SYSTEMS APPROACH TO BRIDGE STRUCTURE REHABILITATION OR REPLACEMENT DECISION-MAKING

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This paper presents a systems approach to the difficult bridge structure rehabilitation or replacement decision-making. Essential elements of the data base, or structure information system, supporting this decision-making process are indicated. Adequacy for future use and economic criteria for a rational appraisal of alternates are developed and their application is indicated. Constraints; like available and projected flow of funds and of local or legal nature are identified and their impact on the decisions is analyzed. Analytical decision methods, such as pay-off matrix and decision tree, for evaluation of alternate proposals are presented and illustrated in a systematic, step-by-step procedure. Guidelines are also presented to assist the decision-maker in the selection of a method suitable for individual situations.

For a decision-maker, the decision to rehabilitate or to replace a deficient bridge structure and its subsequent justification have not always been easy. One principal cause for this has been the approach of piecemeal synthesis in the existing decision-making that has, in general, been oriented toward emphasizing certain advantages of one alternate and underestimating its disadvantages. Need exists, therefore, to accomplish the decision-making process through a complete, integrated and logical analysis. The systems approach provides such a coordinated step-by-step analysis which, when applied to bridge structure rehabilitation or replacement decision-making, offers several advantages. It integrates essential elements of reliable information, well defined criteria, clearly perceived constraints and uniform evaluation of all available alternatives. Further, it allows for and encourages the use of experience, judgment, and analysis of the impact of uncertainty and of possible future decisions. Thus, the decision-making, based upon systems approach, can take place in a logical and orderly manner, which can facilitate rationally sound decisions and ensure the optimal or near optimal use of the limited public funds.

Systems Approach

The system for decision-making can be described as a logical, clearly defined and step-by-step procedure operating to accomplish the decision-making process. A comprehensive formulation of the decision process; characterizing various technical, economic and other aspects; which is needed before a realistic operating system can be developed is described by the following: objectives, data-base, criteria, constraints, and methodology for evaluation.

Objectives

Objectives of the systems approach are to bring out all possible alternatives, evaluate them on the basis of clearly defined criteria and constraints, and arrive at an optimal or near optimal decision. The ultimate aim of systems logic is to discover and take into account those aspects that truly influence the outcome of an optimal or near optimal (i.e., the best and the second best) decision.

Data-base

A user oriented, up to date, complete and orderly structured data-base is presented in Tables 1, 2, and 3. To facilitate its efficient retrieval, use and ease of updating, this data-base has been divided into the following sections:

Structure Inventory and Traffic. Physical characteristics of the existing structure and traffic related information are presented in this section. Estimates for rehabilitation, relative importance of the bridge to traffic and physical requirements of future replacement structure can be determined from this information.

Structure Inspection and Appraisal. Inspection of the existing bridge structure reveals condition of its superstructure (i.e., deck, stringers, etc.) and substructure (i.e., abutments, piers, footings, etc.). It also reveals unsafe conditions, serviceability considerations, estimated remaining life and the extent of repairs needed.

Table 1. Data-base: Part I

STRUCTURE INVENTORY AND TRAFFIC (SECTION A): (Dated ....; Updated ....)

1. Structure Number ....; Built in ....; Remodeled in ....; Owner ....
2. Inventory Route. ....; Over/Under ....; Location ....
3. Alternate Length ....; Impact on Travel Time. ....min.; kmh (mph). ....
4. Lanes/R.R. Tracks (over) ....; (under) ....; One/Two Way ....
5. Av. Daily Traffic (ADT) on Structure ....; Peak Hour Traffic ....; Year. ....
6. Projected ADT ....; For Year ....; Heavy Commercial ADT ....
7. Design Load ....; Present Structural Capacity ....; Posted Load Limit ....
8. Approach Width: Roadway. ....; With Shoulder ....
9. Angle Skew ....; Is Structure Flared?. ....; Width: Max ....; Min. ....
10. Minimum Clearances: Vertical: Over. ....; Under ....
    Horizontal: Over .... (North/West); .... (South/East) ....
    Under. .... (North/West); .... (South/East) ....
11. Navigation Control: Yes/No; Vertical ....; Horizontal ....
12. Structure Type: Main Span ....; Approach Spans ....
13. Number of Spans: Main ....; Approach ....
14. Structure Length: Total ....; Max. Span ....; Approach Spans. ....
15. Widths: Roadway (curb to curb). ....; Deck (out to out). ....
    Sidewalks: .... (North/West) .... (South/East). ....
16. Wearing Course and Overburden: Type(s). ....; Thickness(es) ....
17. Guardrail: Type .... Length; Other Railings: Type ....; Length. ....
18. Utilities Carried, Location. ....
19. Joints on the Bridge: Type ....; Length. ....
20. Lighting System ....
21. Painted in ....; Type of Paint ....
22. Material Inventory: Roadway ....; Sidewalk ....; Superstructure. ....
    Substructure. ....
23. Other Features (such as safety lights):. ....

STRUCTURE INSPECTION AND APPRAISAL (SECTION B): (Dated ....)

1. Deck: Overall Condition ....
   Type and Extent of Deterioration. ....
   Repairs Needed and When ....
2. Superstructure: Overall Condition ....
   (Other than Deck) Type and Extent of Deterioration. ....
   Repairs Needed and When ....
3. Substructure: Overall Condition ....
   Type and Extent of Deterioration. ....
   Repairs Needed and When ....
4. Safety Considerations: Unsafe or Hazardous Conditions ....
   (Width, alignment, load-limits, steep grades, railings, clearances, etc.)
5. Serviceability: Drainage. ....
   Rideability (Roughness Coefficient) ....
   Lighting. ....
6. Condition of Paint ....
7. Estimate of Remaining Life: Without (with) major repairs. .... (....) Years
8. Description and Estimated Cost of Major Repairs Needed and When. ....

STRUCTURAL CAPACITY AND FUNCTIONAL ADEQUACY (SECTION C): (Dated ....)

1. Load Carrying Capacity ....
   (Based on: Current Legal Loads. ...., Estimate of Deterioration. ....)
2. Minimum Clearances: Vertical. ....; Horizontal ....
3. Adequacy for Present and Projected Traffic ....
4. Waterway Adequacy and Protection (e.g., Pier or Scour Protection). ....
5. Limits for Special Permit Loads. ....; Wheel-Load Configuration Used. ....

Structural Capacity and Functional Adequacy. Load carrying capacity of the structure and functional adequacy are indicated in this section. This information is helpful in appraising rehabilitation alternates.

Maintenance History and Projected Future Needs. This section provides information on the major, or recurrent minor, maintenance and repair work done in the past and projected future maintenance. This information is valuable in appraising the rehabilitation alternates.

Environmental and Other Factors. Information on aesthetic considerations, developmental plans and projected needs of the area served, and major items of information for environmental impact statements are provided in this section.

Relevant Details for Rehabilitation and Replacement. Details relevant to all available rehabilitation and replacement alternatives such as cost estimates, are presented in this section.

Table 2. Data-base: Part II

MAINTENANCE HISTORY AND PROJECTED FUTURE NEEDS (SECTION D): (Dated . . . .)

1. Chronology and a Brief Description of Major Repairs Done: . . . .
   (When, what, at what cost and who made them, improvement in life expectancy). . . . .
   . . . .
2. Brief Description of Minor Repairs in the Past Five Years . . . .
   . . . .
3. Projected Future Maintenance Needs: (e.g., New Overlay). . . . .

ENVIRONMENTAL AND OTHER FACTORS (SECTION E): (Dated . . . .)

1. Aesthetical Considerations (e.g., Paint, etc.). . . . .
2. Developmental Plans and Projected Needs of the Area Served. . . . .
   . . . .

Table 3. Relevant Details for Rehabilitation and Replacement.

RELEVANT DETAILS FOR REHABILITATION (SECTION F)

1. Data-base Sections "A" through "D"
2. Alternate Proposals for Rehabilitation: Details, Cost Estimates, and Improvement in Life Expectancy

RELEVANT DETAILS FOR REPLACEMENT (SECTION G)

1. Data-base Sections "A", "C" and "E"
2. Physical Requirements of Proposed Structure:
   Roadway width (curb to curb): . . . .; Sidewalk widths: . . . .
   Minimum Clearances: Over: Vertical. . . . .; Horizontal . . . .
   Under: Vertical . . . .; Horizontal . . . .
   Traffic Capacity (Peak Hour): . . . .; Design Loads . . . .
   Alignment: . . . .; Related Structures, needed. . . . .
   Approaches:. . . . .; Utilities, to be carried. . . . .
   Other: . . . .
3. Special Features of the Site (e.g., subsurface data). . . . .
4. When is New Bridge Needed?. . . . .
5. Alternate Replacement Proposals: Details, Life Expectancy and Estimates of Initial, Maintenance and
   Other Costs. . . . .

The information provided in Tables 1, 2, and 3 has been so structured and organized that it can easily be maintained manually or on computer. Further, the information from this data-base can be utilized to reinforce an agency's decision-making process.

Criteria for Decision-Making

One of the major reasons for difficulties experienced in rehabilitation or replacement decision-making is the lack of appropriate and clearly defined criteria for a comparative appraisal of available alternates. Further, major investment decisions like bridge structure rehabilitation or replacement must be consistent with the agency objectives and policies.

The first important criterion is adequacy, for projected future use, of the rehabilitated or replacement structure. This adequacy must be determined to establish a rehabilitation or replacement proposal as a realistic alternate. Developmental plans and projected future needs of the area served influence the functional adequacy of the rehabilitated bridge. These plans can change traffic patterns, thus influencing the type and frequency of traffic at a bridge-crossing. Inadequacy to sustain the projected traffic may eliminate a simple and economical rehabilitation alternate, thereby requiring selection of an acceptable replacement alternate. In addition to adequacy for present and projected traffic, the rehabilitated or replacement structure shall also need to meet the minimum requirements of horizontal and vertical clearances, roadway width, waterway opening, and safety.

Analysis of highway improvements on the basis of engineering economics, which is the second group of criteria, began over 100 years ago. The illusory nature of initial costs as decision criteria was recognized by Gillespie, in his book on road-making, published in 1853 (2, 9), who recommended use of estimated total costs and benefits in the selection of highway improvements. This principle of estimated total costs as a decision criterion still underlies all rational economic analyses in highway engineering. Three most commonly used criteria for comparing total costs of alternate investment proposals are: present value, annualized costs, and prospective rate of return. In economic evaluations, comparative estimated values of future series of benefits and costs, such as maintenance costs, are arrived at through present value conversion. Where comparisons are for a limited number of years, present value of the cost of the same number of years of service is calculated for each alternative. The second method of economic evaluation is to compare alternates on the basis of equivalent uniform cost using a suitable interest or discount rate. Annualized cost comparisons are convenient to use when many of the estimated costs are essentially the same year after year. The basic data for such comparisons consists of estimated costs associated with the alternatives being compared. Conversions into equivalent annual cost require the use of appropriate factors, obtained from compound interest tables or computed using compound interest formulas. The third criterion, prospective rate of return, provides another way of considering the time value of investments. A comparison between alternatives involving costs and quantified benefits of different amounts at different dates may be expressed by an interest rate that makes the two alternatives equivalent. When one alternative involves a higher present investment and higher future net benefits, possibly as a result of lower future disbursements, the interest rate is called the prospective rate of return on extra investment.

There are many difficulties in applying any of these three criteria to engineering economic analysis of alternate bridge rehabilitation and replacement proposals. Although initial costs can be arrived at with reasonable accuracy, problems emerge while estimating future series of maintenance costs. One way of estimating these costs is by using past experience with similar structures. Such projections tend to be quite subjective and considerable care needs to be exercised in analyzing the past experience. To arrive at a reasonably close estimate, from a range of estimates of future series of maintenance costs, statistical techniques such as expected monetary value (EMV) are utilized. Another difficulty arises in estimating the life of an improvement because in many long-lived projects, such as bridge structures, analyses are made and costs are computed as if the economic life were fifty years. However, life expectancy of a rehabilitated structure is difficult to estimate, although past experience with similar improvements is helpful. Levels of future use and sound engineering judgments based upon performance characteristics of the method and materials used in rehabilitating structure will be valuable. Further, the selection of a suitable interest rate or discount rate to determine time value of money is particularly difficult for the decision-maker. For longer time spans, one could estimate a range of such rates; and with the help of economists, use probabilistic methods to select the most probable interest rate. Quantification of benefits is another difficult proposition. However, it is not likely to be a critical factor in the bridge structure rehabilitation or replacement decision-making.

Constraints of Decision-Making

Lack of a clear perception of all constraints on decision-making has been another major reason for difficulties experienced by a decision-maker. The most important group of constraints are those pertaining to the available and projected flow of funds. No agency ever seems to have enough funds to follow through what it considers to be the most desirable capital improvements. Grants of different kinds, bond and general revenue funds are used to carry out what are considered to be high priority projects. A decision-maker has to take into account not only the availability of funds for initial investment, but also the requirements of future flow of funds that the investment is expected to create. This future investment is particularly difficult for the decision-maker, because of the element of uncertainty associated with it. Statistical techniques, which deal with the element of uncertainty, can provide a clearer perception of this constraint.

Local and legal constraints constitute another group that can substantially influence the decision-making process. In recent years, local groups have increasingly managed to change what a decision-maker had determined to be the best decision. The decisions to rehabilitate or replace bridge structures are no exception to this process. Involvement of local groups and consideration of their concerns, during the decision-making, has become necessary. Where major rehabilitation is intended, some state laws require compliance with minimum clearances, and these legal constraints may render a major rehabilitation proposal totally uneconomical. Recent Uniform Relocation Act requires extensive environmental reviews and complex acquisition procedures even on small bridge rehabilitation projects. Peculiar site conditions, historical value of a bridge, technological limitations, local availability of specialized labor, materials or equipment, etc., also influence a rehabilitation or replacement decision.

Methodology for Decision-Making

Decisions to rehabilitate or replace a structurally deficient or functionally inadequate bridge generally involve outlay of large amounts of money, have long-lasting effects and often require judgmental estimates about future events. In this respect, they are important and generally difficult investment decisions. If the evaluation of such an investment decision is based only on a single estimate--the "best guess"--of the cost of each factor affecting the outcome, the resulting evaluation will be incomplete and possibly wrong. In recent years, increasingly sophisticated methods have become available for analyzing investment decisions. The most widely known of these new developments are the analytical methods that take into account time value of money. However, there have been two troublesome aspects of investment decision-making that need adequate treatment. One problem is handling the uncertainty that exists in virtually all investment decisions. Another problem is analyzing separate but related investment decisions, such as stage construction, that must be made at different points in time. The decision theory approach indicated in the payoff matrix and opportunity loss tables (Tables 4 and 5) provides a basis for reaching objective decisions under uncertainty. Another method, called "decision tree" method (5,6,7,8), is particularly applicable to investments under uncertainty and require a sequence of related decisions to be made over a period of time.

Payoff and Opportunity Loss Tables. These tables illustrate the various dimensions involved in any decision problem. A payoff table indicates all alternatives available to the decision-maker, events that can happen, probability distribution of these events, and monetary payoff (+ sign: benefits, - sign: costs) that result from each alternate/event combination. The formulation of a payoff table is probably the most difficult step in analysis of decision problems under uncertainty. It can also be the most beneficial, because in some decision problems the creation of new alternatives can have a great benefit. Some of the consequences that result from the specified alternate/event combination are not initially in monetary terms, and this causes difficulties in the construction of a payoff table. Although it is not easy, it is necessary to convert non-economic consequences into their monetary equivalent before the decision analysis process can continue. A very useful decision criterion for many decision problems under uncertainty is expected monetary value (EMV). In order to compute the EMV for a given alternate, the payoff is simply multiplied by the probability of that event's occurring, and products for each event are added (see step 1, Table 4). The expected value of a chance event or random variable X, which can take on any one of n values, is defined to be:

$$\text{Expected Value of } X = E(X) = \sum_{i=1}^{n} X_i P(X_i)$$

Where X is the monetary outcome of a decision problem under uncertainty, the expected value of X is usually called Expected Monetary Value, or EMV. The optimal alternative in the payoff table is indicated by the highest EMV.

Another way of analyzing decision problems under uncertainty is to construct an opportunity loss table (see Table 5). The opportunity loss for an alternate/event combination is the difference between payoff for that combination and the best payoff for that event. To construct an opportunity loss table, each event is considered one at a time. All rows of the opportunity loss table are thus completed (see step 1, Table 5). The bottom row shows the Expected Opportunity Loss, EOL, for each of the alternates. The EOL is calculated from the opportunity loss table (see step 2, Table 5), in the same way as EMV is calculated from the payoff table. An alternative which has the lowest expected opportunity loss is the optimal alternative. This optimal alternative will also have the best expected monetary value. In many decision problems, it is quite easy to construct the opportunity loss table directly without going through the payoff table. One principal reason for considering opportunity losses is that it helps a decision-maker understand the cost-structure of difficult investment problems.

Decision Trees. The decision tree approach, a technique very similar to dynamic programming, is a convenient method for representing and analyzing a sequence of related decisions to be made over a period of time (5, 6, 7, 8). Each decision point is represented by a numbered square at a fork or node in the decision tree (Figure 1). Each branch extending from a fork represents one of the alternatives that can be chosen at this decision point. In addition to representing decision points, decision trees represent chance events. The forks in the tree where chance events influence the outcome are indicated by circles. A node representing a chance event generally has a probability associated with each of the branches emanating from that node. This probability is the likelihood that the chance event will assume the value assigned to the particular branch. The total of such probabilities leading from a node must equal one. Each combination of decisions and chance events has some outcome, in terms of Net Present Value (see NPV calculation in Figure 1), associated with it. The key steps in building and using a decision tree for investment project analysis are:

Identification of the problem and alternatives. It is important to identify all alternatives, freedom of action, and present and future uncertainties; and also to estimate costs and probabilities of uncertain events. All future possibilities cannot be identified, but a reasonable job can be done. Those engaged in this analysis should be encouraged to express doubts and uncertainties and to bring out facts about cost estimates, engineering feasibility and forecasts of future conditions in terms of ranges or probabilities.

Layout of the Decision Tree. This formulates the structure of alternatives underlying the decision. The time span over which the analysis must extend will vary for particular decisions. Roughly, the practical time span to consider should extend at least to the point where the distinguishing effect of the initial alternative with the longest life is liquidated, or where, as a practical matter, the differences between the initial alternates can be assumed to remain fixed (see Illustrative Example). Outlining major choices, breaking the problem into two to four decision stages, and thinking out the decision at least through a second decision stage enriches the analysis considerably over a conventional single-stage consideration (see "Discussion of Illustrative Example).

Obtaining the Data Needed. The data needed are: a. probabilities of each uncertain outcome, b. cost estimates associated with each combination of decision alternative and chance outcome, and c. an estimate of discount rate to be applied to future costs and benefits. The estimation of elemental probabilities permits review of the basis for conclusions. It also permits the decision-maker to make use of the intuitions and skills of his staff without abdicating his position as the decision-maker. Further, it permits analysis of the impact of variations in the estimate--that is called sensitivity analysis (see Discussion of Illustrative Example).

Evaluation of Alternatives. A good evaluation test which alternatives appear desirable in light of standards used. It shows whether apparent conclusions are sensitive to changes in doubtful or controversial estimates. It examines the effect of choosing alternate standards, which in turn may lead to revision of standards, further analysis, or reformulation. The optimal sequence of decisions in a decision tree is found by starting at the right-hand side and "rolling backward". At each node, an expected Net Present Value, NPV, is calculated. If the node is a chance event node, the expected NPV is calculated for all of the branches emanating from that node. If the node is a decision point, the expected NPV is calculated for each branch emanating from that node, and the highest is selected. In either case, the expected NPV is carried back to the next chance event or decision point by multiplying it by the probabilities associated with branches that it travels over. The preferred alternative shall be one with greatest net present value (see Typical Calculation, Figure 1).

One modification of a decision tree is stochastic decision tree which is similar to the conventional decision tree approach, except that it uses continuous, instead of discrete, empirical probabilities, and provides results in a probabilistic form.

Use of the decision tree concept, as a basis for capital improvement analysis, evaluation and decision, is a means for making explicit the process which must be at least intuitively present in good decision-making. It brings out the impact of both uncertainty and of possible future decisions, conditioned on future developments. It allows for and encourages use of analysis, experience and judgment. It helps force out into the open those differences in assumptions or standards of value that underlie differences in judgment or choice. A decision tree need be only as complex as the decision itself. If the decision is a simple choice among alternatives, then the decision tree reduces to a single stage analysis, i.e., the use of present value technique applied to alternative benefits and costs. Where the situation is more complicated, more stages and alternatives are necessary. Explicit use of the decision tree concept helps force a consideration of all alternatives, definition of problems for investigation, and clarification for the decision-maker of the nature of the uncertainties present and the estimates that must be made. Thus, the decision tree concept contributes to the quality of the decision a decision-maker must make.

Operational System for Decision-Making

An operational system for bridge structure rehabilitation or replacement decision-making is indicated by the flow chart, in Figure 2. The development of this working system can be described by the following: System Inputs, Constraints and Alternatives, Decision Criteria, Evaluation of Alternatives, and System Output.

System Inputs

System inputs are dictated by various generated alternatives and by methods of evaluation used by the system. These system inputs can be described in the following general groups:

Information from the Data Base. Information from Tables 1, 2 and 3 is used to generate possible alternatives and to provide the basis for evaluation of options or alternatives available to the decision maker.

Probability Estimates. A certain amount of uncertainty underlies all estimates, whether they are estimates of initial and subsequent costs or estimates of life expectancies. The cost of some types of work, such as replacing stringers, are easier to estimate with a reasonable amount of accuracy than others like gunite repair of deteriorated concrete arches. Further, it is possible for any experienced decision-maker to reasonably estimate a probability for each probable state. These probabilities may be objective or subjective. Objective probabilities are derived from actual data. Subjective probabilities are derived by judgment, and reflect the engineer's estimation of the relative likelihood that a particular state would occur. For a decision-maker, expressing professional judgments over a range of values as probabilities is more accurate than simply using a single best estimate value.

Cost Inputs. The criterion of total overall cost in terms of present value is used in this working system to indicate the preference for one option over others. The total overall cost is the sum of the present values of design, construction, future expected maintenance and indirect costs. A number of cost inputs are, therefore, used by the working system for evaluation of different available alternatives. In some cases, these inputs may include quantified estimates of economic, social or environmental losses that may result. For a rational economic analysis, a discount rate or interest rate needs to be used to properly evaluate future benefits and costs. If necessary, statistical techniques can be used to arrive at a reasonable rate.

Constraints and Alternatives

The overall number of feasible alternatives is controlled or limited by a set of specified constraints. These constraints can be located at various stages in the working system. All possible alternatives are analyzed and checked against these constraints. Alternatives are either accepted or rejected at these checks. In general, system constraints and options are part of the decision-maker's decisions to generate a reasonable type and number of alternate solutions. But at certain times, these constraints can be actual physical limitations advocated by conditions of site, design, and construction.

Decision Criteria

The total overall cost, in terms of expected monetary value, expected opportunity loss or net present value, is chosen as the prime decision criterion for the selection of the optimal or near optimal decision strategies. Provisions for additional future structural capacity and functional adequacy, safety and serviceability, and maintenance economics are some of the other criteria which may be relevant in some cases.

Evaluation of Alternatives

Any one of the methods, namely payoff matrix, opportunity loss table or decision tree, may be used by the decision-maker in the evaluation of alternatives. In some simple choice situations, the mental exercise in assessing each of the dimensions is sufficient to give the decision-maker insight into the problem so that the desired course of action will become obvious without further analysis. In general, the payoff matrix or opportunity loss table methods can be used in nearly all situations. Where sequential decisions are to be considered, the decision tree method should be used.

Output

The decision criteria included in the present operating system are not comprehensive enough to make final judgments. It is difficult to quantify the relative importance a decision-maker will ascribe to various economic, social, environmental and experience values. Universally acceptable methods for quantifying such values are not available at the present time. The output for decision, therefore, is arranged in a way that would assist the judgment of the decision-maker. An orderly structured set of alternatives and conclusions of the evaluation process for each of the alternatives are produced in the form of a summary table. This is based on increasing order of the expected present value of total costs (see "Discussion of Illustrative Example).

Illustrative Example

A 4-lane, 456 m. (1500 feet) long, steel girder type river bridge is structurally deficient and in need of rehabilitation or replacement. Future projections indicate the need of 2 additional lanes for mass transit, 25 years later.

Available Alternatives: (all costs are in terms of present values)

Alternative I. Immediate Limited Rehabilitation (Restrict Traffic) . . . . $ 250,000
(Deck repair; replace railings, few stringers, etc.)

Major Rehabilitation, 5 years later. . . 3,500,000
(New deck; replace other stringers, floor beams, joints; sidewalks; repair pier caps, beam seats, etc.)

Widen the Bridge, 25 years later 2,500,000
(Add 2 more lanes, reconstruct portions of piers and abutments, etc.)

Maintenance and Other Costs: 0-5 years @ $30,000/year 150,000
6-25 years 150,000
26-50 years 450,000

Present Value of Total Costs for Alternative I $7,000,000

Alternative II. Immediate Major Repair. $3,750,000
(New deck, sidewalks, railings, stringers, floor beams, joints, repair pier caps, beam seats, etc.)

Widen the Bridge, 25 years later. . . . 2,500,000
(Add 2 more lanes, reconstruct portions of piers and abutments, etc.)

Maintenance and Other Costs: 0-25 years 225,000
26-50 years 450,000

Present Value of Total Costs for Alternative II $6,925,000

Alternative III. Immediate Removal of Existing Bridge and Replacement with Steel Plate Girder (CORTEN-Weathering Steel) Type Bridge and Substructure Provision for Future Widening. 5,750,000

Widen the Bridge for 2 additional Lanes at the end of 25 years 1,100,000

Maintenance and Other Costs: 0-25 years 150,000
26-50 years 250,000

Present Value of Total Costs of Alternative III $7,250,000

Alternative IV. Immediate Removal of Existing Bridge and Replacement with Segmental Post-tensioned Box Girder and Substructure Provision for Future Widening 5,500,000

Widen the Bridge for 2 additional Lanes at the end of 25 years 1,100,000

Maintenance and Other Costs: 0-25 years 100,000
26-50 years 200,000

Present Value of Total Costs of Alternative IV $6,900,000

Additional Information

Beyond 50 years, costs for all alternatives are approximately equal.

Cost overruns in rehabilitation projects are very common.

Estimates for replacement projects could be prepared with a high degree of accuracy.

The two additional lanes of mass transit are not to be constructed at the present time.

All cost estimates are in terms of present values, which have been arrived at by multiplying future costs with discount factors, for inflation and interest rates.

Table 4. Pay-off Table (Time Span = 50 Years)

Events	Rehab. Alternatives (in Dollars)			Replace. Alternatives (in Dollars)		
	Alt. I	Alt. II	Probability of Occurrence	Alt. III	Alt. IV	Probability of Occurrence
Actual Costs 10% Below Estimated	-$6,300,000	-$6,232,500	0.05	-$6,525,000	-$6,210,000	0.05
Actual Costs = Estimated	- 7,000,000	- 6,925,000	0.50	- 7,250,000	- 6,900,000	0.80
Actual Costs 10% Above Estimated	- 7,700,000	- 7,617,500	0.23	- 7,975,000	- 7,590,000	0.10
Actual Costs 20% Above Estimated	- 8,400,000	- 8,310,000	0.22	- 8,700,000	- 8,280,000	0.05
Expected Monetary Value (EMV)	- 7,434,000	- 7,354,350		- 7,358,750	- 7,003,500	

Step 1: Alt. I: (-$6,300,000 x 0.05) + (-$7,000,000 x 0.50) + (-$7,700,000 x 0.23) + (-$8,400,000 x 0.22) = $7,434,000

Step 2: Best expected monetary value (EMV) = lowest expected total cost, i.e., $7,003,500 or Alternative IV.

Table 5. Opportunity Loss Table (Time Span = 50 Years)

Events	Rehab. Alternatives (in Dollars) Alt. I	Alt. II	Probability of Occurrence	Replace. Alternatives (in Dollars) Alt. III	Alt. IV	Probability of Occurrence
Actual Costs 10% Below Estimated	$ 90,000	$ 22,500	0.05	$315,000	-0-	0.05
Actual Costs = Estimated	100,000	25,000	0.50	350,000	-0-	0.80
Actual Costs 10% Above Estimated	110,000	27,000	0.23	385,000	-0-	0.10
Actual Costs 20% Above Estimated	120,000	30,000	0.22	420,000	-0-	0.05
Expected Opportunity Loss (EOL)	$106,000	$ 26,435		$355,250	-0-	

Step 1: Consider in the event that actual costs are 10% below estimate: The best alternative is Alt. IV.

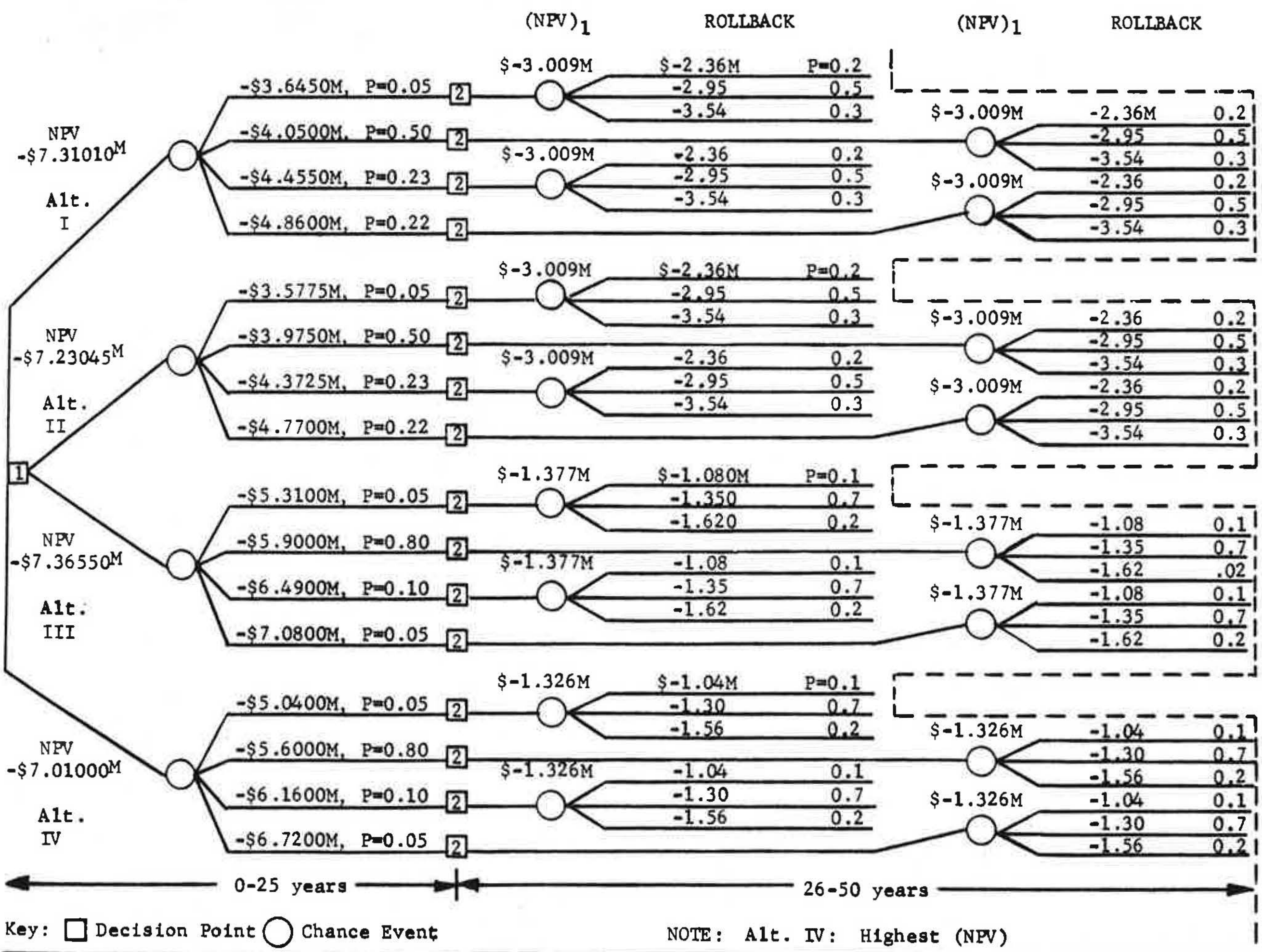
Opportunity loss in selecting:
Alt. I = (-$6,210,000) - (-$6,300,000) = $ 90,000.
Alt. II = (-$6,210,000) - (-$6,232,500) = $ 22,500.
Alt. III = (-$6,210,000) - (-$6,525,000) = $315,000.
Alt. IV = (-$6,210,000) - (-$6,210,000) = 0.

Step 2: Alt. I - EOL = ($90,000) (0.05) + ($100,000) (0.5) + ($110,000) (0.23) + ($120,000) (0.22) = $106,200.

Step 3: Best Expected Opportunity Loss (EOL) = lowest expected opportunity loss, i.e., $0 or Alt. IV.

Negative signs indicate costs.

Figure 1. Decision Tree



<u>Typical calculation:</u> <u>Alt. II:</u> $(NPV)_1 = -[(2.36 \times 0.2) + (2.95 \times 0.5) + (3.54 \times 0.3)]\,M = \$3.009M$

$(NPV) = -[(3.5775 + 3.009)(0.05) + (3.975 + 3.009)(0.50) + (4.3725 + 3.009)(0.23) + (4.77 + 3.009)(0.22)]\,M = \$7.23045$ million.

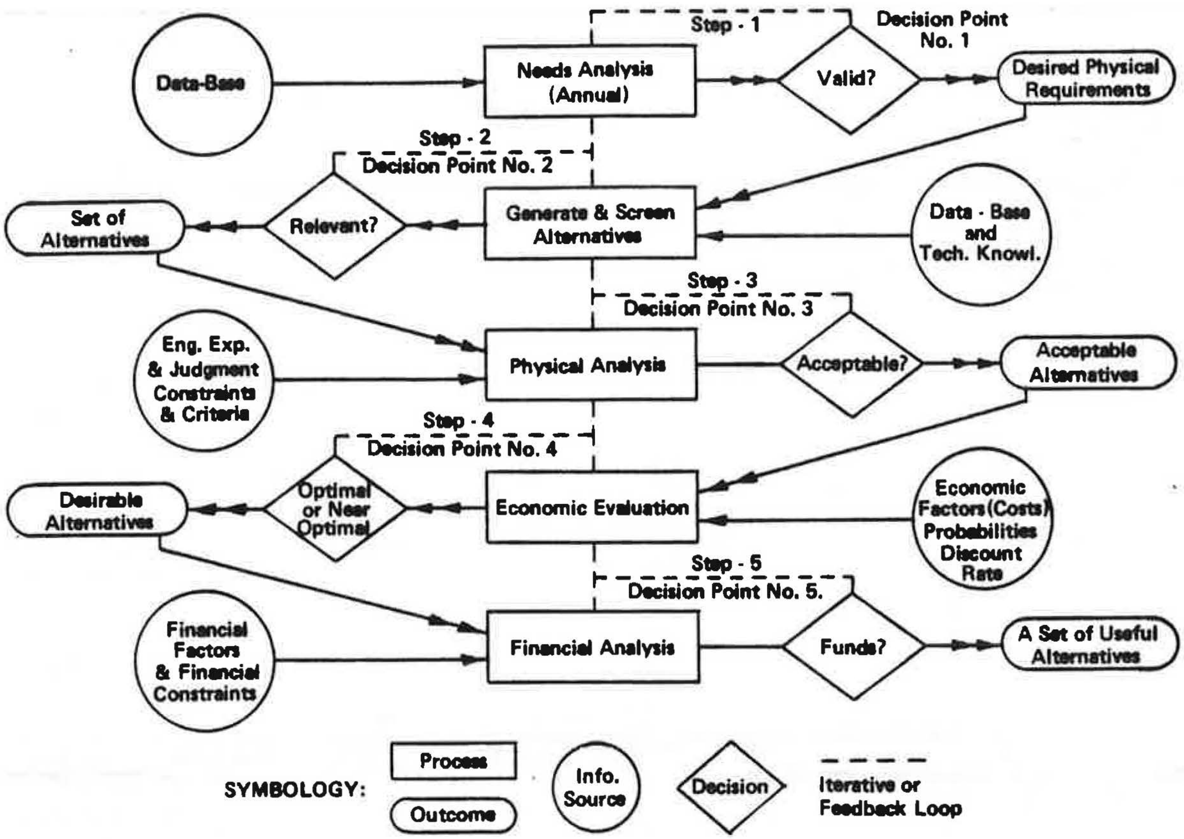


Figure 2: FLOW CHART OF DECISION-MAKING SYSTEM

Discussion of Illustrative Example

Tables 4 and 5, as well as Figure 2, indicate Alt. IV as the optimal or best alternative. Further, all alternatives can be tabulated in increasing order of present value of the total costs. The decision tree brings out two-stage nature of the decision. It uses two separate sets of probability values to reflect increased uncertainty of future costs. Further, it helps a decision-maker match available alternatives with present and future sources of funds. For example, an agency with extremely limited present funds may wish to select Alternative I and defer major capital outlay to a future date. When financing costs are expected to remain high for more than five years, an agency may wish to select Alternative II. When funds are available and present financing costs are reasonable but expected to rise sharply, an agency may wish to select Alternative IV.

Events: Experience indicates the general range of actual costs of bridge projects to be 10% below to 20% above the estimated costs. For simplicity of illustration, indicated events were selected.

Probabilities: 10% or 20% cost-overruns for rehabilitation projects are considered equally likely, but about half as likely as event of no overruns. Accuracy of replacement estimates is considered high. Probabilities of occurrence have been set accordingly. For decision-tree, probabilities of events associated with the second decision are adjusted for increased uncertainties of the future. In case of genuine differences of opinion about selected probabilities, sensitivity analysis with different sets of probabilities can be used to examine the optimality of the decision.

Expected Opportunity Losses are also costs one could incur to obtain perfect information. It indicates the maximum amount of money that could be spent to predict an outcome with absolute certainty (8). For example, a decision-maker could determine the amount he could spend in ultrasonic or other testing to make estimates of rehabilitation with certainty.

Conclusion

This paper has presented a systems approach to the difficult bridge structure rehabilitation or replacement decision-making. The decision-maker can select a suitable method for evaluation of different alternates based upon special requirements of individual situations and future implications of decisions. This system is simple, adaptive, and the decision process is easy to control. The decision-making process based on systems approach can be utilized manually for smaller and simpler investment decisions or can be computer based for large and complex investment decisions. It can be easily adapted to the needs and desires of the decision-maker, and can be no more difficult or involved than the decision itself.

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