Selection of Preferred Pavement Design Alternative Using Multiattribute Utility Analysis

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Pavement design requires the specification of design criteria, the generation of feasible alternatives, the consideration of trade-offs, and the selection of the best overall choice. Pavement design alternatives typically present the engineer with unavoidable trade-offs between initial cost, maintenance cost, and design life. These trade-off decisions entail a great deal of complexity and controversy, making it difficult to select the alternative that might be the best. A rigorous decision-analytic method that can be used to compare alternatives, multiattribute utility analysis (MAUA), is described, and its advantages over two traditional approaches, life-cycle costing and weighting methods, are described. An example that illustrates a pavement design selection problem in which alternatives present the designer with trade-offs between initial cost, maintenance cost, construction flexibility, and pavement life is presented, thus demonstrating the applicability of the MAUA approach.

When designing either a new or a rehabilitated pavement section, it is recommended that a number of feasible design alternatives be generated, with each meeting the design criteria yet possessing unique characteristics that influence overall project costs, constructability, and performance. The skeleton of the preferred alternative can be extremely complex, because various design attributes must be weighed one against another, generally requiring that trade-offs be made between such fundamental characteristics as initial cost, maintenance costs, and long-term performance. The preferred alternative is that which maximizes the overall perceived benefit at the lowest total cost or, in other words, that provides the greatest value. For example, a project with a low initial cost may have a significantly shorter expected life and higher maintenance costs than an alternative with higher initial costs. Thus a decision that maximizes the perceived value of low maintenance costs and longer life against higher initial cost must be made. Because of the complexity and controversy surrounding such a selection process, a systematic and defensible approach must be adopted (*1*).

Life-cycle costing and weighting methods are the two most common approaches to this problem. Other decision-aiding methods commonly used in other industries, but not often applied in pavement engineering, include multiattribute utility analysis (MAUA), fuzzy set theory, and analytic hierarchy process. Described in this paper are the life-cycle and weighting approaches, with emphasis placed on methodology, advantages, and limitations. MAUA is then introduced and illustrated through the use of an example problem. It is argued that because of its ability to systematically accommodate nonmonetary factors and nonlinear preferences and to address interactions between the design attributes, MAUA offers a powerful alternative to the two traditional approaches.

METHODS

A number of methods are currently used to select from among many feasible alternatives. Simple nonsystematic approaches, such as always selecting the alternative with the lowest initial cost or the alternative that has always been constructed in the past, is poor engineering practice and can potentially lead to much higher total costs and poorer overall performance (*1*). Therefore a systematic approach such as life-cycle costing, weighting, or another formal decision-aiding procedure is often applied.

Life-Cycle Costing Methods

Life-cycle costing is based strictly in terms of monetary value, and is thus purely an economic analysis of the various cost components involved in the construction, maintenance, rehabilitation, and salvage of a pavement structure over the analysis period. According to Winfrey and Zeller (*2*) the basic purpose in applying an economic analysis is to achieve the desired goals with the maximum satisfaction obtainable at a given cost or to achieve a defined goal at a minimum cost. More specifically, Peterson (*3*) states that "Engineering economics generally provides a type of formal analysis where the time value of money is considered and where the analysis adheres to well-organized procedures. The basis for the comparison is monetary, and all inputs and outputs must be assigned a monetary value. The effects of time are addressed through the application of a discount rate, which is used to normalize all costs and benefits to a given time period.

Life-cycle cost analysis should include all costs anticipated over the life of the facility. Entering common usage in the early 1970s, the method is a key element in any contemporary discussion of economic analysis as applied to pavements (*3–6*). The concept has been accepted by FHWA, FAA, and most state highway agencies. According to a 1984 FHWA policy statement (*7*), "The economic analysis of design alternatives should be made on the basis of life-cycle costs, which encompass all the costs associated with constructing, maintaining, and rehabilitating the pavement over the analysis period being used."

Cost Components

In a recently completed study, 41 North American transportation agencies reported using an economic analysis in their selection of the preferred pavement design alternative (*3*). The cost components

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included in the analysis varied from agency to agency, with 9 including design costs, 40 including initial construction costs, 26 including maintenance costs, 31 including rehabilitation costs, 12 including salvage value, and 3 including user costs. The results of that study indicate that the application of life-cycle costing techniques is not universally applied and that in the majority of the current approaches all associated costs are not included.

This is in contrast to recommended practice. According to the *AASHTO Guide for Design of Pavement Structures,* (*4*), the major and recurring costs that should be considered in the economic evaluation of alternative pavement strategies include the following:

1. Agency costs
   –Initial construction cost
   –Future construction or rehabilitation cost
   –Maintenance costs
   –Salvage value
   –Engineering and administration costs
   –Traffic control costs
2. Cost to the highway user
   –Travel time
   –Vehicle operation
   –Accidents
   –Discomfort
   –Time delays and extra vehicle operating costs incurred during rehabilitation

This basic breakdown of relevant costs is echoed by other sources (*3,8,9*).

When they are estimating costs most agencies can closely estimate the initial construction cost, engineering and administration costs, and traffic control costs, but they are less certain when they are estimating the timing and costs of future maintenance and rehabilitation. Additionally, the salvage value of the pavement at the end of the analysis period is also difficult to assess. Even greater uncertainty arises when estimating user costs. Epps and Wootan (*9*) state that it is most common only to include initial construction costs, rehabilitation costs, maintenance costs, and salvage value when conducting a life-cycle cost analysis, including user costs only on certain facilities where the impact on the user warrants consideration. Although this simplifies the procedure, it can lead to the selection of alternatives that have higher user costs throughout the analysis period.

By not including all relevant costs and through poor estimation of timing and the costs of the various components that are included, the results of the life-cycle costing procedure can be controversial. If it is perceived that the life-cycle costing procedure unfairly favors one design alternative over another, a transportation agency may find itself in a damaging fight to verify the veracity of its assumptions. Because the difficulties involved in this process are generally recognized, it has forced many agencies to adopt simplistic approaches that contain only cost components that can be easily estimated, neglecting such important components as maintenance, rehabilitation, and user costs.

Discount Rate

Another area of controversy surrounds the discount rate chosen for use in the analysis. According to AASHTO (*4*):

> The discount rate is used to adjust future expected costs or benefits to present day value. It provides the means to compare alternative uses of funds, but it should not be confused with the interest rate, which is associated with the cost of actually borrowing money.

There is a general agreement that the discount rate should be the difference between the market interest rate and inflation using constant dollars (*4*). Epps and Wootan (*9*) suggest the use of a "discount rate of return of 4 percent . . . when constant dollar are used to estimate future rehabilitation and maintenance costs and salvage value," because the "real long term rate of return on capital has been between 3.7 and 4.4 percent since 1966. The value of 4 percent is also endorsed by Peterson (*3*). Oglesby and Hicks (*10*) mention that 4 percent has been estimated by some individuals for government investment, but that higher minimums would be appropriate when the risk is higher. It is further stated that the decision regarding discount rates "has a tremendous influence on the results of economy studies," and therefore the discount rate should be chosen carefully (*9*).

For example, if a low discount rate is selected, design alternatives with lower anticipated future costs will become more appealing. This is because all future costs, such as the costs of maintenance and rehabilitation, are discounted according to the discount rate, with a lower rate resulting in less discounting. If the discount rate was 0 percent, all cost in the analysis would simply be summed, with no adjustment made for the time value of money. The issue is further clouded by the fact that transportation agencies are not in a position to either spend the money now or invest it for future use. Instead, they spend what is appropriated in the present year and hope that in the next year things will not get worse but instead will remain constant or improve slightly. Thus some argue that the discount rate used for transportation projects should more accurately reflect the type of funding and not the discount rates commonly applied to commercial industry.

Advantages

Some advantages of life-cycle costing are that (*a*) it is a systematic, theoretically sound method for examining all of the costs incurred during the life of a pavement structure; and (*b*) through the use of the discount rate the time value of money is accounted for.

Limitations

Some of the limitations of the life-cycle costing procedure are as follows:

- The procedure cannot accommodate nonmonetary factors such as the availability of materials, contractor expertise, agency policies, worker safety during construction, and incorporation of experimental features.
- The accuracy of the estimation of each cost component varies from good (i.e., design and initial construction costs and timing) to poor (i.e., maintenance, rehabilitation, and user costs and timing). Because each cost component has a potentially large impact on the selection of the preferred alternative, that lack of confidence in any estimation is of concern. The use of pavement management will improve the estimations, yet because of inherent variability in pavement structures it is not likely that accurate predictions of pavement

maintenance and rehabilitation needs will be easily forecast in the foreseeable future.

- The procedure treats all costs as if they are considered to be equally important. Thus, it does not address issues of cost distribution, equally weighting user costs with agency costs. Because many agencies are far more concerned with their own costs than those incurred by the user, this may not be desirable. Additionally, initial and rehabilitation costs are generally financed with federal participation, whereas maintenance activities are not. Thus, a transportation agency may desire to more heavily weight maintenance costs, a situation that is not possible under standard life-cycle costing procedures.
- The selection of the discount rate is very important because it can result in the selection of different alternatives if one discount rate is chosen over another. Some advocate that a sensitivity analysis be used to determine the effect of the discount rate, yet if the selection process is found to be highly sensitive, the agency must still make a decision based on a single rate.

Weighting Methods

Weighting methods attempt to address some of the limitations of life-cycle costing through the introduction of nonmonetary factors and a weighting/rating scheme. A weighting method can be used to either supplement the life-cycle costing approach or replace it.

Procedure

The following is a procedure used by one state agency (*1*):

1. Generate alternative designs over a given analysis period.
2. Develop critical design attributes for the selection of the preferred alternative. An example is presented in Figure 1, which includes the design attributes of initial cost, duration of construction, service life, repairability and maintenance effort, rideability and traffic orientation, and proven design life. Note that most of these factors are non-monetary and therefore could not have been included in a life-cycle costing analysis.
3. Each design attribute is assigned a weighting factor on the basis of its perceived relative importance in the design selection process. The weighting factors given in Figure 1 are presented as percentages, with the sum of the weighting factors totaling 100 percent. It is recommended that the decision makers be directly involved in the selection of these weighting factors, because they have a large impact on the resulting selection process.
4. Conduct any analyses required to calculate the attributes.
5. Each alternative is rated independently against the decision attributes by using a selected scale (such as 0 to 100 used in the example in Figure 1). The rating should be conducted for each alternative within a design attribute before moving on to the next attribute. This rating is then placed in the upper left-hand triangle as shown in Figure 1.
6. The assigned ratings are then multiplied by the weighting factors assigned to each attribute, and the values are placed in the lower right-hand triangle in each cell. The total rating for each alternative is then determined by summing the values in the lower triangles across all the attributes. The alternative with the highest total rating is selected as the preferred alternative. In the example in Figure 1, Alternatives 1 and 1A ranked the highest, with ratings of 80.5.

Advantages

The advantages of the weighting method over life-cycle costing include the following:

- Nonmonetary design attributes can be included in the analysis. This allows the use of more generic classification of difficult-to-quantify costs, replacing monetary values with a rating scale. For

	Criteria								
	Initial Cost	Duration of Construction	Service Life	Repairability & Maintenance Effort	Rideability & Traffic Orientation	Proven Design in State Climate		Total Score	Rank
Relative Importance	20%	20%	25%	15%	5%	15%		100.0	
Alternative 1	60 12	60 12	100 25	80 12	90 4.5	100 15		80.5	1
Alternative 2	60 12	60 12	100 25	80 12	90 4.5	100 15		80.5	1
Alternative 3	60 12	60 12	70 18	50 7.5	60 3	40 6		58.0	5
Alternative 4	60 12	60 12	70 18	50 7.5	60 3	40 6		58.0	5
Alternative 5	60 12	40 8	100 25	80 12	100 5	90 14		75.5	2
Alternative 6	60 12	80 6	40 10	20 3	40 2	20 3		44.0	8
Alternative 7	40 8	60 12	40 10	50 7.5	50 2.5	30 4.5		44.5	7
Alternative 8	70 14	80 16	60 13	50 7.5	80 4	40 6		60.0	4
Alternative 9	100 20	100 20	20 5	20 3	40 2	40 6		56.0	6
Alternative 10	30 6	60 12	100 25	100 15	100 5	30 4.5		67.5	3

FIGURE 1 Example of weighting method (*1*).

example, instead of trying to estimate specific maintenance costs, it would be possible to assign each alternative a ranking such as low, medium, or high maintenance costs.

- Monetary design attributes can be weighted to reflect their relative importance to the agency. This can be used to address some of the concerns related to sources of funding (i.e., local versus federal) as well as agency costs versus user costs.
- This procedure helps an agency to define which attributes are really important and which are not. If the procedure is conducted in groups, as recommended, all of the decision makers can work together, allowing a balanced decision criterion to be established. Additionally, this procedure is conducive to a sensitivity analysis, allowing weighting factors as well as individual ratings to be varied to assess their impacts on the selection process. This not only helps in developing a systematic approach but also helps in defending the approach if required.

Limitations

Although a weighting system addresses many of the limitations that exist within the life-cycle costing approach, a number of limitations still exist, including the following:

- The establishment of weighting factors in this procedure is somewhat arbitrary and may not accurately reflect the true preferences of the decision makers. Thurston (*11*) has shown that assignment of weighting factors to reflect relative importance can lead the designer to develop and select inferior alternatives.
- When establishing the rating for each alternative, it is important that a scale that represents the entire feasible range of the attribute is established. A systematic procedure should be used to establish consistency throughout the rating and to eliminate biases. This is difficult, as biases are easily introduced into the rating process because each design alternative is being rated one after another in an open format.
- The weighting method might not accurately establish the preference function because preference is assumed to be linear over the entire range of the attribute. Considerable research has shown that this assumption is not correct, because preference is most commonly nonlinear (*12*). Additionally, without the use of a systematic methodology, preference may actually be discontinuous or inconsistent, resulting in ambiguous results.
- Interactions that may occur between attributes are not readily identifiable, possibly leading to confusing results.

These limitations can only be addressed through application of more sophisticated decision analysis tools.

MAUA

A number of decision analysis tools are currently in use to assist in the decision-making process. These methods include fuzzy set theory, analytic hierarchy process, and MAUA. Only MAUA will be considered in this paper.

General Description

MAUA is a systematic, theoretically based decision-aiding procedure. It rests on a number of axioms that state that preferences exist, that they are transitive, that preference is monotonic over the domain of interest, that probabilities of outcomes exist and can be quantified, that preferences are linear with probability, that ranking of preferences over any pair of attributes is independent of the other attributes, and that the utility function is independent (*13,14*). A detailed description of these axioms and their implications has been provided previously (*11*). It is noted that if the basic axioms can be met a MAUA can be conducted.

A key element of this type of analysis is the concept of utility. Utility is simply a way of establishing value through ranking the order of relative preference between sets of consequences, of benefits and costs (*12*). What makes it extremely useful is that its units have meaning relative to each other, sharing a common metric. Thus it is possible to evaluate choices analytically, even if preference is nonlinear, as illustrated in Figure 2. Additionally, the use of a common metric allows for various utility functions from separate attributes to be combined and analyzed through a MAUA. In general, the utility scale is set between 0 and 1, with 0 having the least acceptable preference offered by any given attribute.

A MAUA requires that a set of design criteria or attributes be established and that single-attribute utility functions be determined, and the various single-attribute utility functions are then combined to calculate the multiattribute utility for any given design alternative. This procedure is easily computerized and extremely flexible, allowing a wide range of monetary and nonmonetary attributes to be considered.

Procedure

The following is the recommended procedure for conducting a MAUA (*13*):

1. Specify a set of design attributes that accurately represents the entire design problem. Once the design attributes are selected, the upper and lower ranges of interest are established, as are the most and least preferred tolerable extremes.
2. Verify preferential independence for the selected attributes. It is recommended that a few pairs of two attributes be ranked, and then determine if changes in the ranking would occur through vari-

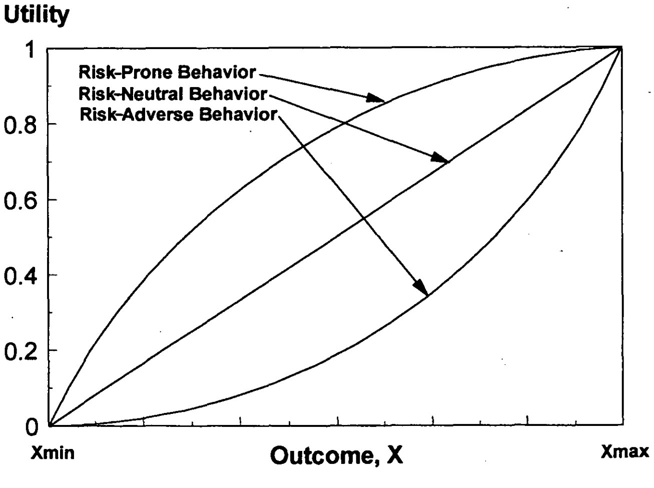

FIGURE 2 Nonlinear preference functions (*12*).

ations in the levels of other attributes. This process should be repeated for each two pairs of attributes. If no change in ranking is reported, preferential independence can be assumed.

3. Single-attribute utility functions are established through a series of questions that force the decision maker to choose between certainty and a lottery. A lottery is simply a condition in which chance is introduced through the use of probabilities. For example, a simple binary lottery is illustrated by the condition in which there is a 50 percent chance of receiving $1,000 or a 50 percent chance of receiving nothing. To assess a decision maker's utility, such a lottery is generally compared with a certainty, such as $500. The decision maker is then asked to choose either the certainty or the lottery or to state indifference. A lottery can also be compared with a lottery to obtain the same result. If preference exists, the conditions of the problem are reformulated by changing either the amount of the certainty or the probabilities of the outcome in the lottery until indifference is obtained. Through careful construction and execution of the problem, the utility function of the decision maker can be assessed over the entire feasible range of each attribute. This procedure, although it sounds complex, is straightforward and quickly accomplished when conducted by someone familiar with MAUA.

At the conclusion of this process a single-attribute utility function is determined for each attribute. These functions model the decision maker's preferences, indicating where riskadverse, riskneutral, and riskprone behaviors exist.

4. After obtaining the single-attribute utility functions, the scaling factors (k_i) used to relate the attributes are determined through the use of a certainty-lottery approach. The method used sets the certainty equivalent to the most preferred value for the attribute in question, whereas all other attributes are set at their least preferred value. A binary lottery is then constructed. The binary lottery has as one outcome all attributes set at their most preferred value and as the other outcome all attributes at their least preferred value. The probability of obtaining the preferred outcome is varied until indifference is reached between the certainty and the lottery. This probability is the scaling factor.

5. The next step is calculation of the normalizing parameter K (*14*):

$$K + 1 = \Pi (Kk_i + 1) \tag{1}$$

The normalizing factor ensures consistency between the numerous single-attribute utility functions and the multiattribute utility function so that the multiattribute utility will always lie between 0 and 1.

6. Determination of the multiattribute utility is done by using the following formula (*14*):

$$KU(X) + 1 = \Pi [Kk_i U(X_i) + 1] \tag{2}$$

The multiattribute utility [$U(X)$] is determined from the normalizing factor (K), the individual scaling factors (k_i), and the individual single attribute utilities [$U(X_i)$]. In an analysis of multiple alternatives the actual design values are used to determine the single-attribute utility for each attribute. These are then used to compute the multiattribute utility for each design. The design alternative with the highest utility is then selected as the most preferred.

Advantages

MAUA shares many of the advantages that the weighting system has, with the following additional strengths:

- MAUA allows for all attributes to be treated independently, minimizing bias in the analysis. It is much less susceptible to bias than the weighting method.
- The entire procedure is systematic and theoretically sound, and thus as long as the axioms are met, consistent results will be obtained.
- MAUA encompasses the entire tolerable range of each design attribute and is thus not sensitive to preexisting alternatives. Thus it is easy to evaluate additional designs after the initial analysis has been completed.
- The procedure is easy to computerize. This not only allows for ease of use but also permits a sensitivity analysis to examine how sensitive the recommendation is to changes in the scaling factors and the values of individual attributes.
- Nonlinear preferences are systematically integrated into the design selection process. This is one of the major advantages of MAUA.
- Because of the rigorous procedure interactions between attributes are quantified.
- Uncertainty in expected attribute performance can be accommodated by calculating expected utility.

Limitations

The following are limitations of MAUA:

- The rigorous procedure requires that an individual trained in MAUA be involved in the process. This is most critical initially, but as an agency develops in-house expertise, the need for outside assistance would diminish.
- The time required to set up the problem, assess utility, and complete the analysis makes this technique difficult to use in situations in which an answer is required immediately. This is not believed to be a constraint in the selection of the preferred pavement design alternative.

EXAMPLE OF MAUA IN PAVEMENT DESIGN SELECTION

MAUA can be used in the design selection process both for new construction and for rehabilitation. The example presented below is based on an ongoing project examining how MAUA can be used in conjunction with historical performance data to select the preferred new pavement design alternative.

Problem Statement

This illustration is based on historical distress data collected on low-volume pavements. The pavement sections evaluated in the study are distributed over a wide geographical area, providing an interesting mix of different pavement types subjected to varying climatic conditions.

All pavement sections were designed by a standardized design procedure. Depending on the layer thicknesses and the materials used, three distinct pavement types were identified. For the purpose of this illustration they are simply labeled ALT1, ALT2, and ALT3. As expected, each alternative has unique characteristics that result in different initial costs, maintenance requirements, and anticipated useful life.

The orientation of the region under study results in significant climatic differences, with the northern region receiving more severe winter weather and the southern region having hotter summer conditions. Pavement performance is dramatically affected by climate, and to reflect these differences the study area was divided into three separate climatic regions.

Pavement condition data have been collected since 1980. Inspections were conducted on a 2-year cycle, meaning that each airport was inspected once every 2 years. The data collected were in accordance with the pavement condition index (PCI) procedure (*15*).

The PCI is a numerical rating between 0 and 100, with a rating of 100 corresponding to a pavement in perfect condition. A rating of 0 would be given to a pavement that is impassable. Typically, the range in PCI values lies between 50 and 100, with 50 being considerably below acceptable condition levels. In the present study the administrative agency considers a pavement having a PCI below 70 to be near the end of its useful life and in need of rehabilitation.

Because these procedures are well documented and repeatable, the rate of pavement deterioration can be monitored year after year. These data can then be used to program rehabilitation and monitor the effectiveness of various construction and maintenance techniques related to improving pavement life.

The PCI data were used to estimate pavement life for the three pavement types in each of the climatic regions previously identified. Only pavement sections that have not been previously rehabilitated were considered. The results of this analysis were used to develop regression models of PCI versus age for the various pavement type-climatic region combinations. Both linear and nonlinear regression techniques were applied. For the purpose of demonstrating MAUA in this illustration, the linear models were considered to be adequate. The predicted pavement lives for each pavement type in each climatic region are provided in Table 1.

MAUA

After identifying the problem a MAUA was conducted to determine which pavement type provided the greatest utility for each climatic region. This analysis consisted of identifying attributes, determining single-attribute utility functions, conducting the MAUA, and running a sensitivity analysis.

Design Attributes

A great number of design attributes were initially considered for this illustration, including soil strength, aircraft weight, number of aircraft repetitions, and pavement functional use, to name but a few. For matters of simplification the list of relevant attributes was reduced to four: pavement life, initial cost, annual maintenance costs, and construction flexibility. It is noted that in a real application additional attributes would likely be required. This would not add significantly to the complexity of the MAUA analysis

Pavement Life As discussed previously pavement life is considered to be one of the most important design attributes. The longer the pavement serves traffic at a high condition level the more value is obtained. The administrative agency desires to design and construct pavement sections that continue to perform adequately for the design period.

TABLE 1 Tabulation of Design Attributes

		Attribute Levels Set for Each Alternative			
Climatic Region	Pavement Type	Pavement Life (Yrs)	Initial Cost ($/m2)	Maintenance Costs($/m2/yr)	Construction Flexibility
Northern	ALT1	14	29.30	0.16	2
	ALT2	12	32.85	0.12	5
	ALT3	16	34.00	0.07	0
Central	ALT1	8	27.00	0.21	2
	ALT2	20	29.30	0.08	5
	ALT3	40	30.50	0.02	0
Southern	ALT1	10	24.65	0.19	2
	ALT2	16	27.00	0.09	5
	ALT3	40	29.30	0.03	0

Through examination of the pavement condition data this attribute range was set from 5 to 40 years. A 5-year pavement life was considered to be the minimum expected reasonable age, and a 40-year life was about the maximum life one could hope to obtain. It is noted that in some cases pavement lives have been recorded outside this range, particularly for some of the long-lived sections recorded in the central and southern climatic regions. Although this is true the established range is representative of the minimum and maximum expected pavement lives and thus was used. The estimated life for each pavement alternative in each climatic region is listed in Table 1.

Initial Cost Another important attribute was initial cost. Measured in dollars per square meter of pavement surface, this attribute is the cost of initial pavement construction, not including markings, electrical work, or excessive groundwork. Through review of construction bid tabulations for 1991 and 1992 and discussions with agency personnel, the range of this attribute was set at $23.50 to $35.20/m^2. This range covers the wide spectrum of construction types as well as regional and local variations that occur owing to labor rates, competition, and material availability. Listed in Table 1 are the initial costs used in this illustration.

Maintenance Costs The agency considered this to be a very important attribute, because pavement maintenance is the responsibility of the local managing authority, which is typically financially strapped. Through examination of agency records, $0.00 to $0.24/m^2/year was estimated as a feasible range of annual maintenance expenditures for these types of pavements. The maintenance costs established for use in this illustration are listed in Table 1.

Construction Flexibility Construction flexibility was established as an attribute in an attempt to account for the advantage of some pavement types that allow staged construction. An arbitrary range was established with a minimum value of 0, indicating little flexibility, to 5 for pavement types offering maximum flexibility. The values chosen for this illustration are listed in Table 2.

Single-Attribute Utility Functions

After establishing the attributes and their ranges a certainty equivalent-lottery procedure was prepared and administered to two

TABLE 2 Results of Single-Attribute Utility Analysis

Attribute	Single Attribute Utility Functions	Scaling Factors
Pavement Life	$U(X_{pl}) = -0.413 + 0.110X - 0.00397X^2 + 0.0000523X^3$	0.7
Initial Cost	$U(X_{ic}) = 1.831 - 0.00159X - 0.00198X^2$	0.2
Maintenance Costs	$U(X_{mc}) = 1.002 - 2.344X - 13.102X^2$	0.5
Construction Flexibility	$U(X_{cf}) = 0.00172 + 0.0248X + 0.112X^2 - 0.00153X^3$	0.05

senior agency personnel. At the onset of the interview utility independence was established between the attributes. The results of the certainty equivalent-lottery procedure were used to establish the single-attribute utility functions summarized in Table 2. Note that in all cases the preference functions were nonlinear.

Scaling Factors

The scaling factors presented in Table 2 were determined by using a certainty equivalent-lottery approach. Because they do not sum to 1 the multiplicative form of the MAUA was used.

MAUA

The normalizing parameter K was calculated to be -0.7684 by Equation 1. The multiplicative form, shown in Equation 2, was then used to conduct the MAUA. The results of the analysis are presented in Table 3. These results suggest that the ALT3 pavement type is providing the best overall utility for all climatic regions. The difference is most evident in the central and southern climatic regions, where its estimated long life and low maintenance costs dominate the utility analysis. In the northern climatic region, the difference is not as dramatic, yet the ALT3 option enjoys a sizable utility advantage over the other two pavement types.

Sensitivity Analysis

A sensitivity analysis was conducted to examine the effect of changing the values of the various attributes and the scaling factors on the outcome of the MAUA.

Pavement Life Pavement life was varied for each pavement type in each climatic region to determine at which point the ranking of the alternatives changed. In the northern climatic region, the ALT1 pavement would need to have an increase in life from 14 to 27 years before its total utility became greater than that of the ALT3 pavement. The ALT2 option would need an increase from 12 to 19 years to overtake the ALT3 pavement type in overall utility. For the ALT3 pavement to have less utility than the next closest alternative, life must decrease from 16 to 10 years. These results indicate that significant changes in anticipated pavement life are required before either the ALT1 or the ALT2 pavement options are more highly ranked than the ALT3 option.

TABLE 3 Results of MAUA

		Single Attribute Utilities				
Climatic Region	Pavement Type	Pavement Life	Initial Cost	Maintenance Costs	Construction Flexibility	Multi-Attribute Utility
Northern	ALT1	0.499	0.554	0.417	0.376	0.580
	ALT2	0.431	0.235	0.637	1.0	0.601
	ALT3	0.552	0.120	0.814	0.0	0.684
Central	ALT1	0.243	0.748	0.116	0.376	0.374
	ALT2	0.626	0.554	0.774	1.0	0.768
	ALT3	1.0	0.452	0.950	0.0	0.946
Southern	ALT1	0.346	0.925	0.292	0.376	0.502
	ALT2	0.552	0.748	0.731	1.0	0.741
	ALT3	1.0	0.554	0.920	0.0	0.946

In the central and southern climatic regions the analysis was even more robust. Even if the ALT1 and ALT2 lives were maximized to 40 years no change in ranking would occur. If the ALT3 pavement life were reduced from 40 to 14 years the ALT2 option would become the preferred choice.

The impact of the scaling factor k_{pl} was evaluated by raising and lowering it from 0.5 to 0.9, a range selected as representative of possible extremes. It was found that no change in rank occurred in any of the climatic regions.

Initial Cost The initial cost sensitivity analysis indicated that within the range of the attribute, even if the initial cost for either the ALT1 or the ALT2 option were minimized or if the ALT3 initial cost were maximized, no change in the ranking would occur. Only in a situation in which the ALT3 initial cost was maximized and the ALT2 initial cost was minimized would a change in rank occur.

A sensitivity analysis for the scaling factor for initial cost, k_{ic}, was also conducted. This analysis varied k_{ic} from 0.1 to 0.5. This did not result in any change in rank in any of the climatic regions.

Maintenance Costs The sensitivity analysis indicated that maintenance costs could have an impact on the results of the MAUA in extreme instances. For example, in the northern climatic region a reduction in annual maintenance costs from \$0.16 to \$0.08/m^2/year for ALT1 pavements or from \$0.12 to \$0.05/m^2/year for ALT2 pavements would change the ranking. A change would also occur if the ALT3 maintenance costs were raised from \$0.07 to \$0.14/m^2/year. Once again, in the central and southern climatic regions the analysis is more robust, with no change in ranking observed even if maintenance costs were minimized for either the ALT1 or the ALT2 option. Only if ALT3 maintenance costs were increased to \$0.22/m^2/year would the ALT2 option have greater utility in the central climatic region.

The value for the scaling factor k_{mc} was varied from 0.3 to 0.7 in a sensitivity analysis. No change in order was observed in any climatic region as a result.

There is a great amount of uncertainty in estimating maintenance costs. Thus, further research should be instituted to better quantify this attribute. Changing it to a nonmonetary attribute, simply ranking expected maintenance costs on a 5-point scale, would address some of this uncertainty.

Construction Flexibility The MAUA was relatively insensitive to this attribute. Because this attribute already had the minimum value for the ALT3 option and the maximum for the ALT2 option, no changes in rank were incurred in any case.

A sensitivity analysis was also conducted by varying the scaling factor k_{cf} from 0.0 to 0.1. This effected no change in the order in which the pavement types were ranked.

CONCLUSIONS

Reviewed in this paper are two methods currently being used for comparison of pavement design alternatives: the life-cycle costing method and the weighting method. Examined are the procedures, advantages, and disadvantages of each, proposing that a MAUA approach can address the limitations observed while providing additional flexibility and power.

MAUA is a more sophisticated decision-making tool than life-cycle costing or weighting methods. Its advantages are that it can deal with both monetary and nonmonetary attributes, reflect nonlinear preferences over an attribute range, accurately measure a willingness to make trade-offs between attributes, and incorporate the decision maker's attitude toward risk. These benefits come at the cost of an increased level of analytic effort during the alternative comparison stage of pavement design. The motivation for developing MAUA was that simpler methods did not yield satisfactory results. As with any engineering analytic tool, it is up to the designer to determine whether the complexity of the decision problem warrants the extra effort that MAUA entails. The theoretical underpinnings of the MAUA were developed years ago, but it is only with the recent availability of microcomputers that widespread implementation has been feasible.

The approach facilitates organized, logical, depoliticized discussion, either in technical group decision making or in a public forum. It does this by disaggregating the problem into separate components on which diverse interests can reach consensus; performance is first separated from any particular alternative, and minimum performance criteria are established and separated from negotiable performance attributes, which in turn are dealt with separately from trade-off issues.

An illustration was presented to demonstrate the feasibility of the MAUA approach. It was shown that some of the limitations encountered in the selection of the preferred design alternative by using the more common methods can be addressed while adding additional flexibility. The initial experience with this methodology is favorable, and it is hoped that this effort can be expanded to incorporate a wider selection of design attributes.

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