Approach To Combine Ranking and Optimization Techniques in Highway Project Selection

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In pavement and bridge management systems, often two different techniques are employed for selecting rehabilitation and replacement projects. Prioritization or ranking techniques provide a list of projects ranked according to a given set of criteria. Optimization, on the other hand, gives a list of projects that satisfies a set of criteria including budget and other constraints over a certain period. The two may produce two different sets of results because of the difference in approaches. To have consistency in decision making, it is desirable to connect the two project selection models so that their results are comparable. The ranking and optimization models would then have a direct correspondence and the results could be compared and analyzed on the basis of common criteria. An approach combining ranking and optimization techniques is presented. The approach is illustrated by using an example of bridge management for Indiana. First, the ranking and optimization models are briefly introduced, and the concepts of the new approach based on the existing models are presented and explained. A numerical example is given, and the results from the new approach and the existing ranking model are compared and discussed through the example.

Ranking and optimization are two of the techniques most widely used to select highway projects. However, these two approaches are very different in concept. Ranking techniques evaluate several related factors of a project simultaneously and yield a quantitative ranking value based on the evaluation of these factors. Thus, all the considered projects are ranked according to their corresponding ranking values. The ranking methods do not necessarily give an optimal solution. Nevertheless, a ranking approach is simple to use and provides the relative order of importance of different projects. Such an ordered list can be used to make final decisions on the basis of project ranking values.

On the other hand, an optimization technique produces an optimal solution of a highway system while the projects are selected subject to a set of constraints. The optimal solution is obtained either by maximizing the system benefit or by minimizing the total negative effect on the system caused by undertaking the selected projects. Different from ranking methods, optimization techniques do not follow the rule of "choosing the projects with the worst conditions." Instead, the optimization techniques select the projects that contribute the most benefit to the highway system, while all the constraints are satisfied simultaneously.

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Like many other pavement and bridge management systems, the Indiana Bridge Management System (IBMS) provides two models, ranking and optimization models, for selecting bridge rehabilitation and replacement projects. Thus, decision makers have two alternative methods for bridge project selection. However, because of the different concepts of the two techniques, the two models produce two different sets of results. It would be desirable to combine the techniques so that the ranking and optimization models would have a direct connection, and the results could be compared and analyzed on the basis of common criteria. An approach to combining ranking and optimization techniques is presented. The existing ranking and optimization models are briefly introduced, and the concepts of the new approach based on the existing models are presented and explained. An example is given to illustrate the proposed approach, and the result of the approach and that of the existing ranking model are compared and discussed through the example.

RANKING MODEL

Setting priorities on pavement and bridge-related projects is usually a multiattribute decision-making problem, requiring decision makers to evaluate simultaneously several related factors. The ranking model of IBMS was developed using the technique of the analytic hierarchy process (AHP) (*1*). This model not only helps decision makers set the relative order of importance of different projects, but also indicates how much importance one may have over the other.

The AHP method is a useful tool to rank projects when subjective judgments are involved. However, a direct application of the method may not be practical when the number of projects is large. For example, even when there are only 22 bridge projects to compare, one must make 231 pairwise comparisons for each evaluation criterion [22(22 − 1)/2]. Assuming that six criteria are under consideration, the number of pairwise comparisons is 1,386. The number of projects may range between 500 and 1,000, and the direct use of the AHP is thus impractical.

This problem, however, can be solved by including the concept of utility. In a highway facility management system, utility is the level of overall effectiveness that can be achieved by undertaking a project. If an appropriate utility is assigned to projects with respect to certain evaluation criteria, the expected utility of each alternative project can be evaluated. Then, the top priority project is the alternative with the highest expected utility value. An example of a utility curve is shown in Figure 1. In order to apply the concept, it is necessary to find factors common to all projects. The best candidates for bridge projects are physical attributes of the bridges because all bridges can be described by such attributes as structural condition and deck widths.

Figure 2 illustrates the hierarchy system of the ranking model for IBMS. This four-strata hierarchy consists of an overall goal of the ranking exercise, objectives that bridge managers would like to achieve, evaluation criteria with utility curves, and individual bridges. The criteria weights can be obtained by applying the eigenvector approach proposed by Saaty (*1*).

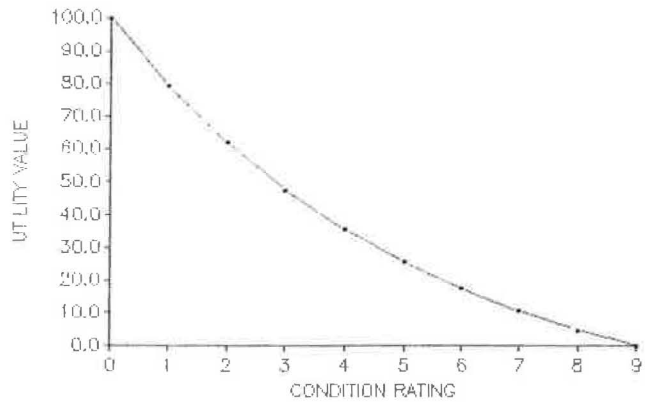

FIGURE 1 Utility curve of bridge condition rating.

OPTIMIZATION MODEL

Optimization techniques are used to obtain a list of projects so that an objective function, such as systemwide condition or level of service, can be optimized subject to a set of budget and other constraints over time. For the IBMS, such a model was developed on the basis of dynamic programming and integer programming (*2*). Markov chain transition probabilities of bridge structural conditions were used in the model to predict or update bridge structural conditions at each stage of the dynamic programming (*3*).

The dynamic programming considers the available federal and state funds of each year in terms of several possible spend-

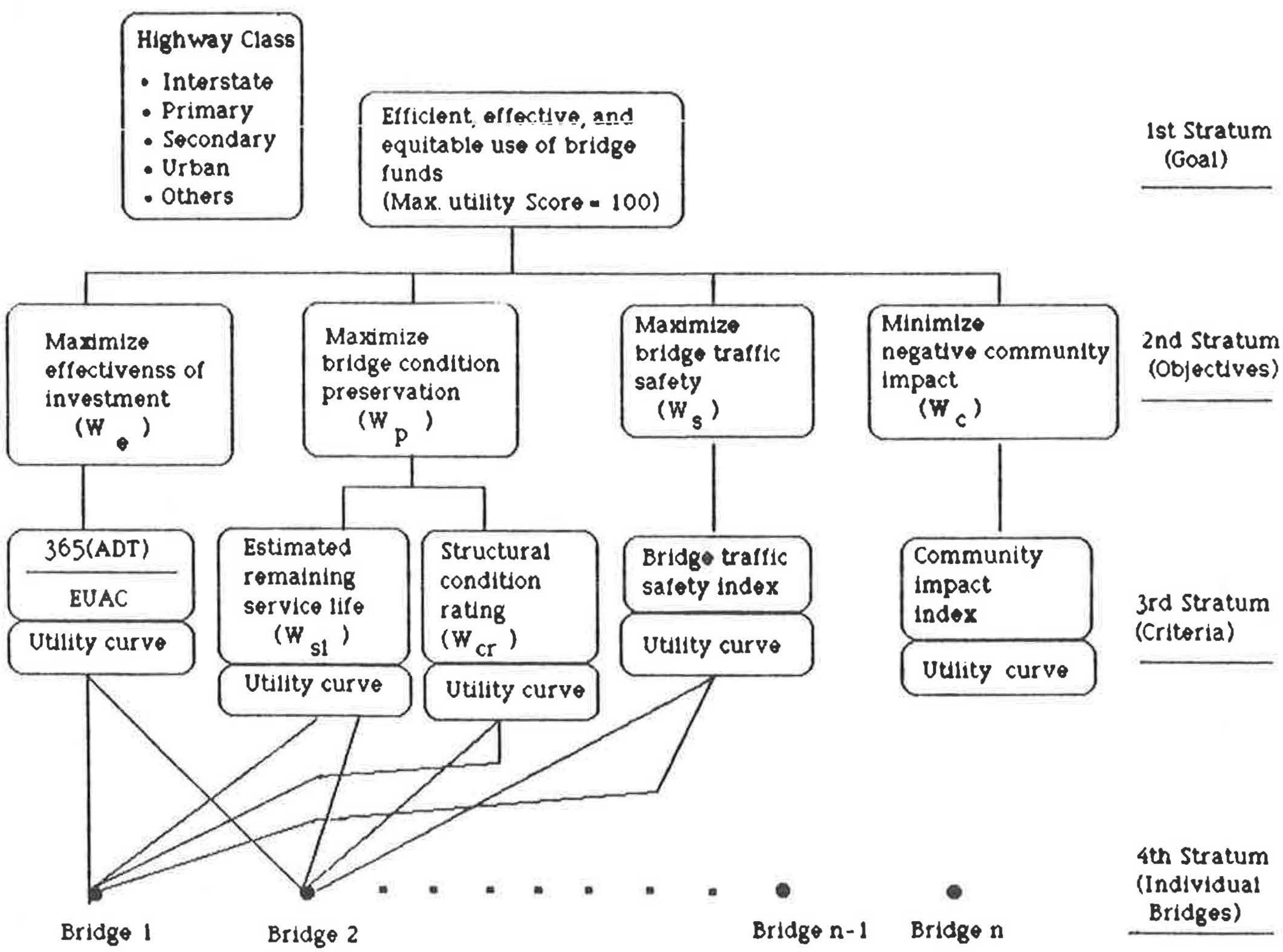

FIGURE 2 Hierarchy system of the ranking model.

ing portions, and the integer linear programming selects projects by maximizing yearly systemwide effectiveness subject to different budget spendings. The dynamic programming chooses the optimal spending policy, which maximizes the system effectiveness over a program period, by comparing the values of effectiveness of these spendings resulting from the integer linear programming.

In dynamic programming, each year of the program period is a stage. The federal and state budgets are state variables. Each activity of a bridge is a decision variable of the dynamic programming as well as of the integer linear programming. The effectiveness of the entire system is used as the return of the dynamic system.

At each stage, a decision must be made as to the optimal solution from Stage 1 to the current stage. When a decision is made, a return (or reward) is obtained and the system undergoes a transformation to the next stage. The bridge conditions are updated for the next stage by the Markov transition probabilities obtained in the performance model (*3*). For a given program period, the objective of the model is to maximize the effectiveness of the entire system. The formulation of the model along with the definition of system effectiveness is discussed as follows.

The effectiveness of a bridge improvement activity was defined as follows:

$$E_i = \text{ADT}_i * A_i(a) * (1 + \text{Csafe}_i) * (1 + \text{Cimpc}_i) \quad (1)$$

where

- E_i = effectiveness gained by bridge i if activity a is chosen;
- a = improvement activity (a = 1 corresponds to deck reconstruction; a = 2 to deck replacement; and a = 3 to bridge replacement);
- ADT_i = average daily traffic on bridge i;
- $A_i(a)$ = representation of average area under performance curves of components of bridge i due to the increase of condition ratings caused by undertaking activity a;
- Csafe_i = transformed coefficient of traffic safety condition (primarily based on bridge geometrics) of bridge i, ranging from 0.0 to 1.0; and
- Cimpc_i = transformed coefficient of community impact of bridge i in terms of detour length, ranging from 0.0 to 1.0.

Considering that budgets can be carried over from year to year, the mathematical model for maximizing the overall effectiveness of various activities over a program period T was formulated:

$$\max \sum_{t=1}^{T} \left[\sum_i \sum_a X_{i,t}(a) * E_i * d_i(t) \right] \quad (2)$$

The model is subject to the following constraints:

Available federal budget,

$$\sum_{t=1}^{T} \left[\sum_i \sum_a X_{i,t}(a) * c_i(a) * F_i \right] \le C_{BF} \quad (3)$$

Available state budget,

$$\sum_{t=1}^{T} \left[\sum_i \sum_a X_{i,t}(a) * c_i(a) * (1 - F_i) \right] \le C_{BS} \quad (4)$$

One activity cannot be undertaken more than once on one bridge in T years,

$$\sum_{t=1}^{T} X_{i,t}(a) \le 1 \quad (5)$$

Constraints in Equations 6 to 10 correspond to an integer linear programming:

Maximize system effectiveness of year t,

$$\max \sum_i \sum_a [X_{i,t}(a) * E_i * d_i(t)] \quad (6)$$

Spending constraint of year t for federal budget,

$$\sum_i \sum_a [X_{i,t}(a) * c_i(a) * F_i] \le \eta_{tF} \quad (7)$$

Spending constraint of year t for state budget,

$$\sum_i \sum_a [X_{i,t}(a) * c_i(a) * (1 - F_i)] \le \eta_{tS} \quad (8)$$

No more than one activity can be chosen on one bridge in year t,

$$\sum_{a=1}^{3} X_{i,t}(a) \le 1 \quad (9)$$

Decision variable,

$$X_{i,t} = 0 \text{ or } 1 \quad (10)$$

Update bridge conditions by Markov chain transition probabilities if bridge i is not selected in year t,

$$R_{i,t+1} = R_{i,t} * p_i(R,t) + (R_{i,t} - 1) * (1 - p_i(R,t)) \quad (11)$$

Improvement of bridge condition if bridge i is selected in year t for activity a,

$$R_{i,t+1} = R_{i,t} + R_i(a) \quad (12)$$

where

- $X_{i,t}(a)$ = 1, if bridge i is chosen for activity a;
  = 0, otherwise;
- $d_i(t)$ = the absolute tangent value on performance curve of bridge i at time t;
- C_{BF} = total available federal budget for the program period;
- C_{BS} = total available state budget for the program period;
- F_i = federal budget share of bridge i;
- $1 - F_i$ = state budget share of bridge i;
- $c_i(a)$ = estimated cost of bridge i for activity a;
- η_{tF} = spending limit of federal budget in year t;

$\eta_{t,S}$ = spending limit of state budget in year t;
$R_{i,t}$ = condition rating of bridge i in year t;
$p_i(R,t)$ = Markov condition transition probability of bridge i with condition rating R in year t; and
$R_i(a)$ = condition rating gained by bridge i for activity a.

Equations 2 through 12 constitute a dynamic programming that includes an integer linear programming (Equations 6 to 10) as part of the constraints. The model's objective is to obtain optimal budget allocations and corresponding project selections over T years so that the system effectiveness can be maximized. The number of spending level combinations, N, can be expressed in terms of the number of possible spendings of each year, S, and the program period, T, as $N = S^{T-1}$. When T is large, the number of possible spending combinations becomes so large that the search for the optimal path of spendings from year 1 to year T requires great effort and computation time.

Dynamic programming is an efficient technique to search for the optimal path among the combinations of spendings. Rather than examining all paths, dynamic programming looks at only a small number of these paths. According to the principle of optimality, at each stage the programming finds the optimal subpath up to the current stage, and only this subpath is used to search for the optimal subpath to the next stage. Paths that do not belong to the optimal subpath are abandoned as the search goes on. This makes the search efficient and saves a great deal of time.

PROPOSED APPROACH

Either of the two models for project selection, ranking or optimization, can be used to select bridge projects based on priority order or optimization with respect to systemwide benefit. However, because the two models rely on different techniques and concepts, it is difficult to find a common ground for comparing the result of the ranking model with that of the optimization model. That is, there is no direct relationship between a utility value of the ranking model and an effectiveness value of the optimization model. It is desirable that the results of different approaches be comparable. A common criterion should be adopted to make the two models interacting.

As can be seen, the AIIP ranking model for IBMS used such factors as average daily traffic, bridge activity cost, estimated service life, structural condition rating, bridge traffic safety index, and community impact as ranking criteria. Inclusion of these factors in the process of bridge project selection made the resulting utility values reflect the main concerns of bridge rehabilitation and replacement activities. The utility values produced by the ranking model thus can be used to measure the effectiveness criterion in the optimization model.

With utility values as common measures for the ranking and optimization models, the proposed approach can be developed easily by modifying the existing models. Because the utility values range from 0 to 100, with 0 being the utility value of a "perfect" bridge and 100 the value of the "worst" bridge, the utility value of a bridge will decrease after a rehabilitation activity is undertaken. Thus, the difference in utility values before and after a bridge activity is undertaken indicates the improvement in overall utility. This difference, therefore, can be defined as the effectiveness or benefit of the bridge activity. Incorporating this definition into the dynamic optimization model, the programming objective thus becomes to maximize the total decrease in utility values of the bridge system subject to the budget constraints.

The only modification of the dynamic programming formulation needed to combine the two models is to change Equation 1 to the following:

$$E_i = U_{ib} - U_{ia} \qquad (1a)$$

where

E_i = effectiveness gained by bridge i if an activity is undertaken,
U_{ib} = utility value of bridge i before the activity is undertaken, and
U_{ia} = utility value of bridge i after the activity is undertaken.

Thus, the formulation of the new approach is obtained by substituting Equation 1a for Equation 1; Equations 2 through 12 remain unchanged. The value of E_i would be available from the ranking model. This value is the weighted summation of individual utility differentials for economic efficiency, remaining service life, structural condition, traffic safety, and community impact.

The change of Equation 1 to Equation 1a combines the ranking model and the optimization model. Thus the result obtained from the optimization model can be directly compared with that of the ranking model in terms of the total gain in utility values. The change in the computation will be to have Equation 1a as a subroutine of the dynamic optimization program. This subroutine is, in effect, the ranking program. At each stage of the dynamic optimization process, the ranking program, as a subprogram, computes the system benefit, or the total gain in utility values, and the dynamic programming as the main program makes optimal project selection according to the system benefit.

APPLICATION EXAMPLE

To compare results of the ranking model with the new approach, 50 state highway bridges in Indiana needing rehabilitation or replacement were selected and the ranking and new approach programs were run. Table 1 presents the result of the ranking model.

Because the project selection in the new approach depends on available budgets, the new approach program was run several times using different given budgets. One result, shown in Table 2, was obtained with a given budget of $11,128,000, or about 25 percent of the total budget needed for repairing and replacing all 50 bridges. The total gain in utility, or the systemwide benefit, was 900.0. With the same budget, one can also select bridge projects from the ranking list in Table 1. Selecting the bridges from the top of the list, the first six bridges in Table 1 could be chosen with the given budget. With this selection the total cost is $10,081,180 and the total gain in utility is 272.6.

By dividing the total gain in utility by its corresponding total cost, the gain in utility for the proposed approach is

TABLE 1 OUTPUT OF THE RANKING MODEL

Bridge No.	Priority	U_i	E_i	ΣE_i	C_i	ΣC_i	Activity
31	1	72.9	52	52	2159	2159	BRP
30	2	72.5	50	102	1210	3369	BRP
47	3	72.3	46	148	1549	4918	BRP
27	4	70.4	53	201	5000	9918	BRP
49	5	69.9	51	252	65	9983	DRC
24	6	69.0	21	273	98	10081	DRC
25	7	68.9	18	291	1993	12074	DRC
26	8	68.0	52	343	500	12574	BRP
46	9	67.6	50	393	965	13539	BRP
33	10	65.0	50	443	545	14084	BRP
50	11	65.0	50	483	280	14364	BRP
28	12	63.2	48	541	6228	20593	BRP
37	13	61.2	50	592	840	21433	BRP
48	14	60.5	50	642	420	21853	BRP
32	15	60.1	51	693	3409	25262	BRP
42	16	60.1	50	743	1571	26833	BRP
40	17	59.4	50	793	193	27026	BRP
17	18	59.0	46	839	1090	28116	DRC
43	19	59.0	50	889	1029	29145	BRP
44	20	59.0	50	939	388	29533	BRP
45	21	59.0	50	989	288	29821	BRP
23	22	55.7	40	1029	296	30117	DRC
35	23	52.7	42	1071	635	30759	BRP
34	24	51.7	42	1113	1297	32049	BRP
10	25	51.7	29	1142	330	32379	DRC
38	26	50.0	41	1183	3153	35532	BRP
36	27	49.2	38	1221	840	36372	BRP
39	28	46.0	37	1258	295	36667	BRP
11	29	42.0	15	1273	269	36936	DRC
29	30	42.0	33	1306	2192	39128	BRP
13	31	36.0	23	1329	201	39329	DRC
22	32	36.0	13	1342	164	39493	DRC
41	33	35.9	29	1372	385	39878	BRP
9	34	32.6	15	1387	257	40135	DRC
12	35	32.0	19	1406	201	40336	DRC
21	36	31.9	9	1415	247	40583	DRC
8	37	30.3	15	1430	1300	41883	DRC
18	38	28.6	8	1438	66	41949	DRC
7	39	28.4	12	1450	210	42159	DRC
3	40	28.2	12	1462	387	42546	DRC
6	41	27.0	10	1472	121	42668	DRC
20	42	26.9	8	1480	119	42787	DRC
14	43	26.8	4	1484	476	43262	DRC
16	44	26.6	10	1494	154	43416	DRC
15	45	23.0	4	1498	74	43491	DRC
4	46	22.3	8	1506	281	43771	DRC
5	47	21.9	8	1513	107	43878	DRC
1	48	20.4	8	1521	235	44113	DRC
2	49	20.0	8	1529	276	44389	DRC
19	50	19.9	4	1533	124	44512	DRC

Note: U_i = Utility Value of Bridge i.
E_i = Effectiveness, or Change of Utility Value, of Bridge i.
C_i = Cost of the Activity of Bridge i, in $1000.
BRP = Bridge Replacement.
DRC = Deck Reconstruction.

TABLE 2 OUTPUT OF THE PROPOSED APPROACH

Bridge No.	E_i	C_i	Activity
1	8	235	DRC
4	8	281	DRC
6	10	121	DRC
7	12	210	DRC
9	15	257	DRC
10	29	330	DRC
11	15	269	DRC
12	19	201	DRC
13	23	201	DRC
15	4	74	DRC
16	10	154	DRC
17	46	1090	DRC
18	8	66	DRC
19	4	124	DRC
20	8	119	DRC
21	9	247	DRC
22	13	164	DRC
23	40	296	DRC
24	21	98	DRC
26	52	500	BRP
33	50	545	BRP
35	42	635	BRP
36	38	840	BRP
37	50	840	BRP
39	37	295	BRP
40	50	193	BRP
41	29	385	BRP
44	50	388	BRP
45	50	288	BRP
46	50	964	BRP
48	50	420	BRP
50	50	280	BRP

Note: E_i = Effectiveness, or Change of Utility Value, of Bridge i.
C_i = Cost of the Activity of Bridge i, in $1000.
BRP = Bridge Replacement.
DRC = Deck Reconstruction.

900.0/11,128,000 = 81 units per million dollars, and that for the ranking method is 272.6/10,081,180 = 27 units per million dollars. Therefore, the value of the proposed approach is three times as large as the value of the ranking method in this example.

Figure 3 presents a comparison of the results from the two approaches in terms of system benefits and available budget. The proposed approach always gives a better solution than the ranking approach when the available funds are less than 100 percent of the need.

CONCLUSIONS

By defining the system benefit as the total gain in utility values, the ranking and optimization models can be combined.

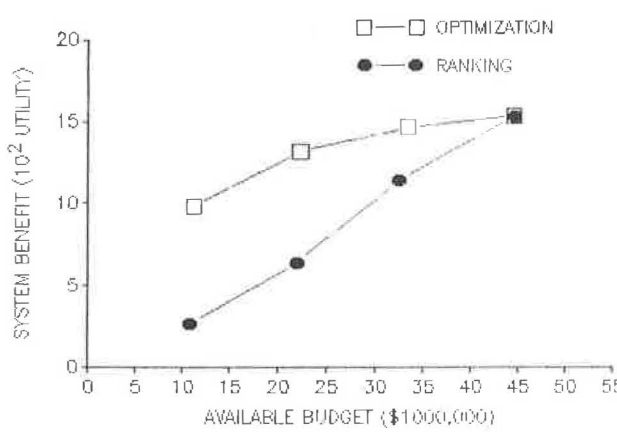

FIGURE 3 Comparison of ranking and optimization approaches.

An example of 50 bridge projects demonstrated the usefulness of this proposed approach. In pavement and bridge management systems, both ranking and optimization techniques are used for project selection. By adopting an approach that allows a direct linkage of these two approaches, decision making can be improved.

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