THE SELECTION OF BRIDGE MATERIALS UTILIZING THE ANALYTICAL HIERARCHY PROCESS

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ABSTRACT

Effective decisions on the use of natural resources often require the input of many individuals. Determining how specific criteria affect the selection of materials can lead to better utilization of raw materials. Concrete, steel, and timber represent over 98% of the materials used for bridge construction in the United States. Highway officials must often consider alternate materials for the best application for bridges. The Analytical Hierarchy Process (AHP) was used to characterize the bridge material decision process of highway officials in selected states. State Department of Transportation Engineers, private consulting engineers, and local highway officials were personally interviewed to identify this often subjective decision and to model the selection decision for different groups of decision makers. Prestressed concrete was the material choice in the majority of cases. This was followed by reinforced concrete, steel, and timber. The most important criteria were maintenance requirements, lifecycle costs, and lifespan of material. Local highway officials chose timber more often than other highway officials.

Key Words: AHP, Steel, Timber, Concrete, Decision Making

INTRODUCTION

The need for bridge replacement has been well documented (Brungraber et al. 1987, Cheney 1986, USDA 1989, USDOT 1989). Current materials in bridges as classified by the FHWA (1992) include prestressed concrete (15%), reinforced concrete (40%), steel (37%), and timber (8%). However, since 1982, prestressed concrete and reinforced concrete have been used in over 70 percent of bridge replacements, while steel and timber represent less than 30 percent. All too often the evaluation of strengths and weaknesses of competing products

(materials) is limited to tangible characteristics such as price or physical attributes, disregarding intangibles such as perceptions and attitudes (Dickson 1974). However, it is these perceptions that often determine belief about a material, which formulate an attitude and influence the design decision.

Many factors are known to effect the choice of a bridge material. *Physical characteristics or site specific factors* include: roadway alignment, length of clear span, clearance above waterway, hydraulic capacity requirements and required loading capabilities. Yet, there are numerous *non-structural characteristics* of the material such as initial cost, maintenance requirements, and others (Table 1) that also may influence this decision. These are the areas which manufacturers can address in trying to influence the choice of bridge material by design engineers.

Scott and Keiser (1984) state that much of the research that is done in industrial markets to identify and evaluate new opportunities is qualitative and unstructured. We demonstrate in this study that quantitative and structured analysis of decision makers can be a useful tool for understanding customers and their perceptions. We develop a behavioral model of bridge material selection for several states and for several levels of decision makers. The AHP model helps us analyze how important decision criteria directly influence the overall bridge material decision.

THE ANALYTICAL HIERARCHY PROCESS (AHP)

Although various techniques exist for modelling decision making, the Analytical Hierarchy Process (AI-P) was chosen for this study. The AHP can be used as a behavioral, as well as a normative model of decision making. The Analytic Hierarchy Process, developed by Thomas Saaty in the early 1970s, allowed us to quantify and aggregate subjective opinions. Saaty (1980) states that the practice of decision making is concerned with weighting alternatives which fulfill a set of desired objectives. This multicriterion, multiperson model structures the decision process into a hierarchy. Through a set of pairwise comparisons at each level of the hierarchy, a matrix can be developed, where the entities indicate the strength with which one element dominates another with respect to a given criterion.

Harker and Vargas (1987) indicate that there are three principles used in the AHP for problem solving: (1) *decomposition* - structuring the elements of the problem into a hierarchy, (2) *comparative judgments* - generating a matrix of pair-wise comparisons of all elements in a level with respect to each related element in the level immediate y above it where the principal right eigenvector of the matrix provides ratio-scaled priority ratings for the set of elements compared, and (3) *synthesis of priorities* - calculating the global or composite priority of the elements at the lowest level of the hierarchy (i.e., the alternatives).

METHODS

To identify the most important decision factors in the material selection process, a mail questionnaire was sent to a stratified sample of bridge engineers across three decision making groups; State Department of Transportation (DOT) engineers, private consulting engineers, and local highway officials. These groups are most influential in the bridge material decision because of their involvement in the allocation of bridge replacement funds. In addition, state/local authorities are responsible for 90% of rural bridge maintenance and replacement decisions (USDA 1989).

In order to understand why the adoption of bridge materials varies between regions of the United States, five discrete geographical areas were utilized for this study. These regions were Northwest, South, Mid-Atlantic, Northeast and Midwest. These five areas accounted for over 70% of bridges replaced since 1982 (FHWA 1992) and include 28 states. To establish a representative sample of the various engineering groups, each region was sampled with approximately 240 decision-makers or 80 at each decision-making level.

A disguised questionnaire with a cover letter explaining the purpose of the study was mailed to 1330 engineers in April of 1993. No correspondence stated that the study was being conducted by the Department of Wood Science at Virginia Tech as it was felt that this would bias some respondents answers or have a negative affect on the response rate. A total of 848 surveys were returned, 751 which were usable, resulting in a adjusted response rate of 61%. Non-usable responses indicated that the decision-maker was not involved with bridges or the private consulting firm was no longer in business.

Once the most important factors in the decision process were identified, personal interviews were conducted in four states: Mississippi, Virginia, Washington, and Wisconsin. The purpose of these interviews was to have the different decision groups (DOT, private consultants, and local highway officials) complete an AHP questionnaire. Between 4 and 12 individuals were interviewed in each group in each state. The individual AHP questionnaires were then combined to form a group decision model for each group. These states were chosen because of their different resource base, decision making protocol, climatic conditions, geographical locations, and past history of bridge materials selection.

RESULTS

The results of the mail survey indicated that the six highest rated decision criteria included: *lifespan of material, past performance, maintenance requirements, resistance to natural deterioration, initial cost, and lifecycle cost* (Table 1). The four material alternatives for the decision were prestressed concrete, steel, wood, and reinforced concrete. Based upon this information, a AHP decision

model was built to evaluate the decision making process in four selected states (Figure 1)

Table 1. Ratings of Decision Factors

Material Decision Factor	Mean Rating	Material Decision Factor	Mean Rating
Lifespan of material (1)	5.95	Environmental concerns (13)	4.66
Past performance (2)	5.92	Inspection requirements (14)	4.65
Maintenance requirements (3)	5.84	Bridge loading variations (15)	4.56
Resistance to natural deterioration (4)	5.82	Contractors familiarity with material (16)	4.41
Initial Cost (5)	5.54	Average daily traffic count (16)	4.41
Life-cycle Cost (6)	5.51	Aesthetics (18)	4.34
Ease of repair (7)	5.25	Preference by local highway officials (19)	4.23
Standards specified in AASHTO (8)	5.24	Stimulate the local economy (20)	4.11
Time of traffic interruption(9)	5.08	Bridge ownership (21)	3.98
Designer's familiarity with material (lO)	4.86	Government research efforts (22)	3.82
Availability of design information (11)	4.85	Industry promotional efforts (23)	2.81
Resistance to de-icing chemicals (12)	4.84		

Rating Scale: 1 (below average) to 7 (above average)
Number in parenthesis indicates over-all ranking

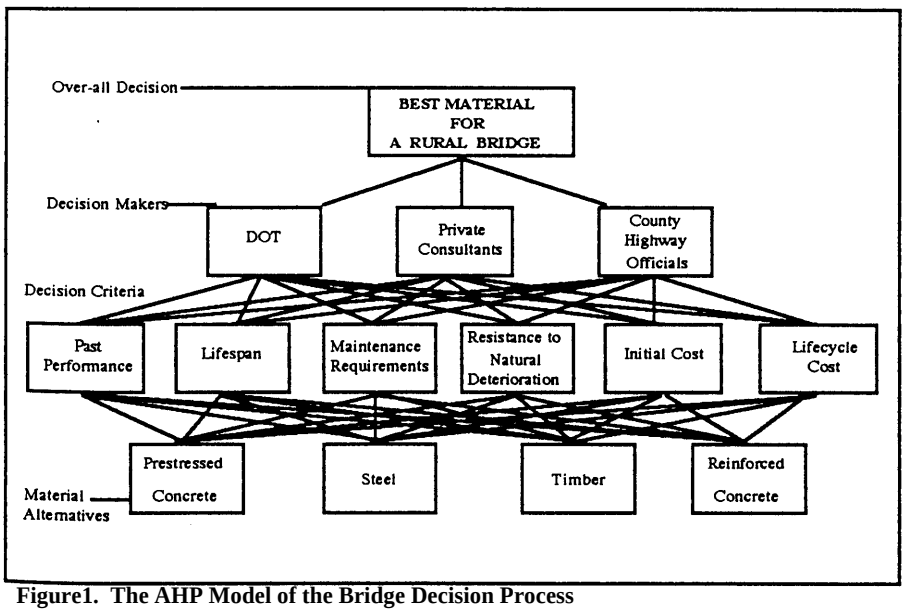

Figure1. The AHP Model of the Bridge Decision Process

To determine if the four selected states (Mississippi, Virginia, Washington, and Wisconsin) were representative of their respective geographic regions, a Multivariate Analysis of Variance (MANOVA) was calculated for the selected criteria between the individual state and its region. No significant difference (a < .05) between each state and its region on these six factors could be shown. Analysis of Variance was used to determine if the states differed from others in the respective regions based on perceptions of timber as a bridge material. Again, no statistical significant differences could be shown. These results indicate that each state is representative of the region in which it is located and should provide a good indicator of bridge decision making in that region.

AHP Calculation

To demonstrate how the AHP model was developed for each highway official, an example based on county engineers in Wisconsin is provided. In August of 1993 nine county highway commissioners/engineers agreed to participate in completing the paired comparison questionnaire used to develop the AHP decision models.

The responses were entered into a personal computer using the program Expert Choice (1992). Individual results were geometrically averaged and one composite matrix was developed. A rating scale from 1 to 9, as recommended

Table 2. Geometric Mean of Paired Comparisons of Bridge Factors as Rated by 9 Wisconsin Highway Officials.

	Pasperf	Lifespan	Maintenc	Resistance	Initial	Life-cycl
Pastperf	1.0	1.10	0.71	1.0	0.53	1.0
Lifespan	0.91	1.0	0.71	1.4	0.83	1.5
Maintenc	1.4	1.4	1.0	1.7	1.3	1.6
Resistac	1.0	0.71	0.59	1.0	0.67	0.40
Initial	1.9	1.2	0.77	1.3	1.0	1.2
Lifecycl	1.0	0.67	0.63	2.5	0.83	1.0
Total	7.21	6.08	4.41	8.90	5.16	6.70

Normalized Matrix of Paired Comparisons for Wisconsin Counties

Pastperf	0.14	0.18	0.16	0.11	0.10	0.15
Lifespan	0.13	0.16	0.16	0.16	0.16	0.22
Maintenc	0.19	0.23	0.23	0.19	0.25	0.24
Resistac	0.14	0.12	0.13	0.11	0.13	0.06
Initial	0.26	0.20	0.18	0.15	0.19	0.18
Lifecycl	0.14	0.11	0.14	0.28	0.16	0.15

by Saaty (1980), was used for the paired comparisons. The number 1 indicating that compared factors were equal in importance and 9 indicating that one factor was extremely more important than another. First, paired comparisons of importance were made between the six selected bridge criteria. Under each criteria, paired comparisons were made for preferences of bridge materials (Table 2). Calculation of a final priority vector for bridge material preference proceeds

in the following way. First, the data in the bridge criteria matrix are normalized by column. Second, the values in each row are averaged to produce a vector of priorities for each bridge criterion (Table 3).

Table 3. Vector of Priorities for Wisconsin Counties

	Total of normalized row	Average of normalized row	Vector of Priorities
Pastperf	0.84	.84/6	0.14
Lifespan	0.99	.99/6	0.17
Maintenc	1.33	1.33/6	0.22
Resistac	0.69	.69/6	0.12
Initial	1.16	1.16/6	0.19
Lifecycl	0.98	.98/6	0.16

Third, similar calculations are then repeated for each matrix of material preference under a given bridge criterion, (Example: past performance, Table 4). Upon completion of these steps, the final composite preference vector for bridge material is the matrix product of (1) the matrix composed of bridge material preference vectors and (2) the vector of bridge criteria (Fig. 2). This is the choice of bridge material for the decision maker (in this case, county highway commissioners engineers in Wisconsin) based upon the criteria measured (Fig. 3).

Table 4. Matrix of Paired Comparisons for Preferences of Bridge Materials Under the Bridge Factor (Past Performance) for Wisconsin Counties

	Prestressed Concrete	Steel	Timber	Reinforced Concrete
Prestressed Concrete	1.0	4.9	1.4	0.71
Steel	0.20	1.0	0.56	0.24
Timber	0.71	1.8	1.0	0.56
Reinforced Concrete	1.4	4.1	1.8	1.0

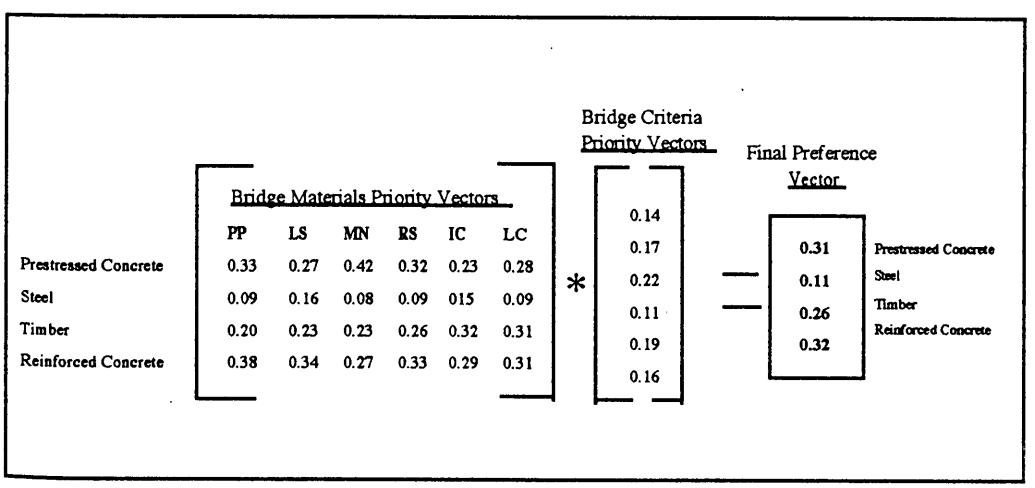

Figure 2. AHP Computation of the Final Preference Vectors

State-wide Comparisons

Table 5 summarizes the AHP models developed for each state and decision group. Individual decision models can be combined arithmetically to perform statistical analyses (Saaty 1993). To determine if differences existed between states or decision making groups, non-parametric statistical procedures were utilized. Non-parametric procedures are recommended when sample size is small or the distribution of the population from which the data is obtained is uncertain (Hollander and Wolfe 1973).

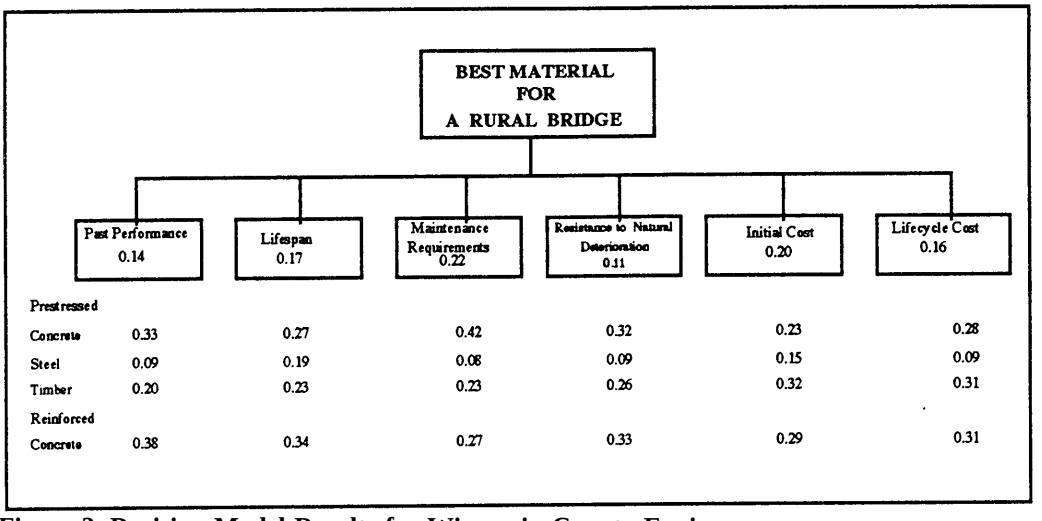

Figure 3. Decision Model Results for Wisconsin County Engineers

The importance of the six major criteria in the bridge decision were quite uniform across decision making groups and between states (Table 6). This agrees with earlier findings by the authors (Smith and Bush 1995) that major criteria are similar by groups and regions. Only for the criteria of *maintenance* did significant differences ($p = .05$) exist between the four states. This is to be expected because maintenance is strongly affected by climatic differences and local procedures.

Among the three major decision groups (DOT, private engineers, and local officials), aggregated across the four states, differences existed in the choices of steel and timber. Among the four states aggregated across the three decision groups only reinforced concrete was not statistically different. In the states of Virginia and Wisconsin differences existed between decision makers' preferences for timber. Both prestressed concrete and reinforced concrete were deemed to have different preferences across decision groups in Mississippi. Only in Washington were the preferences for bridge materials not statistically different by decision group. These results indicate that even though decision criteria are viewed similarly, the extent to which various bridge materials are perceived as meeting those criteria varies between states and between decision making groups.

Sensitivity analysis was run on each model to determine if increasing the perceived performance on one or more criteria would effect the bridge

Table 5. Summary of AHP Models by State and Decision making Level

State	Sample Size	Incon Ratio	PRE	STL	TMB	REF	PP	LS	MN	RS	IC	LC
All states in study			Priority ratings of material and decision criteria									
State DOT	29	0.01	0.44	0.15	0.07	0.33	0.16	0.17	0.20	0.16	0.13	0. 17
Private Engineers	20	0.01	0.38	0.15	0.12	0.34	0.19	0.13	0.22	0.15	0.14	0.17
County Engineers	24	0.01	0.40	0.12	0.12	0.36	0.13	0.17	0.20	0.15	0.18	0.16
Mississippi												
State DOT	5	0.05	0.53	0.15	0.04	0.27	0.12	0.19	0.21	0.16	0.17	0.13
County Engineers	8	0.04	0.37	0.14	0.08	0.41	0.14	0.11	0.17	0.19	0.19	0.12
Virginia												
State DOT	12	0.01	0.33	0.20	0.09	0.37	0.17	0.15	0.27	0.16	0.09	0.16
Private Engineers	7	0.03	0.33	0.26	0.14	0.27	0.24	0.12	0.26	0.11	0.08	0.19
Washington												
State DOT	4	0.03	0.49	0.13	0.07	0.30	0.18	0.15	0.17	0.14	0.16	0.19
Private Engineers	7	0.04	0.47	0.13	0.08	0.33	0.13	0.12	0.23	0.21	0.13	0.18
County Engineers	7	0.05	0.49	0.11	0.07	0.32	0.09	0.16	.21	0.16	0.14	0.23
Wisconsin												
State DOT	8	0.02	0.41	0.12	0.09	0.37	0.18	0.18	0.17	0.18	0.10	0.19
Private Engineers	6	0.02	0.34	0.09	0.13	0.45	0.20	0.17	0.15	0.14	0.22	0.12
County Officals	9	0.02	0.31	.11	0.26	0.32	0.14	0.17	0.22	0.11	0.20	0.16

Legend

Incon.Ratio - Inconsistency Ratio
IC - Initial Cost
LS - Lifespan
LC - Lifecycle Cost
MN - Maintenance Requirements
PP - Past Performance
PRE - Prestressed Concrete
REF - Reinforced Concrete
RS - Resistance to Natural Deterioration
STL - Steel
TMB - Timber

decision. Prestressed and reinforced concrete were rated so much higher than steel and timber, that changes in the criteria seldom resulted in changes in the decision. Only if initial cost become dominant in the decision would private consultants or local officials chose timber over steel. In no situation would Department of Transportation officials select timber based upon the six criteria mesured. Department of Transportation engineers favored prestressed concrete. This may be attributed to their exposure to state and Federal highway bridges and a lack of familiarity with timber design. Private consultants and county officials favored prestressed and reinforced concrete for rural bridges.

In Mississippi, only if *initial cost* became extremely important would county engineers consider using timber instead of steel. No changes would effect the Mississippi DOT engineers' decisions concerning timber. Private consultants in Virginia would choose timber above all other materials if *initial cost* became very important. No changes in criteria importance would affect the decision of DOT engineers in Virginia. In Washington, as *initial cost* becomes more important, local engineers and private consultants would favor timber over steel, but never over concrete. Again, no changes in criteria importance would affect the decision of Washington DOT engineers. Wisconsin highway officials would prefer timber as *initial cost* became very important and DOT engineers would favor timber over steel when *maintenance* became increasingly important. No changes in criteria importance would affect the bridge material decision of private consultants in Wisconsin.

CONCLUSIONS AND DISCUSSION

Decision making applications of this research indicate that the Analytic Hierarchy Process can be utilized in a group situation to understand material choices by customers and to assist highway officials in their choice of a bridge material. This model reflects the current bridge situation in the United States, with prestressed and reinforced concrete being the major bridge material chosen over seventy percent of the time by highway officials.

Decision makers are in good agreement about the criteria that are important in the design decision. Across the United States, these individuals rated the most important criteria similarly by region and decision group. *Maintenance requirements, initial cost, and past performance* were the most influential criteria in choosing a bridge material. However, these criteria, when applied to the AHP decision models, influenced the choice of bridge material differently. Nevertheless, prestressed concrete and reinforced concrete were the materials of choice by every group in each state.

This study illustrates how decision modelling can be used to represent material choices of a select group of decision makers. A thorough understanding of the material choice decision can allow better utilization of these natural resources and allow highway officials to make better product decisions.

Table 6. Statistical Comparisons Between Decision Making Groups and States

Kruskai-Wallis Paired Sample or One-way ANOVA P-Values						
Comparison / Criteria	**Decision-Groups[1]**	**States[2]**	**Decision-Groups within Mississippi**	**Decision-Groups within Virginia**	**Decision-Groups within Washington**	**Decision-Groups within Wisconsin**
Past performance	0.09	0.10	0.88	0.08	0.63	0.67
Lifespan	0.09	0.29	0.88	0.44	0.39	0.74
Maintenance	0.59	0.05	0.56	0.86	0.79	0.67
Resistance to natural deterioration	0.68	0.90	1.0	0.61	0.63	0.27
Initial cost	0.60	0.23	1.0	0.93	0.86	0.08
Lifecycle cost	0.56	0.08	0.66	0.55	0.69	0.42
Material Preference						
Prestressed concrete	0.86	0.00	0.03	0.80	0.42	0.43
Reinforced concrete	0.88	0.47	0.03	0.18	0.74	0.06
Steel	0.01	0.00	0.24	0.20	0.80	0.08
Timber	0.07	0.00	0.38	0.04	0.92	0.00

1. Comparison between 3 decision maker groups: state DOT, private engineers, and local officials
2. Comparison between 4 states decision makers: Mississippi, Virginia, Washington and Wisconsin.

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