of that individual attribute. This evaluates the attribute independent of the alternative in terms of risk.

Utility *i*: The utility *U* is the final utility value of each alternative. The utility of each alternative is calculated by first multiplying the attribute specific severity by the conversion factor to convert to a dollar amount. This value is then multiplied by the relative weight of each attribute. The results give a dollar value which is comparable among all of the attributes. This value is then multiplied by the likelihood to give the utility of each attribute. This is done for each attribute, and the results are summed.

The baseline assumption for the MAU additive model is that the attributes are conditionally monotonic with one another, and the utility functions have an additive form that aggregates single attribute utility functions and incorporates weighting factors. The sum then becomes the utility of the alternative.

Automating the Process

In order to simplify the hybrid decision analysis technique described above, the process has been automated using a spreadsheet program. Two modules have been created to handle the entire process.

AHP Module: The AHP module is interactive and requires some user input. It applies the analytical hierarchy process to screen an initial set of decision-making attributes. The user must input these attributes and the pairwise comparison data. From this information, the module will calculate the relative weights of these attributes. The module will also average the results if there are multiple sets of data. These results allow the user to screen the attributes based on the relative weights. The module will also indicate the consistency of the data. This information allows the user to make a decision on the validity of the data. Inconsistent data can then either be redone and re-entered, or discarded. The user can proceed with inconsistent data, however, it is not recommended.

The screening process can span several iterations. With each iteration, the user should solicit new pairwise comparison data. This data is re-entered along with the remaining attributes until the critical set of decision-making attributes is obtained.

Once the critical set of decision-making attributes is determined, the module can be applied one final time to calculate the final relative weights.

MAU Module: The MAU module is also interactive and requires some user input. However, this module is very user friendly and is constructed with on-screen instructions and buttons. Once the core set of data is entered, it is a very simple process to manipulate the data in order to compare variations on cost, or to update data.

The user must first input the critical set of decision-making attributes along with their corresponding relative weights. Then, the attribute-specific inference factors must be input for each attribute. For each inference factor, the scales must be entered into the module. The scale can be divided into any number of categories to represent the state of knowledge regarding the inference factor in question. The final set of initial input values are the cost conversion factors. The module then assigns each value of the input data a variable name. This variable name can then be used throughout the module to represent that value. The final set of input values are the actual costs of each alternative being assessed. This includes both capital costs and life-cycle costs.

The next step is to use the defined variables to assess the utility of each alternative. The user must evaluate each alternative using all attributes by assigning each attribute a scale value for each inference factor. This must be done for both the baseline and residual utilities (before and after improvements, respectively) for each alternative. The module then automatically calculates the utility for both conditions and determines the change in utility. It will then use this change in utility to determine the benefit-to-cost ratio. This allows the module to prioritize, or rank-order, the alternatives according to their cost-effectiveness.

Once all of this data has been entered, the it is very simple to manipulate the data in order to perform comparisons for differing construction or implementation methods.

Analysis of the Example Application

To illustrate the usefulness of this hybrid decision analysis technique, the modules described above are used to assess a sample case. This example involves an operating agency of a transit system that is required by a regulatory agency to perform safety improvements to their system. The operating agency is faced with selecting a set of life safety improvement projects from a pool of 100 possible alternatives with limited funding.

The first step in quantifying the benefits of potential safety improvements, is to determine the applicable decision-making attributes. Nine top level attributes for evaluating life safety improvement projects are presented below along with a brief description for each. These top level objectives have been selected from references 10 through 18, and provide an initial starting point for determining the final objectives. The attributes are:

- Regulatory compliance (RC) - Regulatory compliance in this instance is the requirement that the operating agency comply with industry standards, including federal, state, and local regulations. This category also recognizes the importance of adherence to proper procedures and good industry practices.
- Public health and safety (PHS) - This attribute addresses adverse effects on the health and safety of the public. The "public" is defined as patrons of the system and the community.
- Worker health and safety (WHS) - This attribute addresses adverse effects on the health and safety of the workers who are transit system employees or contractors.
- Public perception (PP) - Public perception is the general goodwill on the part of the public toward the transit system. This is based on personal experience or experiences related by others.
- Facilities/equipment damage (FED) - This considers the damage to facilities and equipment.
- Operational impact (OI) - Operational impact is the effect of any project on the ability to continue with little or no disruption to service in both station and transit operation.
- Legal liability (LL) - The legal liability is the result of litigation following an incident involving damage to persons or equipment.
- Management resources (MR) - Management resources are the resources required to carry out the improvements. This includes additional staffing requirements while construction or temporary work are in effect. Also, this includes the increase in staff needed to implement any procedural changes.
- Environmental impact (EI) - The environmental impact is the effect of projects and improvements on the surroundings. It includes those that could result in physical degradation of the ecological system.

The next step was to create a square reciprocal matrix for the above attributes to facilitate the pairwise comparisons. The matrix is shown in Figure 2.

	RC	PHS	WHS	PP	FED	OI	LL	MR	EI
RC									
PHS									
WHS									
PP									
FED									
OI									
LL									
MR									
EI									

Figure 2 - Attribute Matrix

The matrix in Figure 2 was used to collect pairwise comparison data from several different individuals. The attributes and the pairwise data was then entered into the AHP module. The data was checked for consistency, and the screening process was initiated. Several iterations were performed before the critical set of decision-making attributes was obtained. Four of the above attributes were screened out leaving the following five:

- Regulatory compliance
- Public health and safety
- Worker health and safety

- Facilities/equipment damage
- Operational impact.

In addition to the screening, the AHP module provided the relative weights of the critical set of decision-making attributes.

The next step was to determine the inference factors for the attributes. In this case, it was found that the critical set of decision-making attributes could be adequately described by two inference factors: the attribute-specific severity and likelihood. These were further divided into scales. Each attribute was assigned its own scale for the severity. However, it was found that for the likelihood, one scale was applicable to all of the attributes.

The next step was to evaluate the utility of each alternative for both baseline and residual conditions (i.e., conditions following execution of the proposed improvement project). This was done by assessing the risks corresponding to each attribute for each alternative, and for both conditions. The risks were assessed by assigning an inference factor scale value to each attribute. This was done for each attribute, each alternative, and for both conditions.

This information, along with cost data for each alternative, was then entered into the MAU module for the utility analysis. For each alternative, the module calculated a change in utility (i.e., benefit) by subtracting the residual utility from the baseline utility. The benefit-to-cost ratio was then formulated by dividing the change in utility by the cost of the alternative. Alternatives were then prioritized, or rank-ordered, based on the benefit-to-cost ratio. The benefit-to-cost ratio evaluates the alternatives based on their cost-effectiveness. The higher the ratio, the higher ranking of the project.

The results of the analysis for the sample case show that the hybrid decision analysis technique is a very useful tool. It simplifies the process of prioritizing alternatives when multiple attributes are involved. In addition, the AHP and MAU modules were easily adapted to the example and were very effective in accelerating the prioritization process.

Summary and Conclusions

This paper presents a methodology which allows a decision-maker to prioritize a large number alternatives while considering a wide array of objectives. This methodology is a risk-based decision technique that combines the advantages of the Multiattribute Utility (MAU) Theory and Analytical Hierarchy Process (AHP).

The straight forward nature of AHP allows it to be used efficiently as a screening tool for the initial set of objectives (i.e., attributes). Once the critical set of attributes is determined, AHP is then used to determine the decision-maker's opinions of each attributes importance relative to the other attributes (i.e., relative weights).

MAU is then used to assess the risk-benefit for each alternative by aggregating the change in utility (i.e., risk) values of the different attributes. The aggregated utility values are then used to calculate a cost/risk-benefit ratio. These ratios can then be used to prioritize the alternatives based on their cost/risk-effectiveness.

When multiple attributes are involved, this methodology was found to be very useful as a decision tool in prioritizing alternatives. Applying AHP to screen and weight the decision-making attributes simplifies the utility analysis. Using MAU to evaluate the risk-benefit is then a straight forward process. It is then a simple procedure to determine the cost/risk-benefit ratio and the prioritization of the alternatives.

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