FINAL REPORT

USE OF LIFE CYCLE COSTS IN BRIDGE PLANNING AND DESIGN

Project IA-HI, FY 92

Report No. ITRC FR 92-1

Prepared by

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Illinois Transportation Research Center
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16. Abstract

An analytical approach for bridge life cycle cost analysis and the selection of the most cost-effective bridge maintenance, rehabilitation and/or replacement (MR&R) strategy is presented. A parameter, which incorporates age, condition rating and cost, called the "value index" (VI), is used as a basis for comparing various bridge MR&R strategies. The bridge rating data is used as a basis to incorporate the condition of a bridge in the model. Using an optimization approach, the VI and bridge deterioration as a function of time are used to permit rational decisions to be made about scheduling and the type of bridge work to be executed. Using the VI and the present worth (PW), the option with the greatest VI and the smallest PW is taken to be the most desirable one. Although the VI is related to the PW and the optimum VI corresponds to the minimum PW, such constraints as the number of bridge work alternatives, anticipated service life and desired minimum condition rating may give rise to several different optima. In most cases, the scheduling of bridge works can be used as the most critical decision-making step in minimizing the cost. The results from the case studies presented in this study indicate that a minimum cost option is not necessarily the most desirable one. In certain applications it may be desirable to increase the cost so that the time between consecutive bridge works can be lengthened.

17. Key Words

bridge analysis, bridge, decision-making, life cycle cost, optimization, maintenance, planning, rehabilitation, repair

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FOREWORD

This report presents an analytical approach for highway bridge life cycle cost analysis and the selection of the most cost-effective bridge maintenance, rehabilitation and/or replacement strategy. The study was sponsored by the Illinois Department of Transportation through a contract with the Illinois Transportation Research Center (ITRC) and conducted by the Department of Civil and Architectural Engineering, Illinois institute of Technology (IIT). The authors acknowledge the continuous help from IDOT's personnel during the course of the project. The assistance provided by Robert Dawe, Yavuz Gonulsen, Paul Johnson, Lou Haasis and Dick Smith of the Illinois Department of Transportation and Dr. Steven Hanna of Illinois Transportation Research Center is acknowledged.

Notice

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EXECUTIVE SUMMARY

This study presents an analytical approach for highway bridge life cycle cost analysis and the selection of the most cost-effective bridge maintenance, rehabilitation and/or replacement strategy. A parameter, which incorporates age, condition rating and cost, called the "value index" (VI), is used as a basis for comparing various bridge maintenance, rehabilitation and replacement strategies. This enables rational decisions to be made regarding the type of work to be performed that best suits a bridge's needs within the constraints of available funds. Information on the past records of inspection, maintenance and repair of various types of bridges is especially critical to this decision-making process. Bridges in Illinois are regularly inspected and rated on a routine basis. The rating data can be used as a basis to develop models to predict deterioration as a function of time of a bridge or bridge component. These models can then be utilized in bridge life cycle cost analysis for the purpose of estimating the variation in the condition of a bridge over its service lifetime. This study presents an optimization approach which employs the value index (VI) and bridge deterioration as a function of time to permit rational decisions to be made about scheduling and the type of bridge work to be executed.

The decision on the number and timing of bridge works to be made depends on many factors of which the available funding

level is perhaps the most important one. The objective of this study is to develop a procedure that can provide a rational means to analyze the most significant variables affecting bridge life-cycle costs in the decision-making process.

The model developed in this study uses only a limited number of variables in the analysis. These variables are, however, considered to be those most critical ones in bridge life-cycle planning. The concept described herein makes use of the value index (VI) and the total present worth value (PW). Using this concept, the option with the greatest VI and the smallest PW is taken to be the most desirable one. The model developed in this investigation is based on optimization of the value index VI in the decision-making process. It is also based on the notion that the value index is directly related to the magnitude of the present worth PW. Generally speaking the optimum VI value corresponds to the minimum PW; however such constraints as the number of bridge work options planned for the bridge, the anticipated service life and the desired minimum condition rating may give rise to several different optima. The advantage of using both VI and the PW over the PW alone in decision-making is that the VI also includes the optimum time schedule for the selected bridge work options as well as the cost in the analysis. The model developed in this study can also be used to make decisions on the timing of bridge works within a designated life cycle. In most applications, the scheduling of bridge works can be used as the most critical decision-making step in minimizing the cost. The results from the case studies presented in this study indicate that a minimum cost option is not necessarily the most desirable one. In fact, in certain applications it may be desirable to increase the cost so that the time between consecutive bridge works can be lengthened. In a network level analysis, this is especially important because individual bridges can be evaluated and compared for their repair/rehabilitation needs in terms of overall costs. If a particular bridge appears to require higher costs, then the allocation of funds to the other bridges in the network can be adjusted to reflect this.

In long-term planning, the significance of early bridge repair and rehabilitation works can be compared with delayed ones by means of the life-cycle cost approach. Although delaying any particular bridge works may be expedient, and perhaps more expensive in the long term, the functional condition of the bridge and its adherence to safety requirements may be decisive in setting priorities for bridge works.

CHAPTER I

INTRODUCTION

1.1 Introduction and General Background

Bridges constitute a unique class of structures that are influenced by a continuously changing load environment. Due to the nature of their load and field conditions, bridges are subject to a more rapid deterioration process than most other structures. With a wider variety of variables affecting the performance, safety, service, cost of a bridge and its longevity, the decision-making process to rehabilitate, and/or replace the bridge often becomes an overwhelming task. Generally, this process requires a careful evaluation of various alternatives, that can be implemented to upgrade deteriorating and deficient bridges, in terms of such factors as: cost, bridge service, safety, ease of construction, etc. Only when these factors are carefully evaluated and ranked, can a rational basis for selecting the most effective alternative be developed and applied to the decision-making process and to bridge planning and design. With the increasing volume of truck traffic and rapid deterioration of bridge elements, most highway bridges are rapidly approaching a stage that require some type of maintenance, rehabilitation or replacement. Nearly one third of Illinois' 8,000 state maintained bridges are classified as "structurally deficient" or "functionally obsolete" by the current Federal Highway

Administration (FHWA) standards (1)*. Many of these structures are beyond the point where preventative maintenance can be effective and must be substantially rehabilitated or replaced.

Illinois' FY 1992 allocation of bridge replacement and rehabilitation program funds is about $66.9 million (does not include $17.6 million in discretionary bridge replacement funds for the Clark bridge). This is more than a 76 percent increase in program funds over FY 1991 (2). Illinois' FY 1993-97 proposed Highway Improvement Program totals $5.375 billion. This $5.375 billion capital program for FY 1993-97 includes $4.249 billion for improvement to the state system, with the remaining $1.126 billion available for local highway and bridge projects (1). Rehabilitation of the existing system is a program development priority. The $4.249 billion program will improve 3700 miles of highways and replace or rehabilitate 880 bridges. Also, there are $225 million of projects added to the bridge replacement and rehabilitation (1).

If bridge structure and deck deficiencies are not identified and repaired in a timely fashion, further deterioration would require major rehabilitation or bridge replacement. These actions cost significantly more than highway repair on a unit-cost basis. In addition, deferred

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* Numbers in parentheses refer to reference numbers in the bibliography

investment on deficient bridges may lead to unsafe conditions that will be costlier to remedy in the long run. If sufficient funds are not available, or for some reason improvements are not made, minor deficiencies are likely to become more severe. The difference between the cost of fixing the problem when it first develops and that incurred at a later date is the cost of deferral. In most cases, the overall cost will substantially increase due to the cost of deferral.

Considering the volume of deficient bridges and the overwhelming amount of work needed for their retrofit, it is evident that the available funds will not permit the rehabilitation or replacement of all candidate bridges. Thus there is a need to develop an optimization approach that can be used for the proper allocation of available funds to maximize the return on investment. Any such approach will be an important part of bridge management or, as commonly referred to as, the bridge life-cycle cost analysis and management.

In recent years, the importance of life cycle cost analysis has been stressed by various state departments of transportation. References (3), (4) and (5) address several approaches that can be used for the selection of various bridge maintenance, repair or replacement strategies. References (6) and (7) describe the application of bridge management techniques to Illinois bridges to a limited extent.

In these studies, the major parameters that are believed to influence the decision-making process for bridge rehabilitation and replacement are investigated and some important conclusions are drawn. In August 1989, a joint venture between Optima, Inc. and Cambridge Systematics, Inc. was awarded a contract to develop a comprehensive, rigorous and flexible network optimization and planning system, called **PONTIS**, that could be used to formulate network-wide bridge maintenance, repair and replacement and improvement policies. This system has already been completed (8). On another front, Ref. (9) presents the equivalent uniform annual cost (EUAC) method as a means for life cycle cost analysis for highway bridges.

Aside from the above methods, life cycle cost analysis methods have also been developed and applied to highway bridge total capital and maintenance cost management. One such method is reported in Ref. (10) and is built into a simulation method used for highway bridge investment evaluation.

1.2 Objectives and Scopes of Study

The objectives of this investigation are:

- To identify decision-making factors that can be used as a means to select, or to compare the most cost-effective alternatives for bridge maintenance, rehabilitation and/or replacement;
- To determine the relative importance of each factor in

the bridge life cycle cost; and,

- To develop a method that can be used for the analytical treatment of bridge life cycle cost analyses and the selection of the most cost-effective bridge maintenance, rehabilitation and/or replacement strategy.

This study presents an overview of available bridge management systems (BMS), life-cycle cost analysis methods and bridge planning and decision-making techniques used in conjunction with life-cycle cost analyses. Based on a review of current methods, key factors that impose a dramatic effect on bridge life-cycle cost analysis and evaluation of various inspection, rehabilitation and/or replacement are identified and presented. Methods that can be used to evaluate, rank and quantify these factors are examined and implemented in the development of a bridge life-cycle cost analysis method.

The method presented herein is based on such factors as age, available funds and condition rating, among others. A parameter, referred to as the "value index", is then used as a basis for comparing various bridge maintenance, rehabilitation and replacement alternatives. A basic element of the method developed in this study is the use of previous bridge maintenance, rehabilitation and replacement history as a means to: (i) construct an activity profile for the bridge; and (ii) establish analytical functions that can be used to predict bridge deterioration (in terms of a gradual reduction in the condition rating). The scheme used for selection of the most cost-effective bridge maintenance, rehabilitation or replacement alternative is a mathematical optimization process. The "objective function", i.e. the function to be optimized, is written in terms of the key factors that control the decision making process. The method presented in this report is applied to a series of case studies for highway bridges in Illinois. In each application, the methodology for the analysis of bridge life-cycle cost is explained. The significance of certain limits imposed on key factors in the optimization process and various alternatives that can be selected within these limits are also presented and discussed.

1.3 Structure of Chapters

Chapter II presents a brief review of related research in the area of bridge life-cycle cost analyses. The details of several current methods such as the equivalent uniform annual cost and the cost-effective improvement methods are also treated.

Chapter III describes the key factors that can be used as variables in bridge life-cycle cost analysis.

Chapter IV presents the basic concept underlying the model developed herein for bridge life-cycle cost analysis.

Chapter V focuses on the computer implementation of the model.

Chapter VI presents a series of case studies to illustrate the application of the model to highway bridges in

Illinois.

Chapter VII presents the summary, conclusions and recommendations for future continuation of this study.

CHAPTER II

REVIEW OF RELATED RESEARCH WORKS IN HIGHWAY BRIDGE LIFE CYCLE COST ANALYSIS

2.1 Background

Bridge management systems (BMS) comprise the various techniques need to help make decisions on the type of works that need to be performed to maintain the serviceability of a bridge and to extend its useful life. The Federal Highway Administration (FHWA) defines a BMS as "an integrated set of formal produces for directing or controlling all activities related to bridges" (11). In this study BMS is referred to as an automated system that is intended as a design and decision-making tool to select the most economical and viable approach in bridge maintenance, rehabilitation or replacement. The BMS generally leads to conclusions on the basis of: (i) cost-benefit modeling and analysis; (ii) records of previous inspections; and (iii) expert knowledge. Ideally, a BMS consists of several modules, each geared to a specific task. For example, different modules are designed to perform the necessary economic analysis on a specific alternative (e.g. rehabilitation) among various potential alternatives (i.e. rehabilitation, replacement, etc.).

Life-cycle cost analysis is the process by which the total cost of maintaining a bridge over its entire life is computed. In essence, life-cycle cost analysis is a means to evaluate the cost of alternatives, such as: replacement, rehabilitation and maintenance to enable one to select an alternative that offers the lowest cost and longest life. Since, in most cases, the cost analysis is within an allocated budget, the result of the life-cycle cost analysis is often focused on how, where and when to spend money to obtain the most benefit.

Life-cycle cost analysis has already been applied to pavement management (e.g. Jung 1986 and Kulkarni 1984). Applications to highway bridge management have been developed in several recent studies (e.g. Hyman and Hughes 1983; Hudson et al. 1987; Weyers et al. 1983 and FHWA 1987). The importance of the use of life-cycle cost as part of decision-making criteria in an evaluation of alternatives for bridge management has been stressed in Sections 134 and 135 of the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA). According to ISTEA, statewide and metropolitan planning processes shall consider life-cycle cost in design and engineering of bridges, tunnels, and pavements.

Life-cycle cost analysis is based on the concepts of engineering economics and discounted cash flow analysis. All costs expected to occur throughout the entire life of a bridge due to maintenance, rehabilitation or replacement are estimated and converted into an equivalent uniform annual cost (EUAC) for the purpose of comparison. Several methods for implementation of life-cycle cost analysis are introduced herein. These are: (i) the equivalent uniform annual cost

(EUAC) method; (ii) cost-effectiveness improvement strategies; and (iii) computer-based simulation models.

2.2 Equivalent Uniform Annual Cost Method

2.2.1 General

Bridge Activity Profile. To perform a life-cycle cost analysis, it is necessary to construct a life-cycle activity profile. Certain basic information is provided in every bridge activity profile for each bridge work item. Generally, the following information is provided:

- bridge work items and the associated costs
- starting time of bridge work
- duration of bridge work

An example of a bridge life-cycle activity profile is shown in Fig. 2.1.

From Fig. 2.1, it is evident that after 10 years of bridge life has elapsed, a one-time bridge replacement with a cost of $407,900 was performed. At age 40, a deck reconstruction with a cost of $129,500 was performed. Also, routine maintenance works are continuously performed at a cost of $1,500 per year.

The bridge life-cycle activity profile can be developed based on the previous records of bridge inspections, rehabilitation and repair works. Alternatively, mathematical models, that are developed to predict bridge conditions, can be used. In such models, all previous records of bridge

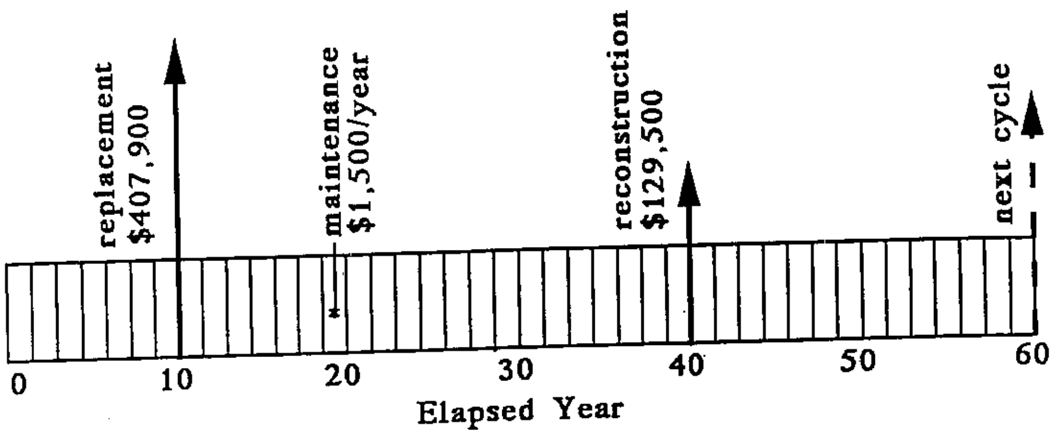

Figure 2.1 An Example of a Bridge Activity Profile

inspections, rehabilitations or repairs are used to arrive at a deterioration curve. Expert knowledge is also utilized in constructing the deterioration curve, especially if reliable data are not available. The curve is then used to assess further needs for inspection, maintenance, etc. and thus to construct a life-cycle activity profile.

Since the amount and timing of future expenditures do not exactly follow the projected activity profile, a profile constructed from a deterioration curve only provides estimates of expected future costs and activities. An example of a deterioration curve appears in Fig. 2.2. As seen in this figure, any improvement in the bridge superstructure condition will result in an extended life and a recovery in the deterioration curve.

Agency and User Costs. Agency costs refer to all expenses associated with maintenance, rehabilitation, and replacement. User costs are primarily attributed to the functional deficiencies a bridge experiences during its useful life. For example, such activities as load posting, clearance restrictions, rerouting, etc. promote an increased cost on the part of the user. The increased cost is primarily due to lost travel time, higher accident rates and perhaps more wear and tear on the vehicle. Although estimated with some accuracy, the user costs are not easy to quantify in the life-cycle cost formulation. In life-cycle cost analysis, efforts

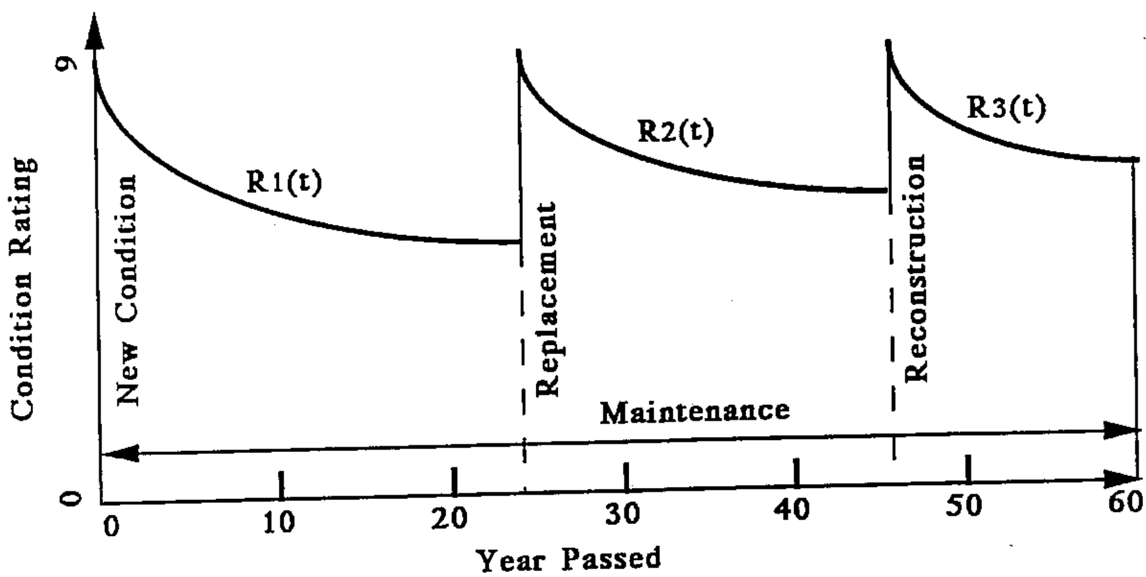

Figure 2.2 Bridge Deterioration Curve

have been made to include the user costs for the purpose of bridge cost optimization. The Indiana State highway bridge management system, for example, uses the average daily traffic (ADT) as a factor in the life-cycle cost analysis. This factor may be considered as one describing the user costs to a limited extent (9).

When added together, the agency costs and user costs make up the total bridge cost. That is,

$$\textit{Total costs} = \textit{Agency costs} + \textit{User costs} \qquad [2.1]$$

The type, amount, sequence, and timing of agency expenditures determine the amount of total costs and their distribution between agency and user costs.

Project and Network Level Analysis. Two levels of life-cycle cost analysis are considered in bridge management systems. These are: (i) the project level; and (ii) network level analyses. The project level analysis deals with alternatives for an individual bridge; whereas the network level analysis offers decision-making for a group of bridges. The first task in bridge cost analysis is to perform project level analysis. The most important part of this job is the computation of the EUAC. A BMS is primarily intended for network level analysis even though it can also provide help for making decisions on individual bridges. According to Ref.

(12), a BMS can "aid in project decision-making by providing an initial indication of the best action to take for each bridge in each budget period and the associated cost."

Figure 2.3 illustrates a flow chart of project level analysis. In the Indiana study (9) a factor called the Effectiveness Measurement Factor (EMF), as defined below, was developed for the network level analysis. This is,

$$EMF = \frac{365\,(ADT)}{EUAC} \qquad [2.2]$$

In essence, the EMF describes the number of vehicles that are served by one dollar of investment. The factor provides for a common measure to compare various alternatives. Figure 2.4 shows the steps involved in a network level analysis.

Perpetuity in Life-cycle activity Profile. When establishing the life-cycle activity profile, one assumes a repeated sequence of maintenance, rehabilitation and replacement (MR&R) works. After the first time an MR&R work has been done, the same work sequence is assumed to repeat itself in perpetuity (9). This simply means that the bridge is eventually replaced by the end of its life and that its life-cycle activity profile is repeated in a cyclic manner.

Because of this repeatability, the equivalent uniform annual cost (EUAC) in perpetuity is thus computed by

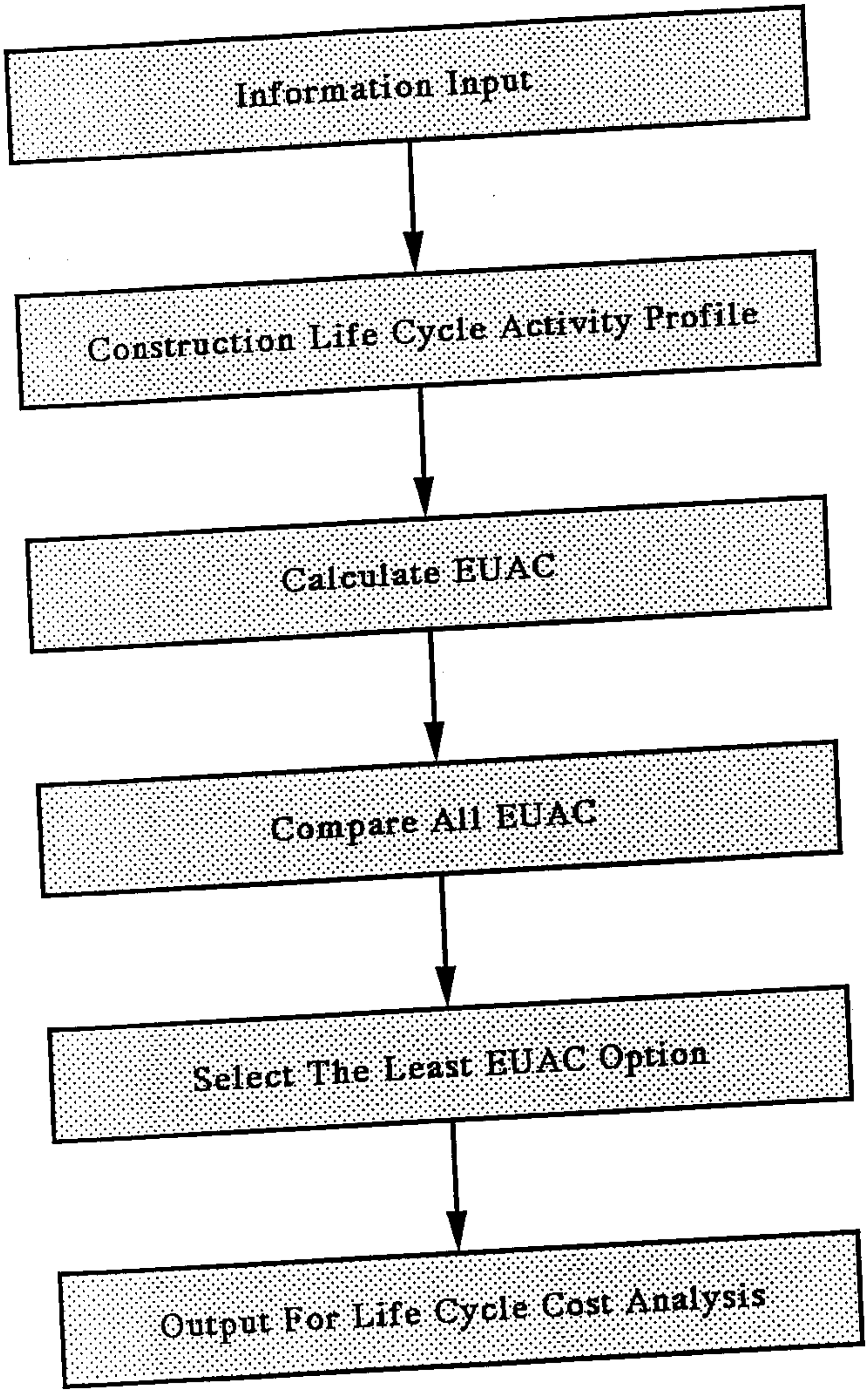

Figure 2.3 Flow Chart of Project Level Analysis (9)

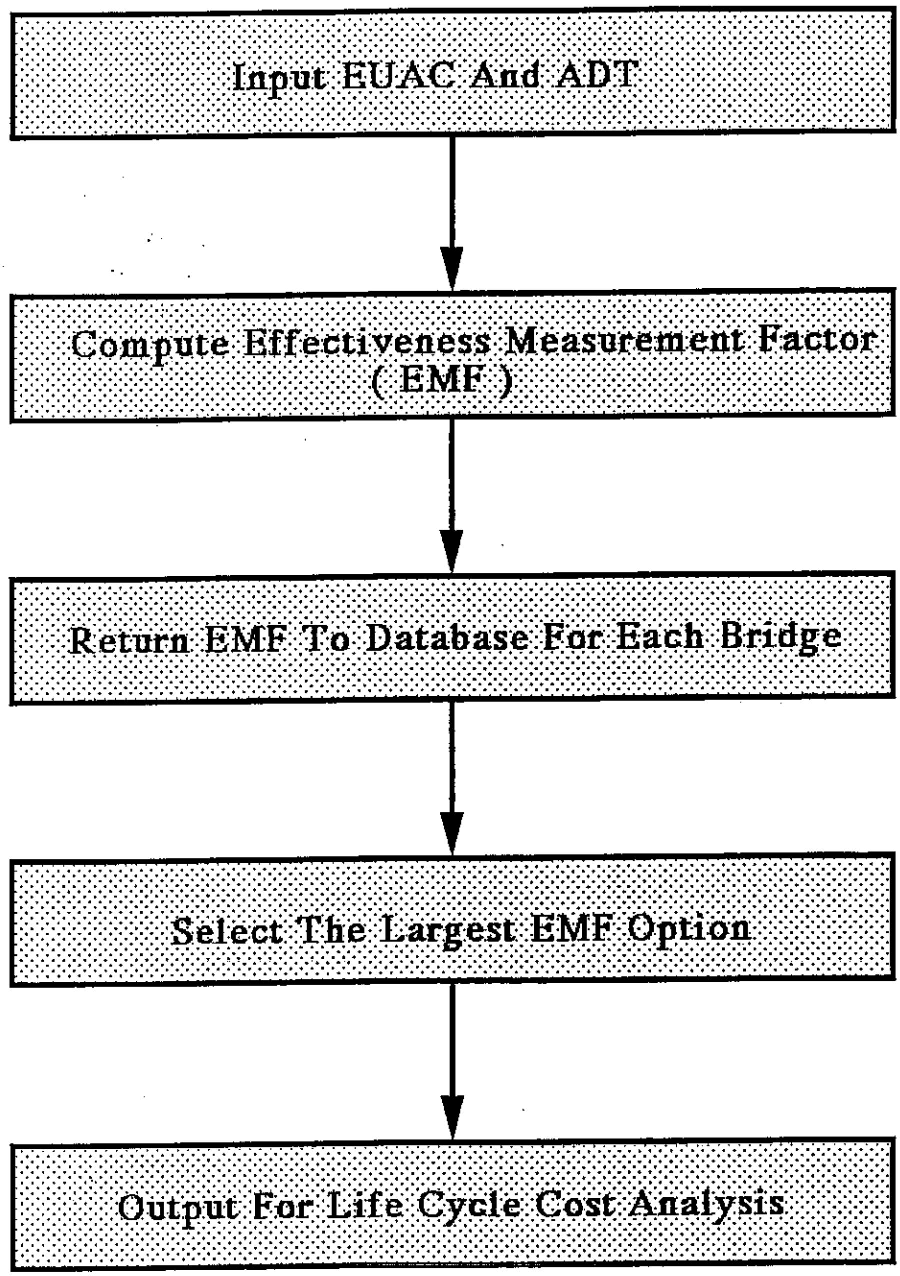

Figure 2.4 Flow Chart of Network Level Analysis (9)

multiplying the present worth of all costs by the annual interest rate (9). The advantage of using a perpetual service is that it eliminates the need to truncate the series and change the MR&R sequence (13). This provides a systematic planning approach in bridge MR&R works with manageable costs.

Assume m payments of an amount **A** are to be paid in n years beginning at year 0 as shown in Fig. 2.5. The present worth (PW) of the series is given by:

$$PW = A + \frac{A}{(1+i)^{n}} + \frac{A}{(1+i)^{2n}} + \ldots + \frac{A}{(1+i)^{(m-1)n}} + \frac{A}{(1+i)^{mn}} \qquad [2.3a]$$

For an indefinite number of recurrences m, the sum is:

$$PW = A\frac{(1+i)^{n}}{(1+i)^{n}-1} \qquad [2.3b]$$

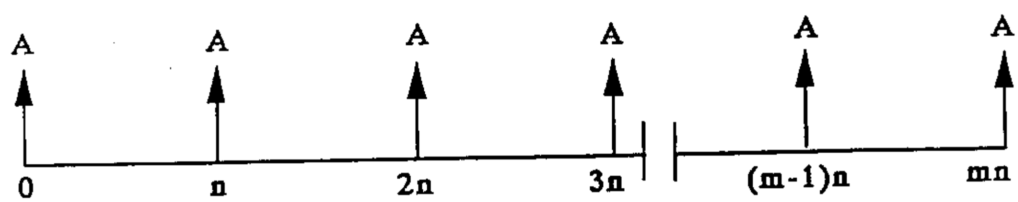

Figure 2.5 Perpetual Series

Thus if the amount **A** represents the life-cycle cost of a bridge that lasts n years, and if the bridge is replaced every n^{th} year repeatedly, then the present worth (PW) of all future costs equals the value of PW given by Eq. [2.3b].

2.2.2 Elements of Life-cycle cost Analysis

Maintenance, Rehabilitation and Replacement. The main objective in a life-cycle cost analysis is to identify the type of work to be conducted on each bridge/element or group of bridges. Then, upon the selection of the type of work, a cost-benefit analysis is performed to investigate the cost-effectiveness of the selected work. In most applications previous records of the same or similar work and its impact upon bridge service life, agency and user costs can be treated as an input to the selection process. If adequate data on the cost and benefits of various maintenance, rehabilitation and replacement (MR&R) works is available, then this data should be summarized in terms of the specific type of work.

Table 2.1 lists several work items within general MR&R activities (9). Ideally, the items in Table 2.1 should be accompanied with cost and benefit data.

Cost Prediction Model. To construct the activity profile of a bridge, estimates of cost for all alternative work items are needed. Methods using some form of mathematical function extrapolated from data on previous work are often used to make cost estimates. When previous records of bridge MR&R works are not available, the cost information for each work item can be obtained from the Federal Highway Administration (FHWA) price index or other indices that may be available through the state's records.

Table 2.1 Example of MR&R Activities (9)

MR&R Activities	
Num.#	Work Items
1	Deck Rehabilitation
2	Deck Replacement
3	Superstr Rehab + Deck Rehab
4	Superstr Rehab + Deck Replacement
5	Substr + Rehab
6	Substr Rehab + Deck Rehab
7	Substr Rehab + Deck Replacement
8	Substr, Superstr and Deck Rehab
9	Substr Rehab + Superstr Replacement
10	Substr Rehab + Superstr Rehab
11	Substr Rehab, Superstr Rehab + Deck Replacement
12	Superstructure Replacement
13	Bridge Widening + Deck Rehabilitation
14	Bridge Widening + Deck Replacement
15	Raise Bridge/Lower Pavement
16	Bridge Replacement
17	Culvert Replacement

In any case, cost prediction models are suitable for short-term planning purposes. This is because any cost prediction is expected to be subject to a lesser degree of uncertainty when applied to the near future.

Service Life and MR&R Time Scheduling. Service life estimation plays an important role in bridge life-cycle cost analysis. Service life is exhausted when the condition rating of the bridge is consistently low and no longer satisfies service requirements.

Time scheduling for maintenance, rehabilitation or replacement alternatives is related to the service life of a bridge or a bridge element. For a new bridge with an expected service life of 50 years, timing for replacement may be considered to be at t=50 years. For a bridge deck replacement the timing is often shorter and may be considered to be at t=20 years. In most applications, however, the significance of such factors as safety, increased ADT, changes in the bridge usage, etc. on bridge life may require major repair or even replacement at an earlier time.

Computation of Equivalent Uniform Annual Cost. The equivalent uniform annual cost (EUAC) is frequently used in bridge life-cycle cost analysis. The procedure using EUAC generally follows the steps depicted in Fig. 2.6. Most current methods of bridge life-cycle cost analysis utilize EUAC mainly as one of several factors that enter into the procedure. This section presents the formulation of EUAC. To

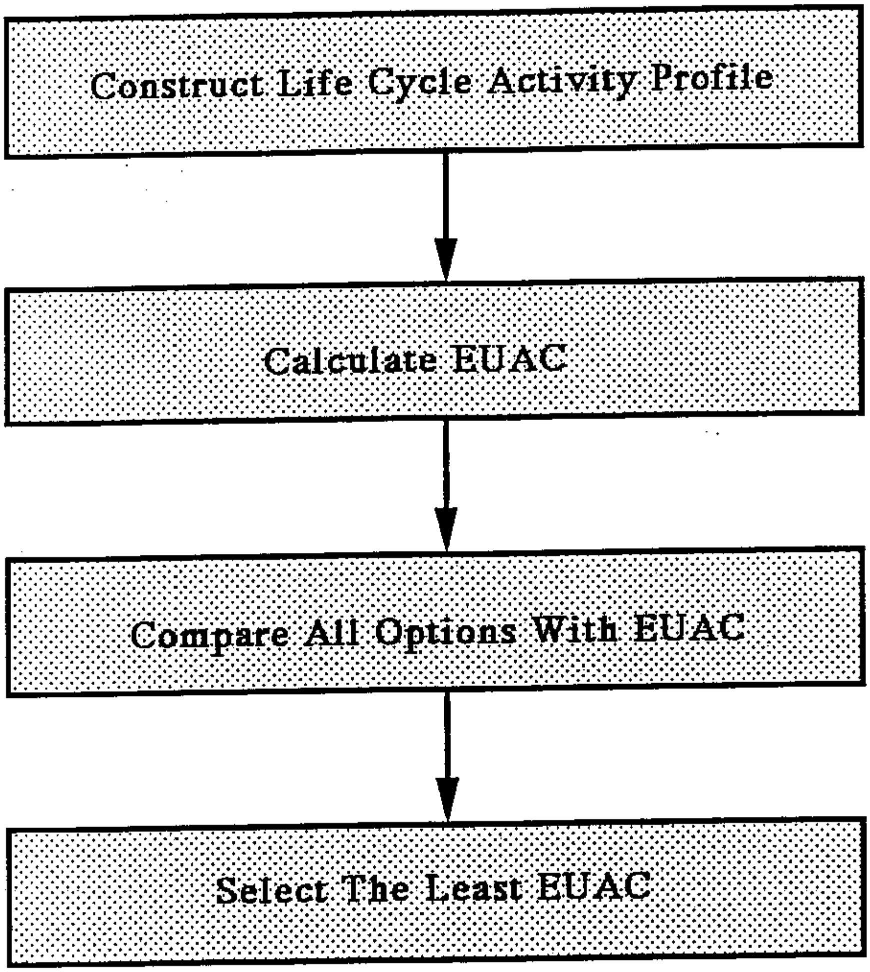

Figure 2.6 EUAC Computation Steps

derive an expression for EUAC several parameters, as described below, need to be defined (9):

(i) **Discount Rate.** This is obtained from the following equation:

$$i = \frac{(1+i^*)\ (1+q)}{(1+f)} \qquad [2.4]$$

where i^* = prevailing discount rate

q = expected rate of increase in highway funding

f = expected rate of inflation

(ii) **Capital Recovery Factor (CRF).** CRF is computed in terms of discount rate as follows:

$$CRF = \frac{i\ (1+i)^{n}}{(1+i)^{n}-1} \qquad [2.5]$$

(iii) **Single Payment.** If F is the capital and PW is the present worth (PW), the single payment present worth factor (SPPWF) is PW/F or (see Fig. 2.7a):

$$PW = F\frac{1}{(1+i)^{n}} \qquad [2.6a]$$

$$SPPWF=\frac{1}{(1+i)^{n}} \qquad [2.6b]$$

(iv) **Uniform Series.** With A being a fixed annual payment, the uniform series present worth factor (USPWF) can be written as PW/A or (see Fig. 2.7b):

$$PW=A\frac{1-(1+i)^{-n}}{i} \qquad [2.7a]$$

$$USPWF=\frac{1-(1+i)^{-n}}{i} \qquad [2.7b]$$

(v) **Uniform Gradient.** Introducing G as an increment describing an increase in annual payments, the gradient series present worth factor (GSPWF)=PW/G or (see Fig. 2.7c):

$$PW=\frac{G}{i}\{\frac{(1+i)^{n}-1}{i}-n\} \qquad [2.8a]$$

$$GSPWF=\frac{1}{i}\{\frac{(1+i)^{n}-1}{i}-n\} \qquad [2.8b]$$

(vi) **Perpetual Series.** This is a payment that repeats in n-year intervals. The perpetual series present worth factor (PSPWF) is computed as follows (see Fig. 2.7d)

$$PW=\lim_{m}^{\infty} A\frac{(1+i)^{n}}{(1+i)^{n}-1} \qquad [2.9a]$$

$$PSPWF=\frac{(1+i)^{n}}{(1+i)^{n}-1} \qquad [2.9b]$$

By using Eqs. [2.4] to [2.9], life-cycle cost can be discounted to the present worth value. The total present worth value of each type of MR&R work can then be determined.

If $(PW)_j$ represents the present worth of the j^{th} selected MR&R work, the EUAC can be computed from (9):

$$EUAC=(CRF)\sum(PW)_j \qquad [2.10]$$

in which Σ indicate that PW's of all future MR&R works are added. For a perpetual series, however, EUAC is obtained from:

$$EUAC=i\,(PSPWF)\sum(PW)_j \qquad [2.11]$$

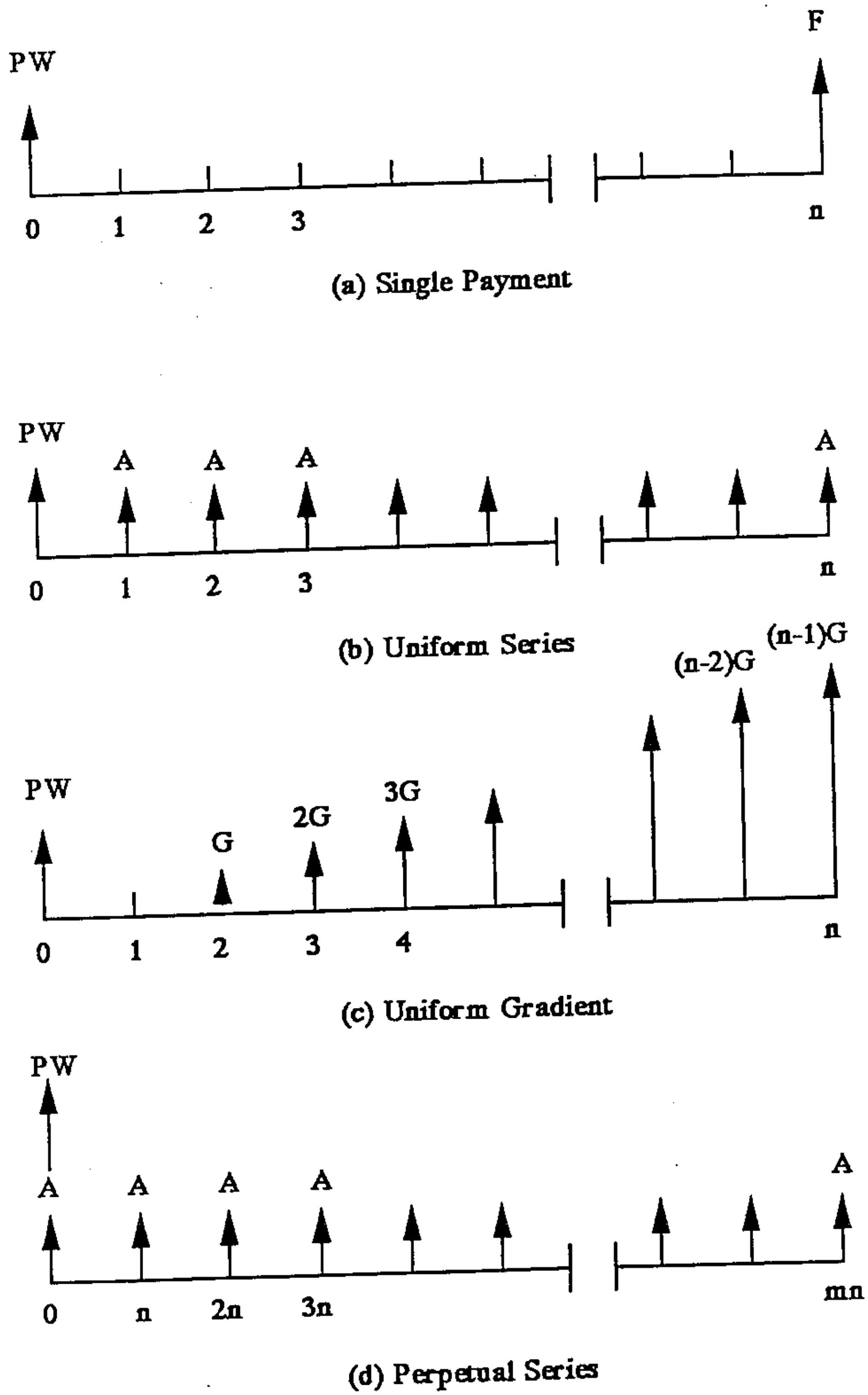

Figure 2.7 Graphical Presentation of: (a) Single Payment; (b) Uniform Series; (c) Uniform Gradient; (d) Perpetual Series

where: i = discounted rate

j = the j^{th} MR&R work during the bridge life cycle

CRF = capital recovery factor

PSPWF = perpetual series present worth factor

Example 2.1 A simple example is presented herein to illustrate the computation of EUAC. The activity profile utilized in this example is given in Fig. 2.8. In this

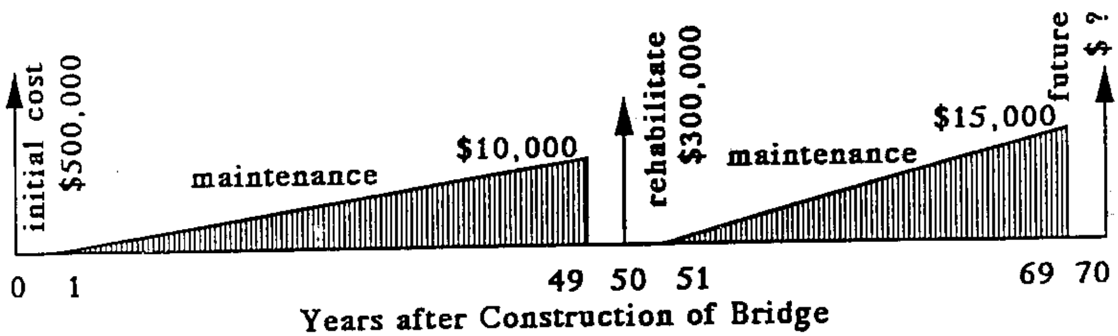

Figure 2.8 Example of Activity Profile for EUAC Computation

example, the following sequences of actions are considered:

- Initial cost=$500,000.
- Yearly maintenance cost increase steadily and reaches 2% of the initial cost at t=49 years (maintenance cost at t=49 years is 0.02×$500,000=$10,000).
- A rehabilitation is executed at t=50 years with a cost of $300,000.
- The maintenance cost after t=50 years steadily increases to 3 percent of the cost at the end of year 69 (0.03×$500,000=$15,000).

From Eq. [2.5] for i=6%,

$$CRF = \frac{0.06\,(1+0.06)^{70}}{(1+0.06)^{70}-1} = 0.061$$

For the initial cost at t=0,

$$PW_1 = 500{,}000$$

For year 1 through 49, the maintenance cost is converted to the present value PW_2 at year 0. Since the maintenance costs form a gradient series, then:

$$G = \frac{10{,}000}{(49-1)} = 208.33$$

and from Eq. [2.8a]:

$$PW_2 = \frac{208.33}{0.06}\left\{\frac{(1+0.06)^{49}-1}{0.06} - 49\right\} = 777{,}621$$

For rehabilitation in year 50, Eq. [2.6a] yields:

$$PW_3 = \frac{300,000}{(1+0.06)^{50}} = 16,287$$

Finally for maintenance from year 51 through 69:

$$G = \frac{15,000}{(69-51)} = 833.33$$

and the present worth at t=50 is:

$$\frac{833.33}{0.06}\{\frac{(1+0.06)^{19}-1}{0.06} - 19\} = 204,999$$

and from Eq. [2.6a] the present worth at t=0 is:

$$PW_4 = \frac{67,765}{(1+0.06)^{50}} = 3,679$$

Thus, the EUAC is:

$$EUAC = 0.061\,(500,000+777,621+16,287+11,129) = 79,608$$

The computation of EUAC for various options at individual levels is the first task in carrying out a life-cycle cost analysis. When two or more alternative activity profiles are compared for a single bridge, their EUAC values can be used to select the least cost option. It is also possible to add the user costs to the EUAC computation if reliable user data is available.

Example 2.2 Reference (13) illustrates an example in which the use of EUAC in life-cycle cost analysis practice is demonstrated. Two activity profiles are selected as alternatives **A** and **B** (see Figs. 2.9 and 2.10). The costs for all MR&R works are also estimated. The bridge is in poor condition and an immediate replacement is desirable. However, if necessary because of financial and/or other reasons, the replacement can be deferred for five years. In this example EUAC is computed for perpetual service. The cash flow diagrams in Figs. 2.9 and 2.10 show the timing and costs of replacement and maintenance works. It is assumed that the bridge has no salvage value. The following data are used:

i = Discounted rate = 5%

I = Bridge replacement cost = $407,900

F = Deck replacement cost = $129,500

A_1 = Maintenance cost during the five-year deferment = $1,700 per year

A_2 = Maintenance cost after replacement = $1,500 per year

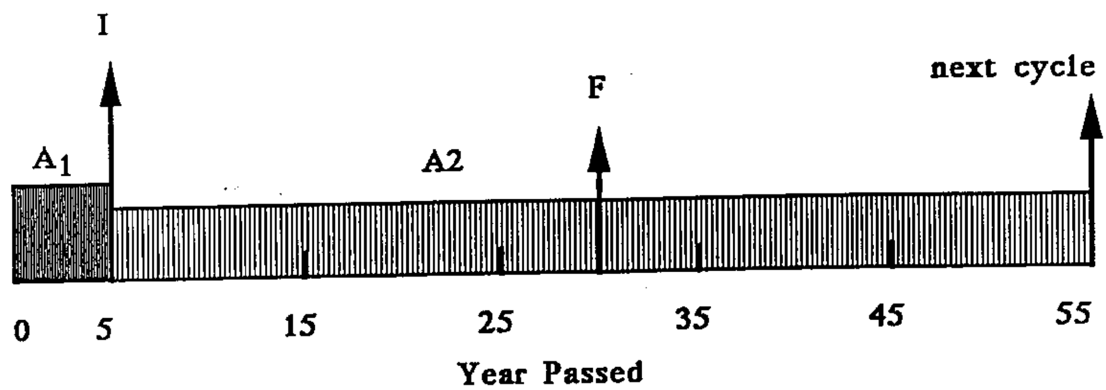

Figure 2.9 Alternative A: Bridge replacement is deferred for 5 years

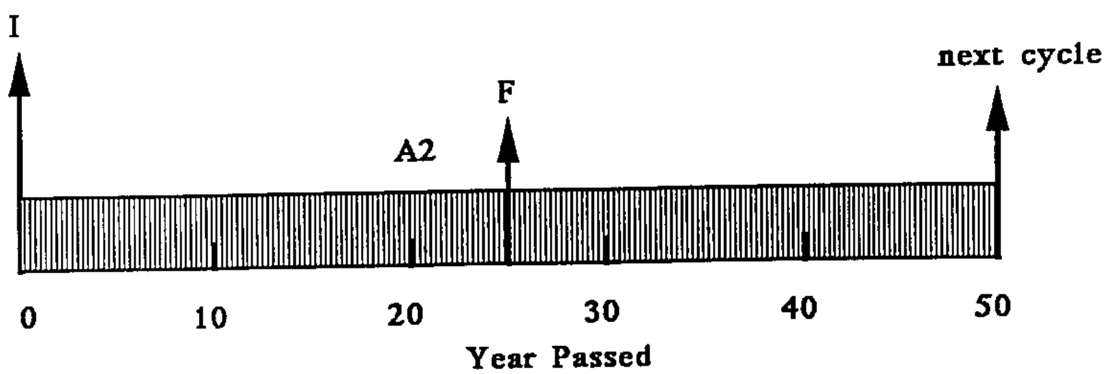

Figure 2.10 Alternative B: Bridge is replaced immediately

From Eqs. [2.6] to [2.9]:

$$SPPWF_{0.05,5} = \frac{1}{1.05^5} = 0.78$$

$$SPPWF_{0.05,25} = \frac{1}{1.05^{25}} = 0.30$$

$$USPWF_{0.05,5} = \frac{(1.05^5 - 1)}{0.05\,(1.05^5)} = 4.33$$

$$USPWF_{0.05,50} = \frac{(1.05^{50} - 1)}{0.05\,(1.05^{50})} = 18.26$$

$$PSPWF_{0.05,50} = \frac{1.05^{50}}{1.05^{50} - 1} = 1.10$$

For alternative **A**, the EUAC is:

$EUAC_A =$

$i\{A_1 \times USPWF + PSPWF \times [SPPWF \times (I + F \times SPPWF + A_2 \times USPWF)]\}$

$0.05\{1700 \times 4.33 + 1.1[0.78(407900 + 129500 \times 0.3 + 1500 \times 18.26)]\}$

$EUAC_A = 20,709$

For alternative **B**, the EUAC is:

$EUAC_B =$

$i\{PSPWF[I + F \times SPPWF + A_2 \times USPWF]\}$

$0.05\{1.1[407900 + 129500 \times 0.3 + 1500 \times 18.26]\}$

$EUAC_B = 26,078$

By comparing the two EUAC values, one may conclude that there is a benefit of $(26,078-20,709) or $5,369 per year in perpetuity by not replacing the bridge immediately. If the bridge is functionally adequate and structurally safe, then the replacement can be deferred for five more years and the funds recovered thereby can be used for others more critical needs.

In summary, in the implementation of the EUAC method, various alternatives for the activity profile are selected first, then computations of the EUAC are made. Finally, the option with the least EUAC is considered to be the best option.

2.3 Cost-effective Method and Improvement Strategies

2.3.1 General

The fundamental principle of the cost-effective method is very similar to that of EUAC method. The EUAC and cost-effective methods are also similar when used in decision-making for project level analysis. The cost-effective improvement strategies are based on cost/benefit analysis of various MR&R options and can be applied to decision-making at the project and network levels.

As briefly described earlier, at the project level the analysis is to compare benefits and costs of maintenance, rehabilitation and replacement options to determine the most beneficial alternative. At the network level fund allocation is emphasized by investigating how the money conserved at one location might achieve benefits at another. In a comprehensive bridge management system this approach is at the network level because the concern covers all bridges in a state's highway network. In contrast, a bridge life-cycle cost analysis is only concerned with one single bridge at a time. The advantage of the cost-effective method is that it can be implemented to a general bridge management system as well as to the bridge life-cycle cost analysis. Although, in principle, the cost-effective analysis is similar to EUAC method, the former also considers the user costs associated with different performance levels of service.

The following definitions are used in the formulation of the cost-effective method (13):

Agency Benefits. Agency benefits are defined as the present worth of the future cost savings to the agency as a result of an expenditure on a bridge or on groups of bridges. Net benefits for the agency are equal to the difference between agency benefits and agency costs.

User Benefits. User benefits are equal to the reduced user costs. User benefits are estimated by subtracting the user costs accumulated before bridge improvement from those accumulated after the improvement has been made. Net benefits are equal to the benefit minus the agency costs:

$$Netbenefit = Agencybenefit + Userbenefit - Agencycost \qquad [2.12]$$

2.3.2 Details of the Cost-effective Method

The method is based on the incremental benefit/cost concept. The incremental benefit/cost concept is illustrated in Fig. 2.11. As costs continue to increase, at some point in time there will be an increment of benefit that is exactly equal to the increment in cost. At this point in time, net benefits are maximum. At levels below this maximum, the slope of the benefit curve is steeper than the slope of the cost curve. This means that in this range, the incremental benefits exceed incremental costs, implying that the incremental expenditure is beneficial. The opposite is true at funding levels above the maximum, i.e. incremental expenditures in that range will not be beneficial. Accordingly, the maximum benefit is considered to be critical for decision-making purposes. Introducing ΔB and ΔC as incremental benefit and cost respectively, by comparing ΔB/ΔC with unity, one can draw conclusions on the cost-effectiveness of an MR&R alternative. The ratio ΔB/ΔC is obtained from the following equation:

$$\frac{\Delta B}{\Delta C} = \frac{B_b - B_a}{C_b - C_a} \qquad [2.13]$$

Where B_b, B_a: benefits at alternative **B** and **A** respectively

C_b, C_a: costs at alternative **B** and **A** respectively

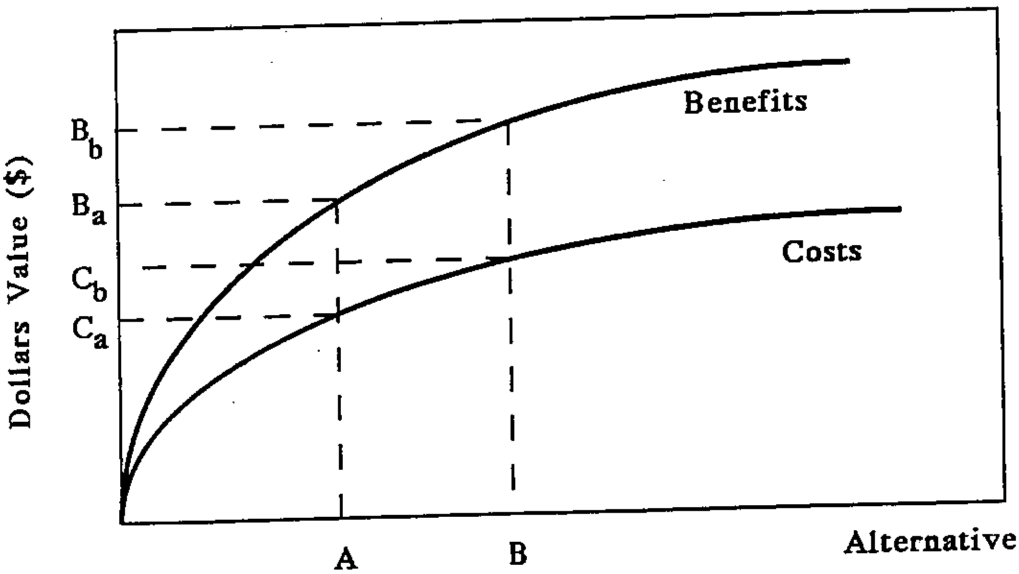

Figure 2.11 Incremental Benefit/Cost Concept (13)

Reference (13) presents an example to illustrate this method. Consider a 400-foot long, 36-foot wide steel multi-girder bridge structure designed for the HS-15 load; and as such it requires posting. The bridge carries an ADT of 5,000 of which 10 percent is made up of truck traffic. The deck width of 36 feet meets acceptable standards. The condition rating for the bridge components are:

Deck:	4
Superstructure:	5
Substructure:	6

The initial construction cost is $60 per square foot, thus the total initial cost is:

Initial cost = (60)(400)(36) = $864,000

The service life of a new bridge is estimated to be 70 years and its life-cycle cost (one life cycle) is assumed to be 1.17 times the initial cost. Therefore the life-cycle cost (LCC) is:

LCC = (1.17)(initial cost)

= (1.17)(864,000)

= $1,010,880

Four rehabilitation options and one replacement option are considered. The net benefits, discount rehabilitation costs, and the initial agency benefit/cost ratios for each alternative are computed and shown in Table 2.2. If incremental benefits do not decrease with each higher cost improvement, then the net benefit function does not have a

Table 2.2 Agency Benefit/Cost Ratios (Amount $1,000)

(1)	(2)	(3)	(4)=(2)+(3)	(5)=(4)/(3)	(6)	(7)	(8)
Alternative	Net Benefit($)	Initial Cost($)	Benefit	B/C	ΔB	ΔC	ΔB/ΔC
A	231	108	339	3.14	(Minimum Improvement)		
B	305	223	528	2.37	189	115	1.64
C	348	241	589	2.44	61	18	3.39
D	139	450	589	1.31	0	209	0
Replace	0	646	646	1.00	57	196	0.29

unique maximum. This is because the maximization of net benefits requires that the net benefit function be convex. If such a condition prevails then it is necessary to recompute the agency benefit/cost ratios. The procedure leads to the decision

- Delete all alternatives for which the incremental benefit/cost ratio is less than or equal to 1;
- Check whether as the cost increases, the incremental benefit/cost decreases. The result of recomputation is shown in Table 2.3.

From Tables 2.2 and 2.3, it may be observed that option **C** provides the maximum incremental benefit/cost ratio among all options. Therefore, it should be selected as the option of choice. If, however, **C** is not favored (due to scheduling problems, for example), then the next best option will be **B**. Note that option **D** and the full replacement option both have a $(\Delta B/\Delta C)<1$ and are thus eliminated.

It is emphasized that the aforementioned example includes only agency benefits and costs. This form of treatment may also include user costs if they are available. Reference (13) includes user costs in the analysis and finds that, based on the values assumed for costs and benefits of various alternatives, **D** becomes the option of choice.

2.4 Description of Various Computer Models

In 1982, the Wisconsin Department of Transportation

(WisDOT) developed a computer simulation model for life-cycle cost analysis to determine the least cost mix of bridge replacement and repair needs for the Year 2000 State Highway Plan (14). Bridge Life-cycle cost Analyzer (BLCCA) is another computer program that was developed by Ernst & Whinney (15) and it too is used for highway bridge life-cycle cost analysis. A brief description of these two computer models is presented below.

2.4.1 WisDOT Computer Simulation Model. This computer model uses life-cycle cost analysis to determine: (i) the least cost mix of bridge repair and replacement work, (ii) the number of bridges that will require repair, (iii) the cost associated with replacement and each type of repair work in each period, and (iv) the bridge current condition. The decision rules for replacement are made if:

- It is less costly to replace the bridge than to repair, taking into account discounted future life cycle costs.
- The age is greater than its life expectancy and the condition appraisal is smaller than a pre-determined minimum value, which indicates the bridge is in immediate need of major repairs, rehabilitations, or replacement; or
- The age is less than or equal to its life expectancy; however, the condition appraisal is smaller than the minimum value.

This computer model can also determine the least-cost associated with a combination of replacement and repair work for up to 25,000 bridges in a 20-year time period. The key input data is the life-cycle activity profile. Figure 2.12 shows the flowchart of the model.

The output from the program consists of:

- The number of bridges replaced in each period and the corresponding costs.
- The increase in deck area after replacement.
- Number of bridges that have received no attention in each time period.
- The number and types of repair work.
- The average condition in each year where repair is in progress or in the planning stage.

There are some limitations inherent in this program. For example, the user costs and benefits are not included. Furthermore, the cost estimates from this program are made without any constraints.

2.4.2 Bridge Life-cycle cost Analyzer (BLCCA). In the bridge life-cycle cost analyzer (BLCCA) program, developed by Ernst and Whinney, the input is based on results of the bridge inventory and appraisal files. These files are prepared on a biennial basis and submitted to the Federal Highway Administration (FHWA) for incorporation into the National Bridge Inventory (15). The major input to the program consists of:

- Bridge construction cost.
- Maintenance intervention cost.
- Expected bridge life as a function of maintenance intervention.

The program performs computations in five steps as described below:

- It finds the missing values in the table of annual costs.
- It inflates all dollar amounts.
- It finds the present worth value of each expense category.
- It converts each present value to an equivalent annual amount.
- It sums the equivalent annual amount over all cost categories to determine the total annualized cost of the cash flow being analyzed.

The major limitation of this program is that the full required data may not be available. As Ref. (15) suggests: "... insofar as the data base deficiencies can be resolved, the scenarios suggest that the methodology could be a very useful tool for identifying cost-effective bridge maintenance policies and programs."

The program was tested using data from the North Carolina Department of Transportation (NCDOT). To a certain extent, the results of the sample runs show the method's practical application and usefulness. The BLCCA program is written in the advanced BASIC language to run on an IBM PC or compatible microcomputers.

Table 2.3 Recomputed Agency Benefit/Cost Ratios ($1,000)

Alternative	Cost ($)	Benefit ($)	ΔB	ΔC	ΔB/ΔC
A	108	339	(minimum improvement)		
C	241	589	250	133	1.88
B	223	528	189*	115*	1.64

* Calculated based on alternative A

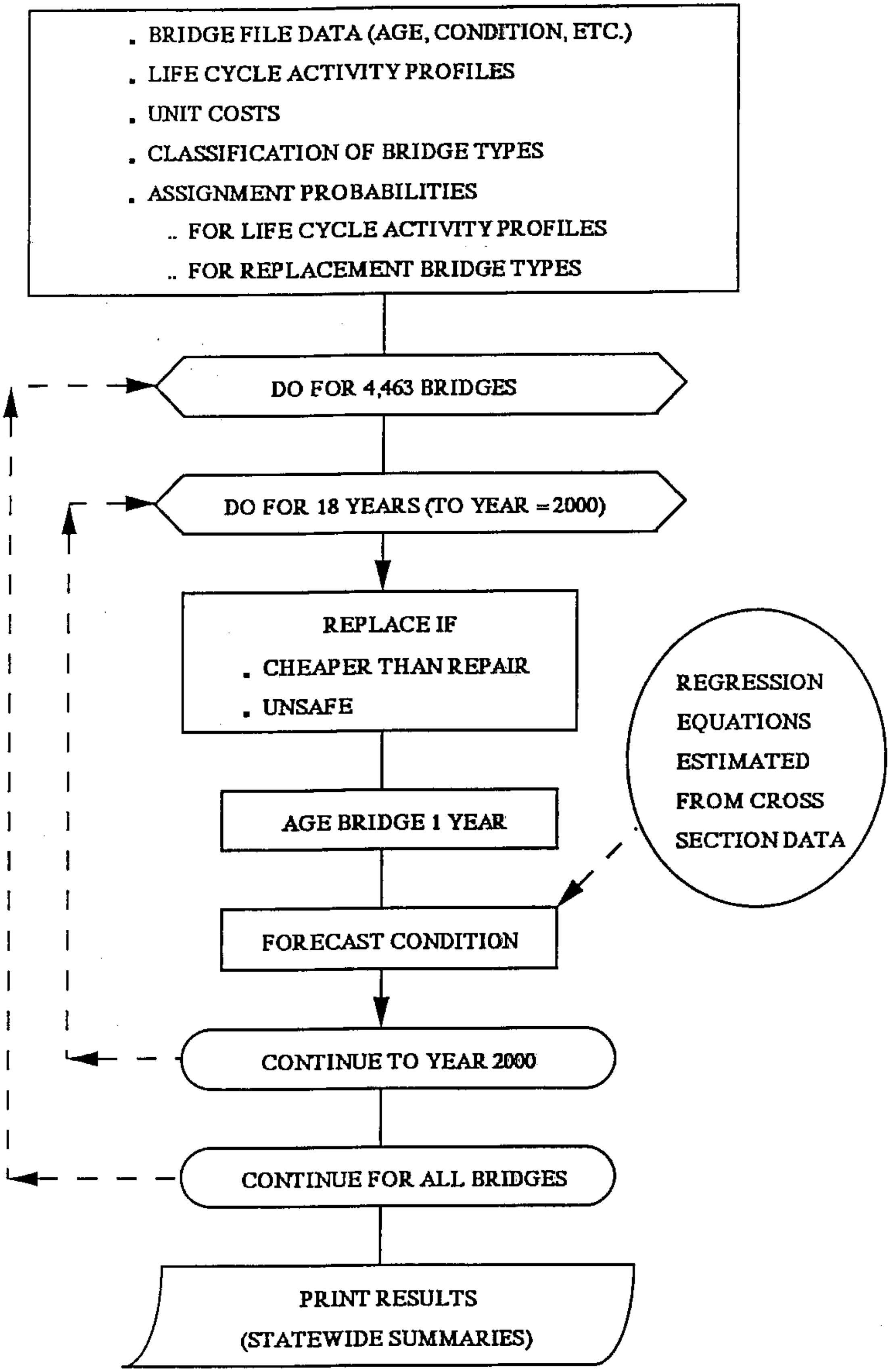

Figure 2.12 Flowchart of WisDOT Computer Model (14)

CHAPTER III

VARIABLES AFFECTING HIGHWAY BRIDGE LIFE-CYCLE COST ANALYSIS

To utilize a bridge management systems (BMS) effectively, one should identify the various parameters that influence all of the activities that are defined within the BMS. Since a BMS concerns bridge planning on a long-term basis, most of the parameters that influence the decision-making process tend to change during the life time of a bridge. Thus, not only is it important to identify all of the parameters; it is also necessary to quantify their respective variations with time. In this chapter a discussion of the variables that affect the highway bridge life-cycle cost analysis is presented. These variables are divided into five groups; namely economics, construction, structure, life-cycle and other variables. Under each group, several variables are identified; however, only those variables that have a dramatic influence on life-cycle cost analysis are ultimately to be used in the modeling. The following is a list of potential variables.

Economic Variables--These include:

- Availability of funds.
- Project cost, including maintenance, rehabilitation and replacement option costs.
- Future maintenance cost of various options.

Construction Variables--These include:

- Feasibility of an option in terms of its ease of construction.

- Quality of construction.
- Duration of the construction project.
- Impact of construction on the traffic, delays, lost revenue (for toll roads and bridges), etc.

Structural Variables--These variables describe the geometry and design of the bridge. They include:

- Bridge and bridge element condition ratings.
- Type of bridge structure.
- Structural safety requirements including overall desired factor of safety, integrity, etc.
- Fatigue of components.
- Bridge load magnitude and frequency, e.g. truck weight, truck traffic volume and their growth in the future.

Life Cycle Variables--These include:

- Age of bridge and bridge elements.
- Bridge and bridge element deterioration rate. (as reflected in a reduction in condition rating).
- Estimated life of bridge and bridge elements.
- Scheduling of various MR&R alternatives.

Other Variables--Aside from the above, several other variables are also important in bridge life-cycle cost analysis. These variables are:

- Historical data of MR&R works on bridge and bridge elements.

- Importance of bridge to the roadway in terms of flow and volume of traffic.
- Environmental conditions, e.g. climatic condition, chemical reactions, reinforcement corrosion, etc.
- Seismic effects.
- Demographics.

To quantify each variable, a rigorous program of bridge analysis, data acquisition, bridge condition assessment and a study of bridge economics will be needed. The type of effort required to quantify one variable may be quite different from that required for another. For example, structural dynamic analysis and historical records of past seismic activities will be needed to quantify seismic effects; whereas the effects of construction activity and duration of construction work requires compilation of data from similar activities or perhaps from expert opinion. In this study, however, only those variables that have a dramatic effect on bridge life-cycle costs are considered. To quantify these variables, historical records of repair and maintenance that may be available (for bridges similar to the one being considered in the analysis) are needed. A discussion of variables used in the life-cycle model is presented in the following sections.

3.1 Bridge Traffic

Bridge traffic is measured by the average daily traffic (ADT), average daily truck traffic (ADTT), and truck weight.

The rates of ADT and ADTT growth are also important in defining bridge traffic. A recent study (16) presents a comprehensive evaluation of the effect of truck weight and traffic increase on Illinois highway bridges. That study addressed the increase in traffic as an important factor in early fatigue damage occurring to bridges in Illinois. With regard to the future growth in the commercial truck traffic, Ref. (16) indicates that the Illinois Department of Transportation compiles a comprehensive set of data on traffic volumes on Illinois highways. This data includes annual traffic growth, traffic growth trends, and average estimates for traffic growth in Illinois. Such data can provide a basis for quantifying the effect of traffic growth on life-cycle costs of bridges.

3.2 Scheduled Time for MR&R Action

A major variable affecting bridge planning is the scheduled time for maintenance, rehabilitation and replacement (MR&R) events.

Reference (9) presents an investigation into the effect of scheduled event times on bridge life-cycle costs. The study indicates that statewide average service life of highway bridges in Indiana is 52 years. Statistical data show that there is a difference in bridge service life with rehabilitation and without rehabilitation. However, the average difference observed was only 4 years. Furthermore, the influence of rehabilitation work upon the entire bridge life was found to be small especially if the work involved replacement.

As for rehabilitation options, two major actions, namely, deck reconstruction and deck replacement were considered. It was found that the first deck reconstruction would take place approximately 20 years after the initial construction of a bridge. The study also showed that the average life of a bridge before it receives the first deck replacement is about 45 years and that very few bridges receive deck replacement as opposed to deck reconstruction. Some bridges receive a second deck reconstruction; but they rarely need a third or fourth replacement (9).

According to Ref. (9), in most bridges, the element rating is unaffected by routine maintenance actions. However, Ref. (9) does not include any systematic time series analysis to demonstrate how the timing of maintenance can affect the rating and thus the life-cycle costs of bridges.

3.3 Age of Bridge

Most agencies possess age distribution data for their bridges. Age is particularly important because it can be used directly as a means to prioritze bridges for rehabilitation, repair or replacement. In a bridge management system, age plays an important role in the decision-making process for long-term planning. It is often needed to identify a desired extended service life and thus to plan appropriate actions accordingly. The current age of a bridge will play an important factor in selecting its desired extended service life for planning purposes.

3.4 The Minimum Cost

It is obvious that cost optimization is considered to be the most important objective by many highway agencies. Cost, as a factor, needs to be clearly identified and estimated as accurately as possible. When necessary, a further breakdown of the cost into sub-categories such as agency and user costs needs to be done for a more comprehensive life-cycle cost analysis. Of course, costs are subject to change with time. Thus appropriate estimates of inflation and interest rates are needed for bridge MR&R planning.

3.5 Structural Adequacy and Functional Obsolescence

The questions to whether or not to base decision making on structural adequacy or on functional obsolescence is an important one that needs to be addressed in a comprehensive bridge management system. It is important to note that the useful life, functional life, and economic life of a bridge are usually different (13). Thus, depending on which of the three is the major concern, the decision to retrofit or replace may have to be made on the basis of structural adequacy or functional obsolescence. In most applications, structural adequacy is of concern in ensuring safety during the lifetime of the bridge. On certain occasions, for economics reasons, a bridge may have to be replaced by a more modern one or perhaps by a wider one. These are the examples in which functional obsolescence becomes the dominating factor in the decision-making process. Of course in such a case, the economic impact of the decision to replace the bridge must be carefully evaluated.

3.6 Top-down versus Bottom-up Guidance and Input

AASHTO guidelines for bridge management systems (12) provide the definitions for "top-down" and "bottom-up" approaches. According to the definition in Ref. (12), a "top-down" approach to bridge program planning begins with an analysis of network-wide goals and constraints, yielding a general network-wide optimal policy. Only then is the policy applied to individual bridges. Usually the optimal policy is the allocation of funds among competing projects based on maximizing net benefits or minimizing total costs. A "bottom-up" approach, in contrast, first finds the optimal strategies for individual bridges for different level-of-service standards, then aggregates the costs of the individual bridge. Ideally, there should be some balance between these two approaches during the initial stages of bridge MR&R planning.

The approach to incorporate various bridge variables in a life-cycle cost analysis is mainly by means of trial-and-error approach. It is often necessary to start with an assumed set of values for the variables in order to proceed with the analysis. However, the trial variables need to be revised as many times as necessary to achieve optimization of cost with respect to operational and budget constraints.

CHAPTER IV

HIGHWAY BRIDGE LIFE-CYCLE COST MODELING

4.1 Introducing Remarks

Highway bridge life-cycle models are intended to provide information for decision-making regarding the type of action (i.e. maintenance, rehabilitation or replacement) that is required to guarantee the extended service lives of bridges. Moreover, with each type of bridge work, an analytical model is needed to determine the optimum time intervals needed to carry out the work. From a review of current models (see Chapter II), it is clear that the basis of most bridge life cycle-models is the optimization of bridge maintenance, rehabilitation, and replacement funds considering: (i) the importance of the bridge (as reflected in its usage in terms of the average daily traffic), (ii) the rate of inflation and (iii) the discounted interest rate. It is evident that the results of previous upgrades (including inspections and rehabilitations) to the bridge as well as its current state ought to influence the decision-making process to achieve life-cycle optimization. Inspection and rehabilitation results can be included in bridge life-cycle models by incorporating a single parameter which describes the condition of a bridge as it deteriorates over time. The bridge rating score may be used as such a parameter.

In this chapter, a bridge life-cycle model based on both cost optimization and bridge condition rating is explained. The model utilizes the variation of the rating score over time as a key element in identifying the specific needs of a bridge for maintenance, rehabilitation and replacement. such a model is referred to as the value index (VI) model.

4.2 VI Model Concept

The underlying concept of the VI model is the development of a single parameter that can be used to help quantify the bridge decision-making process. Specifically, a parameter (referred to as the value index, VI) is introduced to describe the following three major elements of a bridge life-cycle cost analysis:

- Bridge or bridge element condition rating score.
- The cost associated with various bridge works (i.e., maintenance, rehabilitation and replacement).
- Bridge service life expectancy (in years).

The condition rating score can be selected based on one of several types used by various organizations. For example scores ranging from 1 to 9 (1 representing the worst condition) can be used.

It is noted that since the condition rating score changes with time, then the VI is also a time-dependent identity. Ideally, one can formulate the VI in terms of the three independent parameters described above. The VI equation can then be used as "the objective function" in a mathematical optimization scheme in which various constraints on the three parameters as well as on time can be imposed. The final product of the optimization process is an optimum value of the VI that can then be used as a basis to arrive at a decision that represents the best strategy for any particular bridge.

In most applications, the optimization scheme requires an iterative approach with several cycles of computations to arrive at the optimum value of the VI. Furthermore, one can set a target value for the rating score that can be achieved within a given cost and time period. The trial-and-error approach is needed so that several options for the proposed bridge work can be examined to identify the one that represents the optimum value of the VI based on the desired bridge rating and the cost and time constraints.

4.3 Formulation of the VI Model

4.3.1 Description of Objective Function and Variables.

As described later in this chapter, the VI concept is particularly helpful in identifying the type (or types) of actions that lead to the optimum value of the VI in light of the designated constraints on time and budget.

Mathematically-speaking, the VI model is an optimization process using an objective function subject to a given set of constraints. In its generic form, the objective function, *F*, is written in terms of n variable x_i ($i=1,2,...,n$) satisfying the following set of equations:

$$\frac{\partial F(x_1, x_2, \ldots, x_n)}{\partial x_i} = 0 \qquad (i=1,2,\ldots,n) \quad [4.1]$$

The constraints define specific ranges or limitations that are imposed on the variables. In the VI model, the objective function is written in terms of the three variables described in Section 4.2. Denoting these variables as r, t and c for x_1, x_2 and x_3, respectively, where,

r = bridge or bridge element condition rating

c = costs associated with the bridge work

t = bridge service life expectancy

the function F, which describes VI, may be written as,

$$VI = F(r, c, t) \qquad [4.2]$$

The form proposed in this study for F is,

$$VI = \frac{r \cdot t}{c} = \frac{A_s}{C} \qquad [4.3]$$

in which A_s defines the area under the bridge deterioration curve.

The basis for selecting Eq. [4.3] is primarily the fact that an increase in r and t (i.e. higher bridge rating and longer life expectancy) should result in an improvement in VI. It is noted that the variable r (i.e. condition rating) is related to the cost (i.e. c). This is so because an expenditure on a bridge is expected to result in an improvement in its rating. Although a higher expenditure level (i.e. cost) may help to increase the rating and thus increase the VI indirectly, the higher cost tends to decrease the VI (see Eq. [4.3]). Conceivably, a specific cost should result in a balanced or optimum value of the VI that will offset the cost associated with achieving an improved rating.

In conducting the optimization process as implied by Eqs. [4.1] and [4.2], one should derive a specific relation between the rating and cost. As expected, such a relationship depends on many factors among which are the type of bridge, the method of construction used for the bridge, work quality, traffic demographics and the type of rehabilitation work performed on the bridge. Ideally, one can construct the rating-cost relationship based on the previous history of repair and rehabilitation for a specific bridge. This requires a comprehensive set of data revealing the funds spent and the rating improvement achieved. Figure 4.1 depicts a typical variation of rating and cost with time for a hypothetical bridge.

As seen in Fig. 4.1(a), after bridge construction (at t=0), two major rehabilitation or repair jobs were executed at

$t=t_1$ and $t=t_2$, respectively. At $t=T_c$, the bridge was subject to replacement. Figure 4.1(a) shows major cost items (c_1, c_2, ...) at t_1, t_2, and T_c. Between the events of major rehabilitation, repair or replacement there is a constant cost (c_{ri}) associated with routine maintenance. Figure 4.1(b) shows the corresponding bridge rating during the $0-T_c$ time interval. As seen in this figure dramatic increases in the rating are achieved upon a major maintenance, rehabilitation or replacement event. These are shown by RI_1, RI_2, ... on the graph of Fig. 4.1(b). Elsewhere on this graph, there is a gradual reduction in the rating due to wear and tear of the bridge. This reduction is shown by $R_1(t)$, $R_2(t)$, ... and these are defined as bridge deterioration curves. The rating is subject to a minimum and maximum value (R_{min} and R_{max}). Furthermore, upon each improvement in rating, it is noted that a full recovery to the original condition is never achieved unless the bridge is completely replaced.

4.3.2 Mathematics of the Optimization Model. Parameter A_s in Eq. [4.4] defines the area under the bridge deterioration curve. Since the variation of r (rating) with time is not continuous [see Fig. 4.1(b)], then A_s must be found incrementally. Dividing A_s into **n** increments $(A_s)_i$ (i=1,2,...,n), one may write,

$$A_s = \sum_{i=1}^{n} (A_s)_i \qquad [4.4]$$

in which the subscript i corresponds to the time steps at which a sudden increase in the rating occurs. Each increment can be obtained from the equation:

$$A_{si} = \int_{t_{i-1}}^{t_i} R_i(t)\, dt \qquad [4.5]$$

Thus

$$A_s = \int_0^{t_1} R_1(t)\, dt + \int_{t_1}^{t_2} R_2(t)\, dt + \ldots + \int_{t_{n-1}}^{T_c} R_n(t)\, dt \qquad [4.5a]$$

Functions $R_i(t)$ are obtained from a regression analysis of the data related to previous bridge maintenance, repair and rehabilitation activities. If a comprehensive inventory of these activities is kept up to date and a rating of the bridge is periodically carried out and recorded consistently over a extended period of time, then reliable estimates for $R_i(t)$ can be found. Approximate functions assuming linear variation of $R_i(t)$ between t_{i-1} and t_i can be used in lieu of more accurate equations. A linear approximation for $R_i(t)$ requires rating data at t_1, t_2, ... only. These ratings are shown as RI_1, RI_2, ... in Fig. 4.1(b).

Figure 4.2 depicts bridge deterioration based on the idealized linear functions $R_i(t)$. In this figure, the function $R_u(t)$ represents the upper bound values for the rating. This function is made up of several straight line segments.

One may observe that the functions $R_2(t)$, $R_3(t)$ are related to $R_1(t)$ and $R_u(t)$ by,

$$R_2(t) = R_1(t - t_1) - [R_{max} - R_u(t_1)] \quad [4.6a]$$

and

$$R_3(t) = R_1(t - t_2) - [R_{max} - R_u(t_2)] \quad [4.6b]$$

or, in general,

$$R_n(t) = R_1(t - t_{n-1}) - [R_{max} - R_u(t_{n-1})] \quad [4.6c]$$

Another major parameter in Eq. [4.2] is the cost due to all bridge works conducted during a single life cycle period

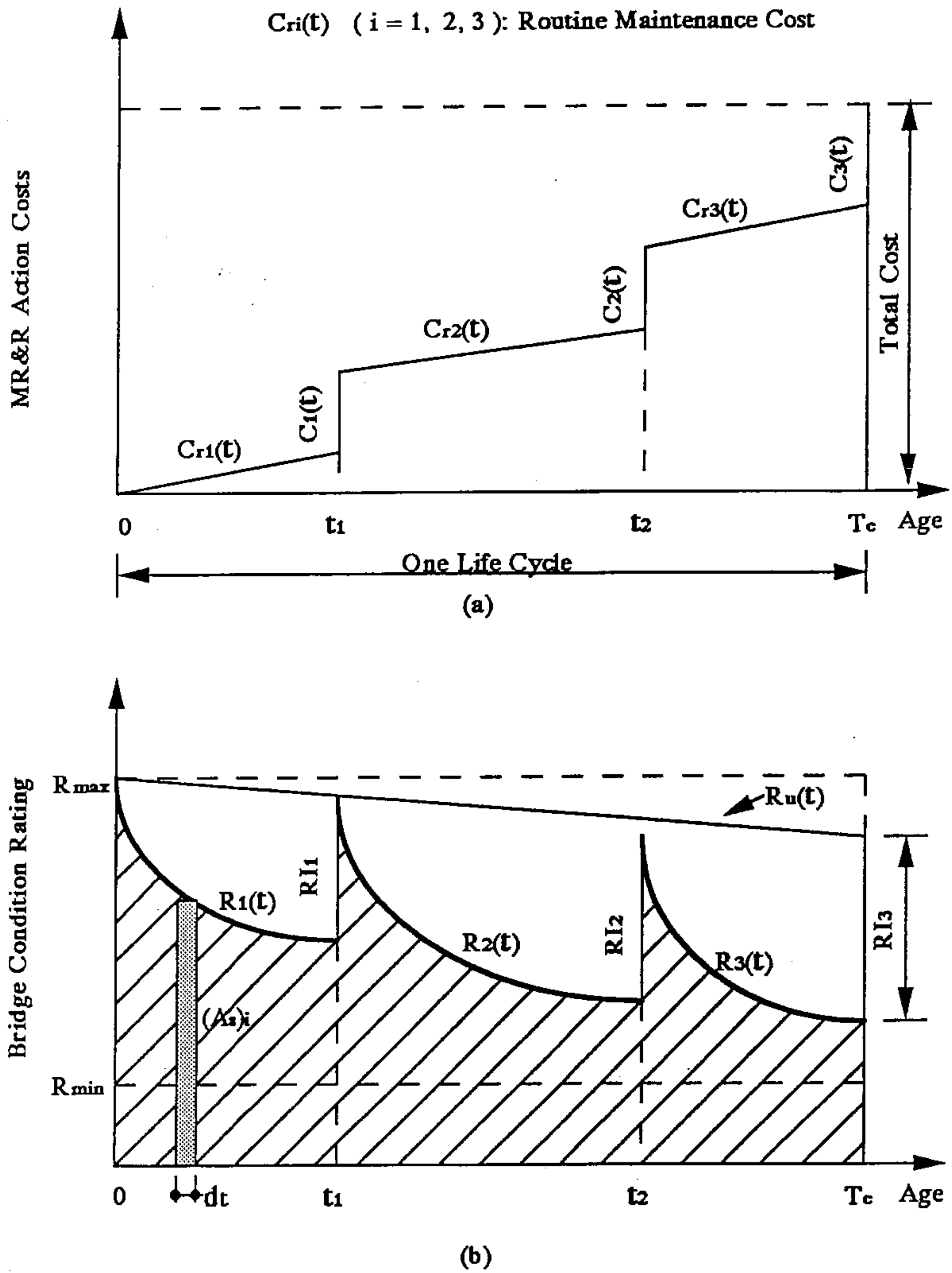

Figure 4.1 Graphical Picture of VI Model

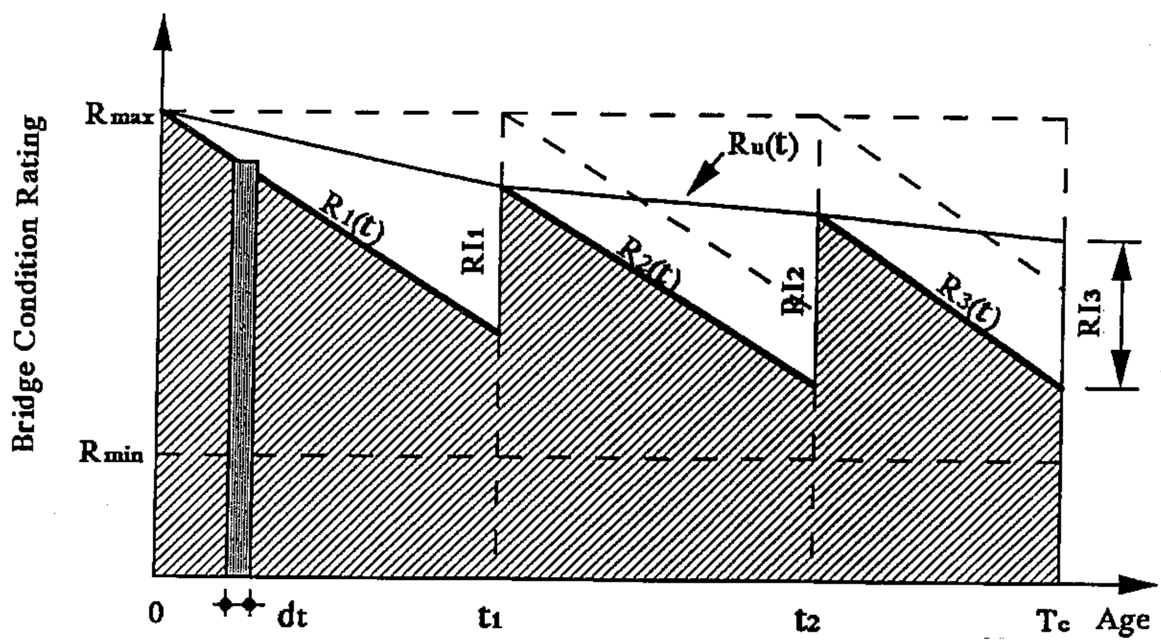

Figure 4.2 Linear Idealization of Bridge Deterioration Curve

(i.e., 0-T_c). The cost $C_1(t)$, $C_2(t)$, ..., $C_n(t)$ due to each activity [see Fig. 4.1(a)] can be obtained either from the cost database or from cost prediction models. When used in an optimization model, cost is taken as a time-dependent variable to account for interest and inflation rates. The total bridge maintenance, rehabilitation and replacement cost, C_T, is,

$$C_T = C_1 + C_2 + \ldots + C_n = \sum_{i=1}^{n} C_i \qquad [4.7]$$

in which C_i (i=1,2,...n) is cost associated with the various types of bridge works. If C_{oi} denotes the cost associated with the bridge work at the time bridge was constructed (i.e. at t=0), then after t_i years elapsed and considering a discounted rate of i^*, C_i is

$$C_i = C_{oi}\,(1 + i^*)^{t_i} \qquad [4.8]$$

The objective function $F(r,c,t)$ in Eqs. [4.2] and [4.3] may be defined as the ratio of A_s to C_T. It is noted that the VI will be a function of time steps t_1, t_2, ..., t_n and initial bridge works costs C_{o1}, C_{o2}, ..., C_{on}. Since C_{oi} is constant, only the t_i's can be treated as variables in the optimization model. The problem is then reduced to:

$$VI=\frac{A_s(t_1, t_2, \ldots, t_n)}{C_T(t_1, t_2, \ldots, t_n)} \qquad [4.9]$$

subject to constraints that impose limits on the R_i and C_i functions as described below.

. At $t=t_i$, the following inequalities must be satisfied:

$$R_i(t_i) < R_{i+1}(t_i) \qquad [4.10]$$

$$R_{min} \le R_i(t_i) \le R_{max} \qquad [4.11]$$

and

$$R_i(t_i) \le R_u(t_i) \qquad [4.12]$$

. Any period between t_i and t_{i+1} shall be shorter than the corresponding life cycle of bridge or bridge element, i.e.

$$t_{i+1} - t_i < T_c \qquad [4.13]$$

Also

$$0 < t_1 < t_2 < \ldots < t_i < \ldots < T_c \qquad [4.14]$$

In addition, the following assumptions are made to simplify the optimization process:

. The duration of a construction activity for any bridge repair or rehabilitation work is very short compared to T_c. Thus the transition from the R_i to the R_{i+1} curve can be assumed to be a vertical straight line with RI_i being a discontinuous increase in the rating (see Fig. 4.2).

. All deterioration curves, $R_1(t)$, $R_2(t)$, ..., $R_n(t)$ are identical functions which have the same deterioration rates.

. Each deterioration curve $R_i(t)$ is a continuous function within the t_{i-1}-t_i time period.

Optimization of the VI is defined with by following n equations:

$$\frac{\partial VI(t_1, t_2, \ldots, t_n)}{\partial t_i} = 0 \qquad (i=1,2,\ldots,n) \qquad [4.15]$$

Selecting an arbitrary value for n and solving Eq. [4.15] within the constraints of Eqs. [4.10] and [4.14] will result in specific time intervals for bridge works that maximize the VI.

4.4 Solution Technique for the VI Optimization Model

Solution of the optimization model explained in Section 4.3 is possible only by means of a numerical approach. This is specially true when the R_i functions are nonlinear. If the derivatives described by Eq. [4.15] can be obtained in "closed form", then a numerical approach is needed only to solve the series of simultaneous equations for t_1, t_2, ..., t_n. In most other cases, arbitrary initial values are substituted into the objective function to observe the effect upon VI. Using well-know methods of optimization, new values for t_1, t_2, ..., t_n are successively obtained until the maximum value of the VI is reached.

A computer program has been developed in this investigation for the numerical computation of the time steps t_1, t_2, ..., t_n that maximize the VI. The computer algorithm includes only linear R_i functions. To use the program a value for n (i.e. the estimated number of times a bridge will be subject to a major repair or rehabilitation work) must be entered. The program, when running, uses the algorithm of Eq. [4.9] to compute the maximum value of the VI along with the respective time steps t_1, t_2, ..., t_n. It is noted that occasionally, the maximum value of the VI may become only an upper limit as dictated by the constraints imposed on the model. Also, in certain problems more than one set of answers for t_1, t_2, ..., t_n may be found. Under such conditions it may be necessary to change the value of n to arrive at a condition that will result in a unique solution for t_1, t_2, ..., t_n.

Since the R_i functions are linear and the time steps are limited in number, a closed form solution to Eq. [4.15] can be found and the optimum value of the VI is then always the global maximum. The test for maximization is executed by evaluating changes in VI at $t_i \pm \Delta t$. The value of the VI which results from the incremental change in t should always be smaller than the optimum value of the VI. Fort the general case in which the R_i are non-linear functions, the algorithm should be modified to enable it to identify the global maximum amongst a series of local maxima. A complete description of the computer program is given in Chapter V.

4.5 Decision-Making Based on the VI Model

As described in Section 4.1, one element of a bridge life-cycle cost analysis is to arrive at a reasonable decision regarding on the type of measure that must be taken to enhance the service life of a bridge at a particular point in its history. Furthermore, the analysis should identify the bridge component that exhibits the highest priority for the designated work. The model described in previous sections of this chapter is based on the assumption that the type of work and the bridge component upon which the work is to be performed are both known. In this section the model is extended to relax this restriction to provide a decision-making scheme to identify: (i) what kind of work should be performed; (ii) which bridge (or bridge component) should be considered for this type of work; and (iii) exactly when the work is to be performed.

4.5.1 Elaboration of the Decision Making Model. The decision making problem consists of the following questions:

W_1 = When to do the work?

W_2 = What type of action should be executed?

W_3 = Which bridge (or bridge component) should be treated?

In this scheme, one accepts (as a first trial), a specific type of action (e.g., repair of deck) and a specific bridge (among a group of bridges) for which the work should be done. Then by running the VI optimization program together with a series of logical decision-making steps based on: (i) availability of funds; (ii) achieving a target rating; and (iii) importance of the bridge in terms of usage, etc., one arrives at an "accept" or "reject" answer to W_2 and W_3 for a given W_1 (i.e., the year the work should be done). If either W_2 or W_3 is rejected, a new option for type of work and/or the candidate bridge will be selected and the process is continued until both W_2 and W_3 are accepted for the given W_1.

Since only two outcomes are possible for each of the three parameters W_1, W_2, and W_3, we can either use 0 or 1 as values for each variable W_i (i=1, 2 and 3). We define the following:

W_i=1 means that the decision has been made and the result for W_i is known. For example if $W_2=1$, it means the type of bridge action is known (the type of action has been identified).

$W_i=0$ means that no decision on W_i has been made. Thus the result for W_i is not known.

The three parameters W_1, W_2 and W_3 form a vector. Denoting this vector as the Decision Array (DA_i), we observe that there are 8 possible combinations for W_1, W_2 and W_3. The possibilities are depicted graphically in Fig. 4.3. The decision array with $W_1=W_2=W_3=0$ (DA_1 in Fig. 4.3) implies that no decision has been made with respect to the type of bridge action, the bridge component or the bridge for which the work is going to be done and the year in which the work is to be done. On the other extreme, a decision with $W_1=W_2=W_3=1$ means the type of action, the candidate bridge or bridge component and the year the work is to be done are all known. It is noted that given the type of action and the candidate bridge, the VI program can then be used to arrive at the year in which the work is to be done. It is obvious that the desirable outcome for the decision array is $DA_8=(1,1,1)$. Since the starting point in decision-making is at $DA_1(0,0,0)$, various paths need to be selected to attain DA_8 starting from the DA_1. Figure 4.4 shows 3 paths by which DA_8 may be attained.

In path 1 $DA_4=(1,1,0)$, i.e. $W_1=W_2=1$. This indicates that the year(s) the work should be done and the type of bridge action are known and thus these are selected first. This can

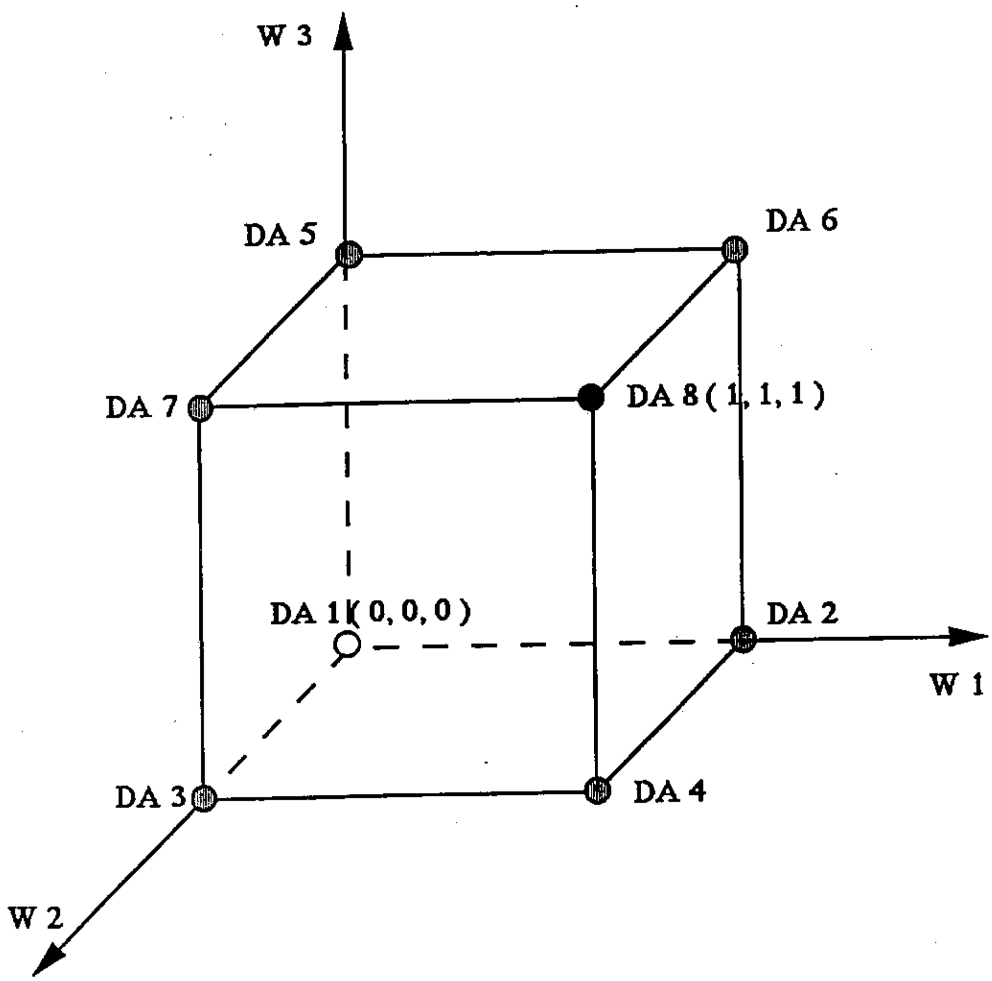

Figure 4.3 Graphical Display of the Decision Arrary

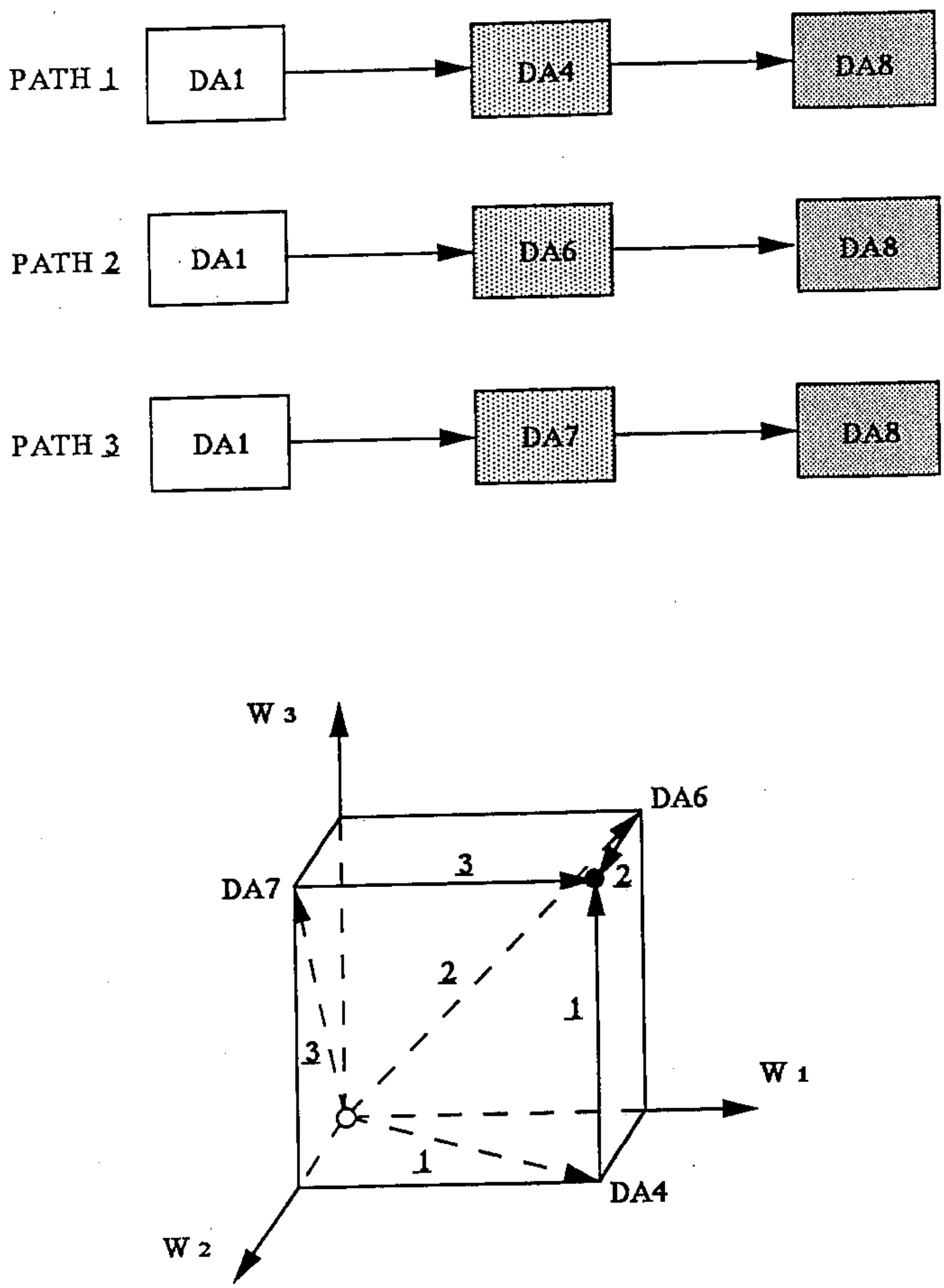

Figure 4.4 Graphical Representation of the Decision-making Process

be, for example, due to: (i) budgetary constraints; (ii) known structural deficiencies; and (iii) generic problems that are known to be specific to a bridge type. The VI model can then be used to help select the candidate bridges or bridge parts.

In paths 2 and 3, only one of the two decisions W_1 or W_2 can be made. To make the other decisions one may select a trial route to reach DA_8 and then determine whether the selected route is feasible or whether the result for the unknown W_i is an acceptable answer. If the trial route does not provide an acceptable answer, new trials are selected until DA_8 is attained.

4.5.2 Decision-Making Procedure. Most decisions involve predictions based on information that is subject to uncertainty. Decisions in engineering planning and design often require the consideration of nontechnical factors such as social preference or acceptance, environmental impact, and even various political implications (17). In light of these, the decision to select the "best" option cannot be based solely on purely technical grounds. In many applications, non-technical factors can only be treated on an "ad-hoc" basis. This requires a comprehensive evaluation of the significance of such factors in the decision-making process and is beyond the scope of the study. In this study, the decision-making process is based solely on technical factors.

The decision process should, at the very least, include the following (17):

- A list of all feasible options, including the acquisition of additional information, whenever appropriate.
- A list of all possible outcomes associated with each option.
- An estimation of the probability level associated with each option.
- An evaluation of consequences associated with each option.
- The criterion used for making decisions.
- A systematic evaluation of all options.

As stated in Ref. (17) a systematic framework that will permit the consideration of all facets of a decision problem is the decision model. Three classes of decision models may be identified:

(i) Decision under certainty.

(ii) Decision under risk.

(iii) Decision under uncertainty.

In most cases, classes (ii) and (iii) are very likely to occur because most decisions are made under some degree of uncertainty.

Two types of decision criteria (17) are described below. It may be noted that the "best" decision may have different meanings to different decision-makers especially at different times. Of course, a rational decision-making process should consider the relative benefit to be gained or lost among the various possible options.

Decision Criterion I

Maximum Expected Monetary Value Criterion (EMV). When the consequences associated with each option in a decision analysis can be expressed in terms of monetary values, a widely used criterion for decision-making is the maximum expected monetary gain. The expected monetary value is:

$$E(a_i)=\sum_j (p_{ij}d_{ij}) \qquad [4.16]$$

in which,

$E(a_i)$ = expected monetary value of option i;

d_{ij} = monetary value of consequence j of optional i; and

p_{ij} = the probabilities associated with the consequences j of option i.

The optimal option is the one whose expected monetary value $E(a_i)$ is the maximum. In Eq. [4.16] one decides what consequences should follow as a result of option i to establish the needed information for d_{ij}. For example, if the decision is to repair rather than replace, one considers a consequence as achieving a desired extended life. There is a probability associated with this consequence. This probability (p_{ij}) can be established based on past events (i.e. the historical records) or merely on experience and intuitive judgment.

The desirability of a particular option may depend on several attributes such as cost, time constraints, etc. To establish a uniform scale for measuring the overall monetary value of an option, the concept of utility may be used (17). Utility is defined as a true measure of monetary value to the decision-maker. If the utility values of all options are available, then the option with the highest utility value will be preferred. It is, however, noted that the maximum EMV may not always offer a suitable parameter for selecting the option that will reflect the decision-maker's actual preference. In such cases, the second decision making criterion, described below, may be utilized.

Decision Criterion II

Maximum Expected Utility Criterion. Once the utility of each consequence is known the expected utility value of option *i*, is given by:

$$E(U_i) = \sum_j (p_{ij} u_{ij}) \qquad [4.17]$$

in which u_{ij} is the utility of the j^{th} consequence of option i. The optimum option possesses the maximum value of $E(U_i)$.

When consequences are expressed in monetary terms, u_{ij} becomes a function of d_{ij}, i.e.

$$E(U_i) = \sum_j [p_{ij} u(d_{ij})] \qquad [4.18]$$

in which $u(d_{ij})$ is referred to as the utility function.

4.5.3 Logical Steps in Decision-Making. As described above, the final outcome of the decision-making process is to determine the decision array DA_8 (i.e., $W_1=1$, $W_2=1$, and $W_3=1$). The logical steps that are needed to determine DA_8 are explained in detail below. Also, several possible cases are explained to clarify these steps. These are denoted by case 1, 2 and 3, respectively. Each case represents one of the several paths shown in Fig. 4.4.

Case 1

Path 1 in Fig. 4.4 is defined by : $(0,0,0) \rightarrow (1,1,0) \rightarrow (1,1,1)$. In this case, the time steps (Y_1, Y_2, ..., Y_m) and the type of actions (A_1, A_2, ..., A_n) are selected first. Before using the VI optimization model, one may decide on the bridges or bridge components that, based on judgment, should be selected for the actions A_1, A_2, ..., A_n . The next step is to optimize VI for the selected bridges or bridge components. This procedure may have to be repeated if the bridges can not be selected a priori. In such instances the bridges (B_1, B_2, ..., B_p) or bridge parts (E_1, E_2, ..., E_q) which display the maximum VI may be selected as the most desirable options. Figure 4.5 illustrates this for two bridge decks which are

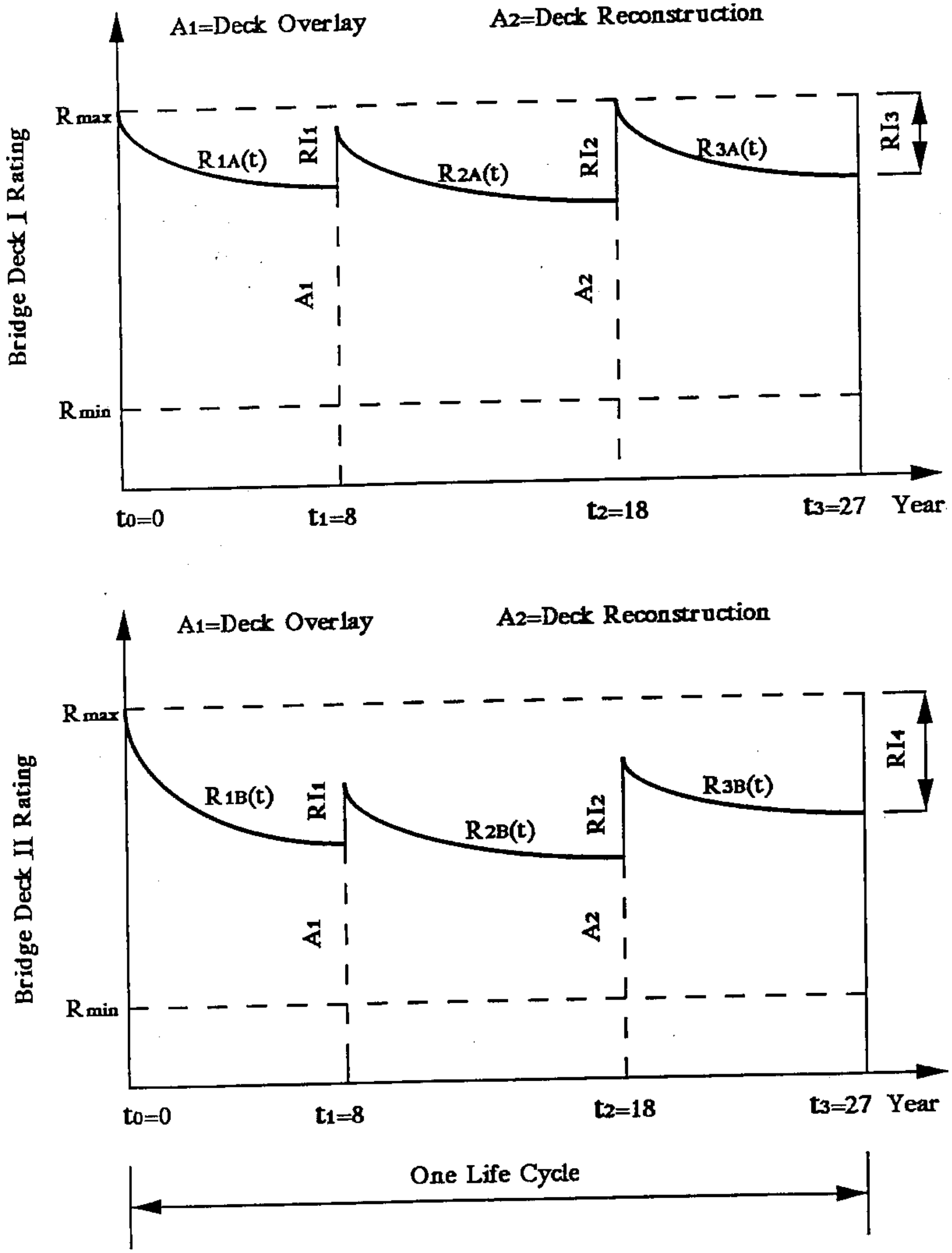

Figure 4.5 Two Bridge Deck Alternatives

denoted: **I** and **II**. The difference between these two alternatives is in their deterioration curves. For each deck the deterioration curves are shown in Fig. 4.5. The time steps are t_0=0, t_1=8, t_2=18 and t_3=27 years after construction of the bridge. The types of bridge action are designated by A_1=deck overlay, A_2=deck reconstruction and A_3=deck replacement. Using the VI model, the alternative (in this case deck **I**) with the greater VI is selected. In this example, the only difference between bridge decks **I** and **II** is in their deterioration curves. This difference may be, for example, due to a difference in the type of construction.

Case 2

Path 2 in Fig. 4.4 is defined by: (0,0,0)→(1,0,1)→(1,1,1). Fig. 4.6 illustrates this case. Two types of work can be done on deck A and these are denoted as (a) and (b). For each type, the VI value is computed. The type of work with the larger VI will be considered to be the most desirable type of action. For example if the alternative shown in Fig. 4.6(a) has the maximum value of the VI, then it will be selected (i.e. the bridge deck A should be replaced at t_1=8 years and then overlayed at t_2=18 years).

Case 3

Path 3 in Fig. 4.4 is defined by: (0,0,0)→(0,1,1)→(1,1,1). This means that on the basis of no information on when to do the work (W_1=0), what action(s) to take (W_2=0) and what bridges or bridge components to select (W_3=0), one then

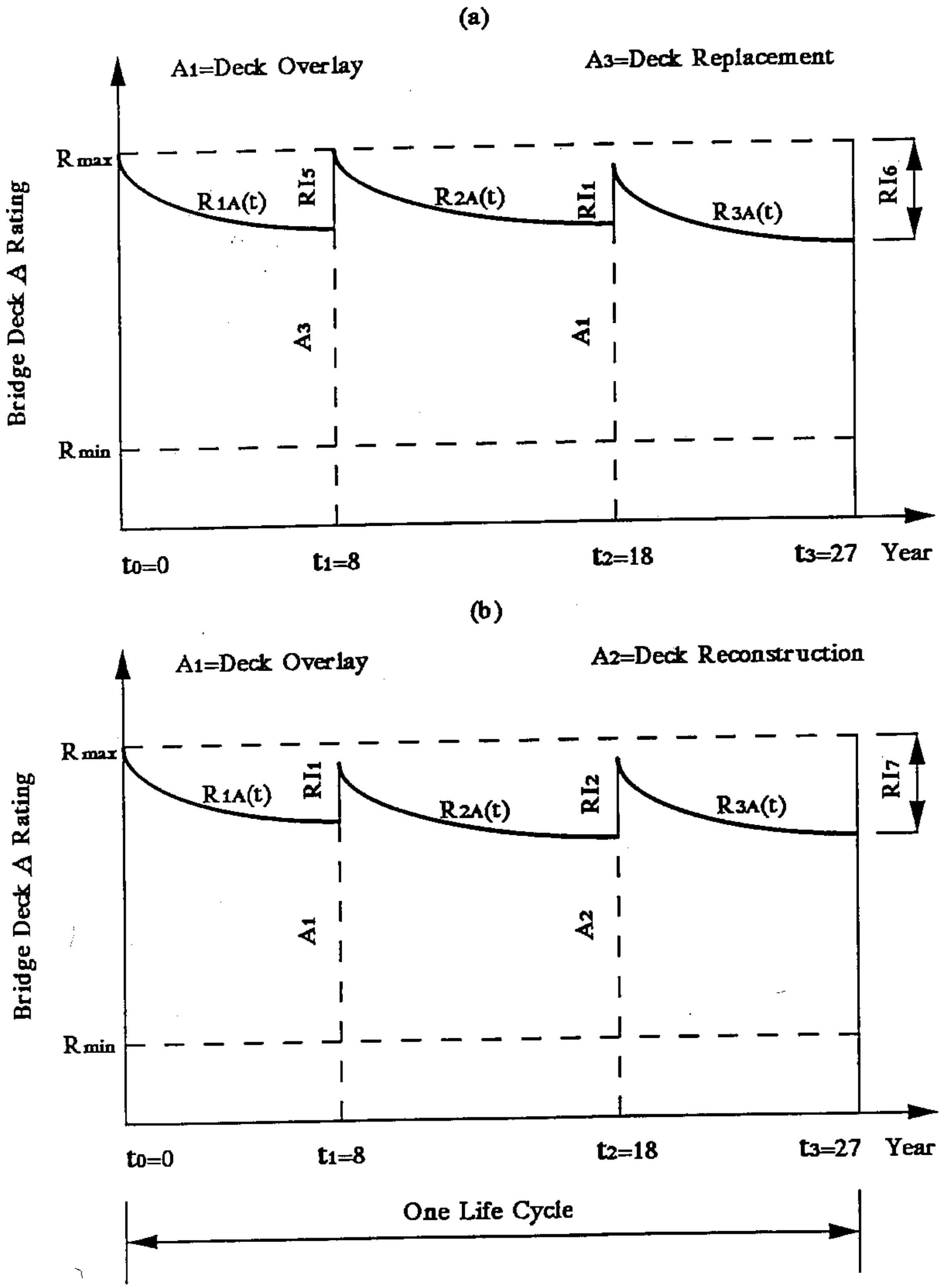

Figure 4.6 Two Possible Scenarios for Actions on Deck A

selects m candidate bridges (B_1, B_2, ..., B_m), n bridge components (E_1, E_2, ..., E_n) and p types of actions (A_1, A_2, ..., A_p) as to start the decision-making process. The next step is to optimize the value of the VI with p types of action in one life cycle for each bridge B_i or bridge component E_j. The results of this procedure are a series of time steps (Y_1, Y_2, ..., Y_q) at which the bridge B_i or bridge component E_j can be considered for the actions (A_1, A_2, ..., A_p) with a maximum value of the value index, $(VI)_{max}$.

There are also several other cases, such as, $DA_1(0,0,0) \rightarrow DA_2(1,0,0) \rightarrow DA_8(1,1,1)$, $DA_1(0,0,0) \rightarrow DA_3(0,1,0) \rightarrow DA_8(1,1,1)$, etc. Among these, the path from $DA_1(0,0,0)$ directly to $DA_8(1,1,1)$ is the most complicated one. As may be expected, many options may be considered for the candidate bridges, the time steps and types of actions. In a real case, the VI optimization process may have to be repeated many times before a final decision can be made for the time steps and type of work on the bridge that will lead to an optimum outcome.

4.6 Demonstration Example of VI Optimization Model

To demonstrate the application of the VI model, a example is presented in this section. Assume that a bridge was built in 1980 and that the deck needs to be rehabilitated now (1993). Only two actions of deck overlay and deck reconstruction are to be selected. Moreover, with an average daily traffic (ADT) of 25,000, it is assumed that a 100%

bridge deck condition rating recovery is attained upon each action (i.e. R=9 is obtained). It is further assumed that the minimum rating requirement R_{min} is 4 and that the required life cycle for the deck T_c is 30 years (see Fig. 4.7).

The deterioration model is given by Eqs. [4.19], [4.20] and [4.21]. This model was developed by the Transportation System Center (TSC), U.S. Department of Transportation, Cambridge, Massachusetts (18) and is given by,

$$DECK = 9 - 0.119\,(AGE) - 2.158E{-}6\,(ADTAGE) \qquad [4.19]$$

$$SUPER = 9 - 0.103\,(AGE) - 1.982E{-}6\,(ADT) \qquad [4.20]$$

$$SUB = 9 - 0.105\,(ADT) - 2.051E{-}6\,(ADT) \qquad [4.21]$$

where: C_{deck}=deck condition; C_{super}=superstructure condition; C_{sub}=substructure condition (all conditions are based upon a 0-9 scale); AGE=age; ADT=average daily traffic on the bridge; and ADTAGE=(ADT X AGE/10). Using ADT=25,000, one obtains,

$$R_1(t) = C_{deck} = 9 - 0.124\,t \qquad (t = deck\ age)$$

In this example, the shaded area A_s in Fig. 4.7 is easily computed by direct integration of the relevant equation as,

$$A_s = -0.124\,t_1^2 - 0.124\,t_2^2 + 0.124\,t_1 t_2 + 3.72\,t_2 + 214.2$$

For demonstration purposes, a simple curve for the function $C_i(t)$ is assumed with zero discount rate, or,

$$C_i(t) = 2\,(RI_i)$$

$$C_T = 2\,(RI_1 + RI_2 + RI_3)$$

$$C_T = 2\,(0.124\,t_1 + 0.124\,t_2 - 0.124\,t_1 + 0.124\,T_c - 0.124\,t_2)$$

$$T_c = 30\ (years)$$

Note that in general the cost function is time-dependent. Finally from Eq. [4.9], the VI (the objective function) is derived as,

$$VI(t_1, t_2) = \frac{A_s}{C_T}$$

or,

$$VI=\frac{-0.124\,t_1^2-0.124\,t_2^2+0.124\,t_1\,t_2+3.72\,t_2+214.2}{7.44}$$

Using the optimization conditions specified by Eq. [4.15], one obtains,

$$\frac{\partial(VI)}{\partial t_1}=\frac{(-0.248\times t_1+0.124\times t_2)}{7.44}=0$$

and

$$\frac{\partial(VI)}{\partial t_2}=\frac{(-0.248\times t_2+0.124\times t_1+3.72)}{7.44}=0$$

Solving the above two equations simultaneously, one obtains,

$$t_1\approx 10\ (years)\ \Lambda\ \ t_2\approx 20\ (years)$$

which means that the first action should be taken within 10 years and the second within 20 years after the initial construction of the bridge. The maximum value of VI(10,20) is,

$$(VI)_{max} = VI(10,20) = \frac{A_s(10,20)}{C_T(10,20)}$$

or,

$$VI = \frac{-0.124(10)^2 - 0.124(20)^2 + 0.124(10)(20) + 3.72(20) + 214.2}{7.44}$$

or,

$$VI = 33.790$$

Checking that the rating exceeds the minimum rating requirement $R_{min}=4$,

At age $t_1=10$:

$$R_1(t_1) = R_1(10) = 9 - 0.124(10) = 7.76 > R_{min}$$

At age $t_2=20$:

$$R_1(20-t_1)=R_1(20-10)=R_1(10)=7.76>R_{min}$$

Hence, based on the results from the application of the VI model, the following decisions may be made:

. Perform a deck overlay at the age of 10 (in year 1990).

. Reconstruct deck at age 20 (in year 2000).

It may be noted that if these two actions are not implemented at t_1 and t_2, the consequence will be an additional cost (i.e., the value of VI will be smaller). If, because of circumstances, the identified actions can not be implemented, then a re-evaluation of options should made to determine a new set of decisions. Such a contingency is described in Ref. (8) and repeated below:

. What should the responsible agency do if there is not enough money available this year to implement the optimal policy?

. What should the responsible agency do when current network-wide conditions are worse than the long-term optimal condition level?

To address the first question, it may be noted that the decision based on the optimization model is the lowest cost option. It is therefore, not possible to spend less money consistently over a long period of time while keeping the bridges open. However, for short-term planning, less money may be spent in anticipation at some time in the future additional funds will become available to upgrade bridge condition. If the available funding level is not adequate to perform the entire recommended program, then one may be forced to select other options for bridge maintenance, rehabilitation and/or replacement by treating the available funding level as a constraint. Regarding the second question (which addresses the problem of rehabilitation backlog), one can impose the constraint that the costs associated with the long term actions should exceed the costs associated with the work that has yet to be finished (i.e. the backlog rehabilitation works).

One may also first estimate the time (year) for a one-time rehabilitation action and then apply the VI maximization model to determine subsequent actions in light of the cost constraint mentioned above. For example, assume that an immediate repair of a bridge deck is still in the backlog and needs to be performed at t_1=5 years. Using the VI optimization model, given t_1=5 years, we find, with t_2=18 years for a subsequent action on the deck, VI=33.474. Comparing this value with the previously obtained maximum value of VI=33.790, we observe that the backlog work has resulted in a smaller VI. Nevertheless, the time of the second action (i.e., t_2=18) is consistent with an optimal value of the VI under the cost constraint that has been imposed.

4.7 Decision-Making and the VI Model

To use the VI model one must first develop deterioration curves for the bridge and cost estimates for the bridge repair/rehabilitation actions. Depending on the particular application, there are four possible types of mathematical functions that can be used to describe the needed deterioration curves.

The minimum rating requirement is R_{min}. The time steps T_{1max}, T_{2max}, T_{3max}, ..., T_{nmax}, are first, second, third, ..., n^{th} Latest Allowable Time for MR&R actions that satisfy the minimum rating requirement, R_{min}. The computation of value for T_{imax} (n=1,2,...,n) depends upon the deterioration function R(t) and the age-related rating degradation function $R_u(t)$.

A simple example of a deterioration function is R(t)=9-kt in which the constant $k \neq 0$. Also, a simple example of the age-related degradation function is $R_u(t)=9$. The latest allowable time for MR&R actions T_{1max}, T_{2max}, ..., T_{nmax} may then be determined to be,

$$T_{1max} = \frac{(9 - R_{min})}{k}$$

$$T_{2max} = T_{1max} + \frac{(9 - R_{min})}{k} = \frac{2\,(9 - R_{min})}{k}$$

... ...

$$T_{nmax} = T_{(n-1)\max} + \frac{(9-R_{\min})}{k} = n\frac{(9-R_{\min})}{k}$$

Another possible choice for the function R(t) is a quadratic function. By including the form of R(t) and cost optimization models used in other similar studies one may consider the following four possible cases:

(i) **Linear Deterioration Function and Straight-line Cost Estimation Function** In this case the deterioration function is linear and is given by R(t)=9-kt, where k is a constant and 9 indicates the maximum rating. Considering i_1 and i_2 to be the rates for interest and inflation respectively, then the cost estimation model may be written as:

$$C_T(t_1, t_2, \ldots, t_n) = C_0\sum_{i}^{n} \frac{RI_i}{9} (I_r)^{t_i} + C_0 \frac{RI_{i+1}}{9} (I_r)^{T_c} \quad [4.22]$$

in which,

$$I_r = \frac{(1+i_1)}{(1+i_2)}$$

The A_s function based on the linear assumption is:

$$A_s(t_1, t_2, \ldots, t_n) = 9T_c - \frac{1}{2}kt_1^2 - \frac{1}{2}k(t_2 - t_1)^2 - \ldots$$

$$-\frac{1}{2}k(t_n - t_{n-1})^2 - \frac{1}{2}k(T_c - t_n)^2 \qquad [4.23]$$

The ratio of $A_s(t_1,t_2,\ldots,t_n)$ to $C_T(t_1,t_2,\ldots,t_n)$ is the VI function.

(ii) **Linear Deterioration Function and Exponential Cost Estimation Function** In this case the deterioration function is linear, i.e. R(t)=9-kt; however, the cost estimation is presumed to be exponential. That is,

$$C_i(t) = 10000\exp[\alpha(RI)_i] \qquad [4.24]$$

in which α is a constant that can be obtained by examining the interest and inflation rates over a relatively long period of time.

Also,

$$(RI)_i = K(t_i - t_{i-1}) \qquad (t_0 = 0) \qquad [4.25]$$

Hence,

$$C_T(t_1, t_2, \ldots, t_n) = \sum_{1}^{n} 10000 \exp[\alpha k(t_i - t_{i-1})] \quad [4.26]$$

$A_s(t_1,t_2,\ldots,t_n)$ and $C_T(t_1,t_2,\ldots,t_n)$ may be obtained from Eqs. [4.23] and [4.26] respectively. The ratio of $A_s(t_1,t_2,\ldots,t_n)$ to $C_T(t_1,t_2,\ldots,t_n)$ is the VI function.

(iii) **Quadratic Deterioration Function and Straight-line Cost Estimation Function** In this case the deterioration function is presumed to be quadratic, i.e. $R(t)=9-k_1t^2-k_2t-k_3$, in which k_1, k_2, and k_3 are constants.

In this case,

$$R_1(t) = 9 - k_1(t-t_0)^2 - k_2(t-t_0) - k_3 \qquad (t_0=0)$$

$$R_2(t) = R_1(t-t_1) = 9 - k_1(t-t_1)^2 - k_2(t-t_1) - k_3$$

... ...

$$R_n(t) = R_1(t-t_n) = 9 - k_1(t-t_n)^2 - k_2(t-t_n) - k_3$$

Taking $R_{max}=R_u(t_i)$ (i=1,2,...,n) and substituting the above equations into Eq. [4.5a], one may obtain the A_s function. The function C_T may be obtained by using Eq. [4.22]. As before, the VI function may then be determined as the ratio of A_s to C_T.

(iv) **Quadratic Deterioration Function and Exponential Cost Estimation Function** In this case A_s may be obtained as above and C_T may be obtained by means of Eq. [4.26]. As before, the VI may then be determined as the ratio of A_s to C_T.

4.8 Other Deterioration Models

Only a few studies have suggested specific functions to describe the deterioration rates of highway bridges. These include studies performed by the Transportation System Center (TSC) in Cambridge, Massachusetts, the Massachusetts Institute of Technology (MIT), the Wisconsin Department of Transportation (WisDOT), the New York State Department of Transportation (NYSDOT), and the Pennsylvania Transportation Institute. Most of these studies (13) concentrate on relating bridge age to numerical bridge inspection condition ratings.

Deterioration is a very basic component of VI modeling. It is used to construct the overall life-cycle performance diagram. A deterioration function is used to estimate the deterioration rate associated with each major bridge component as a function of its present condition. It is affected by many factors. These factors can be classified (19) as those to estimate deterioration rates, while the MIT study examined several discrete variable deterioration rate estimation functions. The models used in the VI optimization are:

$$DECK = 9 - 0.119\,(AGE) - 2.158E{-6}\,(ADTAGE) \quad [4.19]$$

$$SUPER = 9 - 0.103\,(AGE) - 1.982E{-6}\,(ADT) \quad [4.20]$$

$$SUB = 9 - 0.105\,(ADT) - 2.051E{-6}\,(ADT) \quad [4.21]$$

in which ADTAGE = (ADT)(AGE)/10. DECK, SUPER and SUB are deck, superstructure, and substructure ratings, respectively. It is emphasized that these equations do not specifically consider the sensitivity of ratings with respect to the location of bridges in the state. Deterioration rates are subject to changes due to climate. These models do not account for these changes. They were used only as an example in this report. However, the optimization model is open to any desired rating equation. According to the above equations (Ref. 13), a bridge's rating deteriorates at an approximate rate of 0.1 per year (see Fig. 4.8) considering the traffic and age factors only (as pointed out in the FHWA BMS Demonstration Project). Additional limitations on the above equations and the TSC study are (13):

- The analysis was performed for bridges 25 years old or younger.

- TSC presumed linear relationships for deterioration.
- The intercept coefficient in the regression equations was taken to be 9 in all cases.

Nevertheless, the TSC study provides useful insights into the bridge element deterioration process. In essence, the deterioration function developed by TSC has been adopted in the implementation of VI optimization by mean of Eqs. [4.19], [4.20] and [4.21]. The VI optimization process developed herein, however, can easily be modified to include deterioration functions which are not necessarily linear and are more representative of actual Illinois bridge history.

The development of an optimization process through the introduction of the value index (VI) has been discussed in this chapter. The value index includes a consideration of age, condition rating and cost. The model includes a function for condition rating deterioration which is based either on a linear or a parabolic variation with time. Two types of costs constitute the overall cost of performing a specific type of bridge repair or rehabilitation work. These are agency costs and user costs. In most applications these complement one another. That is, a smaller agency cost often results in a higher user cost. The optimization model developed in this chapter considers agency costs only. However, the model can easily be modified to include user costs if specific information regarding respective user costs becomes available. Examples of possible user costs are explained previously in this chapter.

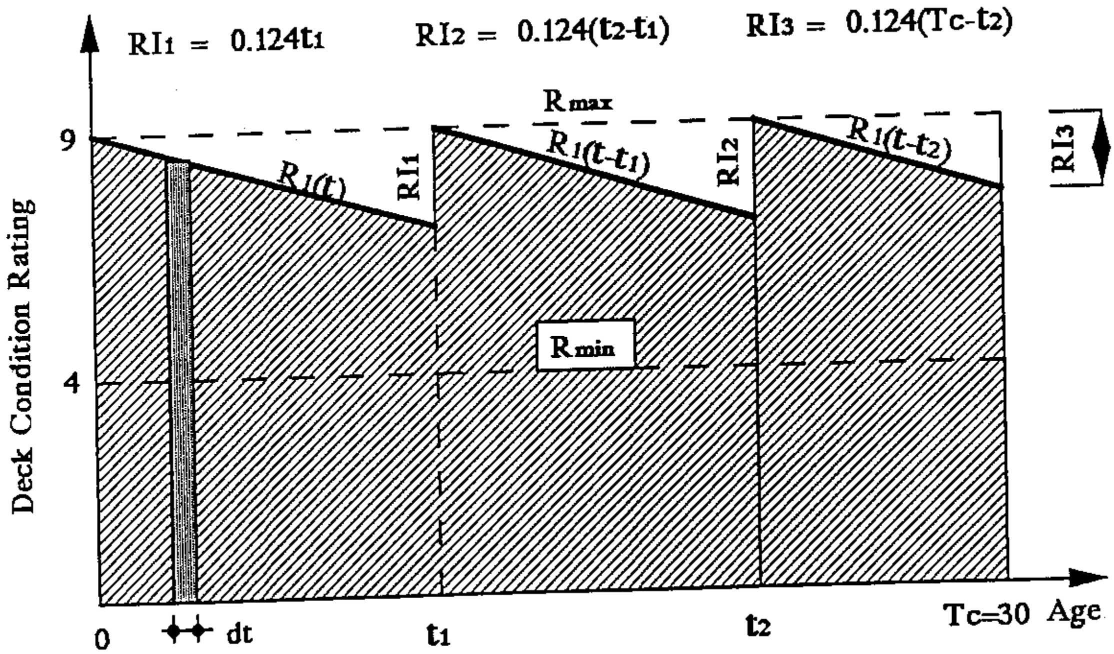

Figure 4.7 Example Application of VI Model

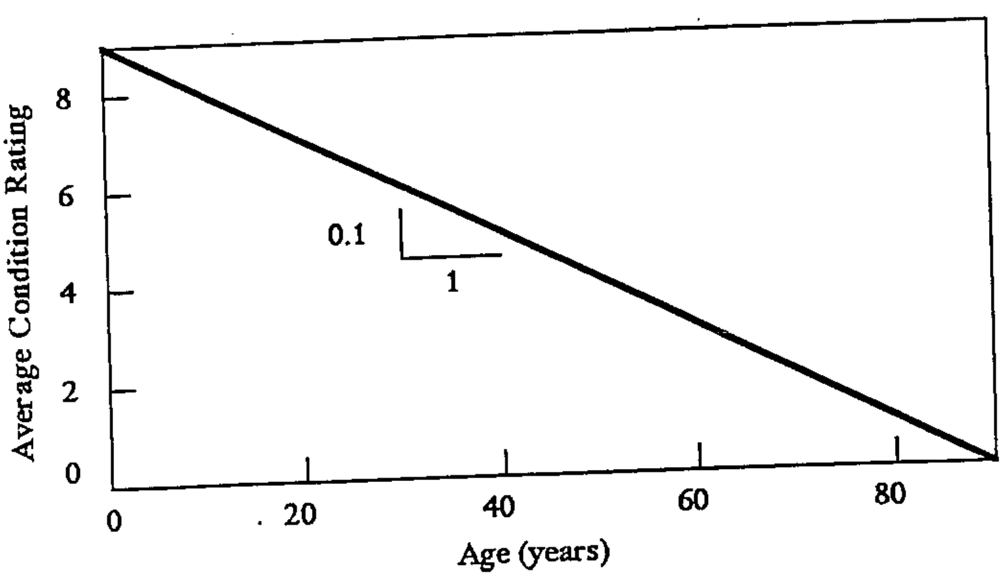

Figure 4.8 Simple Linear Deterioration Function (13)

CHAPTER V

DESCRIPTION OF SOFTWARE

The mathematical formulation of the bridge life-cycle cost model was presented in Chapter IV. In this chapter, the software developed to perform various computations of bridge life-cycle cost analysis is presented. The software provides a convenient means to perform the many iterations needed to determine an optimum solution within the constraints described in Chapter IV.

5.1 Development of Computer Program

The assumptions which underlie the development of the computer programs are explained below. A flowchart of VI computer programming is presented in Fig. 5.1.

5.1.1 Latest Allowable Time for Bridge Rehabilitation.

As previously discussed, the condition rating is expected to decrease with time for each bridge or bridge element. A critical condition is defined as one in which a bridge no longer meets the minimum serviceability and strength requirements. The rating corresponding to this condition is denoted R_{min}. With this low rating, the bridge is regarded as "structurally deficient" or "functionally obsolete" (10). In the bridge life-cycle cost computer model, R_{min} is specified and entered as an input by the user. The program uses the R_{min} as an indication of the critical condition. In conjunction

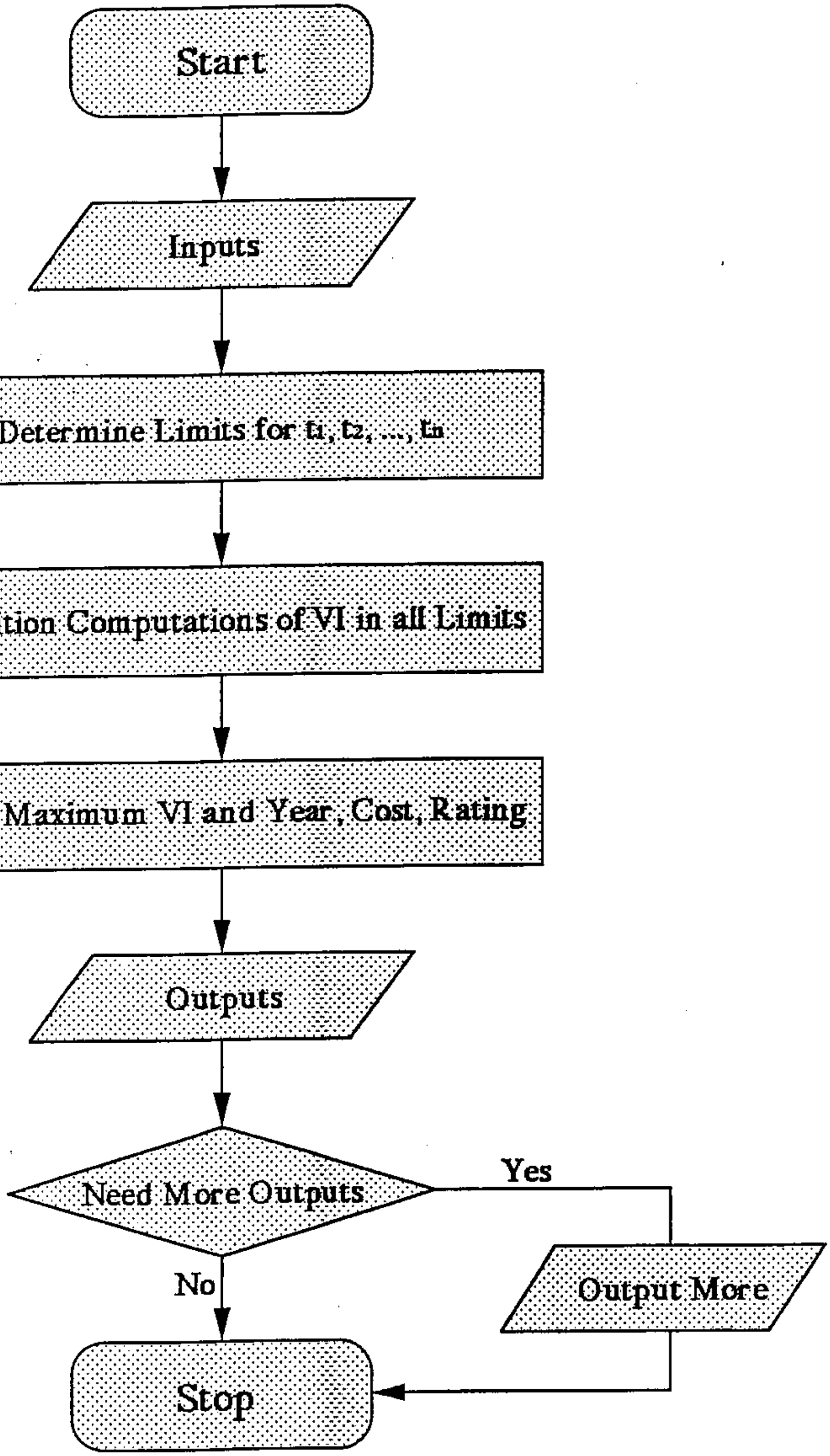

Figure 5.1 Flowchart of VI Computer Programming

with R_{min}, the "latest allowable time (LAT)" for bridge maintenance, rehabilitation and replacement (MR&R) work is therefore defined. If a bridge is subjected to **n** different MR&R works, then the corresponding latest allowable times are T_{1max}, T_{2max}, T_{3max}, ..., T_{nmax} respectively. T_{imax} indicates that at this time, the condition rating of the bridge has been reduced to R_{min} and the i^{th} MR&R work must be performed. Figure 5.2 shows the occurrence of a series of T_{imax}'s in a bridge MR&R profile. Figure 5.3 uses a straight-line method for the deterioration functions to determine relationships for the T_{imax}'s. Based on Fig. 5.3, using R(t)=9-kt (see Chapter IV), one may write:

$$T_{1max} = \frac{(9 - R_{min})}{k} \qquad [5.1a]$$

$$T_{2max} = T_{1max} + \frac{(9 - R_{min})}{k} = 2\,\frac{(9 - R_{min})}{k} \qquad [5.1b]$$

... ...

$$T_{nmax} = T_{(n-1)\,max} + \frac{(9 - R_{min})}{k} = n\,\frac{(9 - R_{min})}{k} \qquad [5.1c]$$

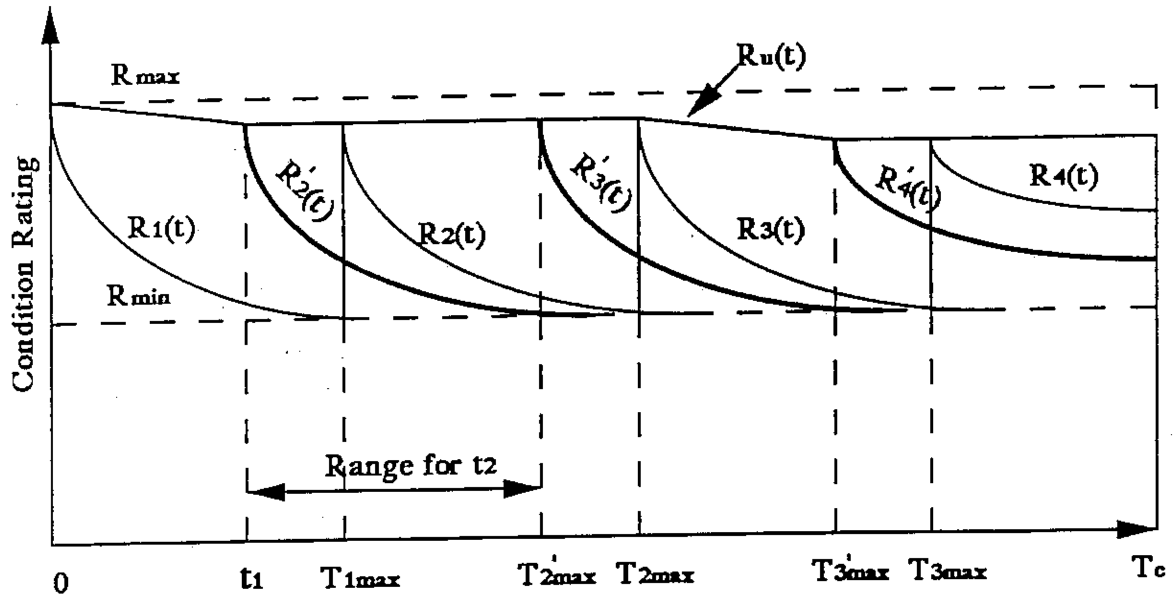

Figure 5.2 Determination of Latest Allowable Time for Various MR&R Works

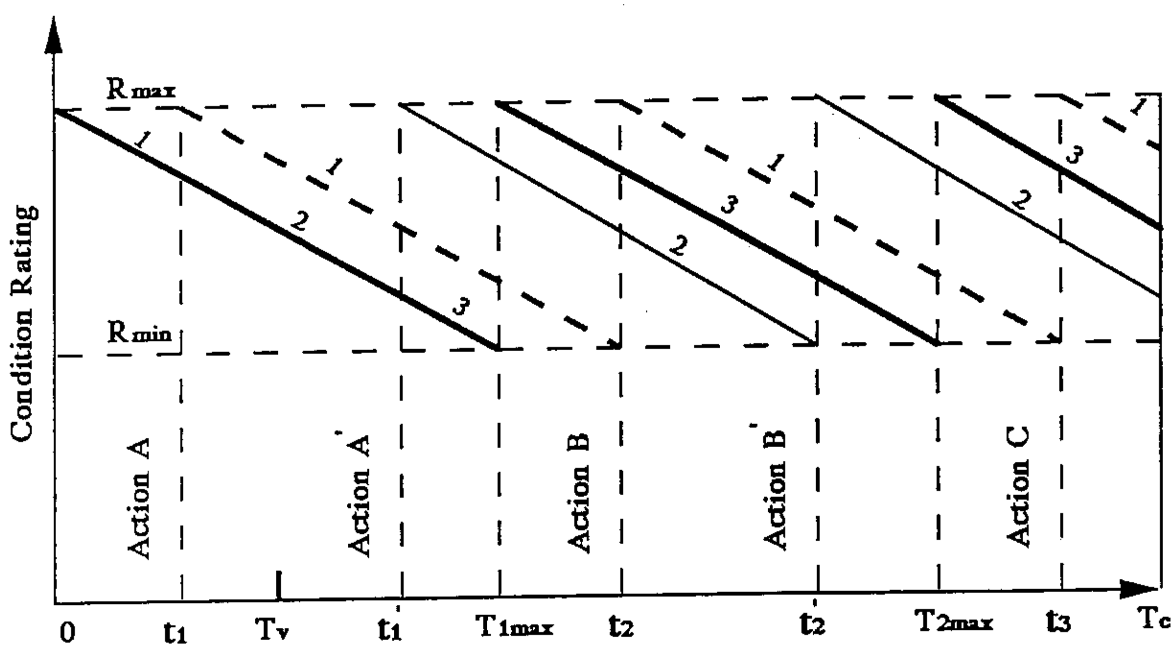

Figure 5.3 Determination of Latest Allowable Time for Various MR&R Works Using a Linear Deterioration Curve

As may be seen from Figs. 5.2 and 5.3, the following inequality holds:

$$R_i(T_{imax}) \geq R_{min} \quad (n=1,2,3) \qquad [5.2]$$

In Fig. 5.2, the first MR&R action occurred at $t=t_1$. However, this could have been delayed until $t=T_{1max}$. Once t_1 is specified, the consecutive T_{imax} are all affected. It must also be emphasized that with $t=t_1$ the time of the first MR&R work, the LAT's are T_{imax}'; however, if the first MR&R work is delayed until T_{1max}, the LAT's are T_{imax} (see Fig. 5.2).

In Fig. 5.2, the following inequalities also hold:

$$t_i \leq T_{imax}, \qquad [5.3]$$

and

$$R_{min} \leq R_i(t) \leq R_u(t) \qquad [5.4]$$

Although in most cases a bridge's rating is not allowed to fall to R_{min}, occasionally this may happen. After many iterations, it is possible to identify a condition rating profile that maximizes the VI function. The maximization may involve changing **n** or letting the condition rating fall to R_{min}

in some cases.

Several possible scenarios are depicted in Fig. 5.3 during the life cycle time 0-T_c.

Option 1:

The bridge rating is allowed to deteriorate to R_{min} at T_{1max} before any MR&R work is performed. Upon improvement in rating as a result of performing a MR&R action for the first time, again the bridge rating is allowed to deteriorate to R_{min} at $t=T_{2max}$ before a second MR&R action is performed. Although only two MR&R actions have been performed during the T_c time interval, the costs associated with these two actions are expected to be high.

Option 2:

The first MR&R action is performed at $t=t_1$. This requires a relatively low cost to implement (Action **A**). Subsequent MR&R works are all performed at relatively short time intervals (Action **A′** at $t=t_1'$, **B** at $t=t_2$, **B′** at $t=t_2'$, etc.). This alternative requires a number of MR&R works to be performed but each is relatively low cost.

Option 3:

Delay performance of the first MR&R work until $t=T_{1max}$; however, perform the subsequent ones at relatively short time intervals (e.g. Action **B**, **B′**, **C**, etc.)

Option 4:

Perform the first MR&R action at $t=t_1$ but delay performance of the subsequent actions to times equal to the respective LAT's.

Other options may be also identified that are a mix of options 3 and 4. As the number of potential MR&R actions (i.e. **n**) increases, the number of possible options multiples. Of course, the cost associated with each MR&R action needs to be properly incorporated into the process. Furthermore, constraints associated with availability of funds, current condition of bridge, the bridge priority in terms of traffic volume, etc. also affect the decision-making process. An efficient computer program is therefore needed to enable the analyst to explore various options to enable a selection of the most economically viable option to be made.

Of particular interest is the selection of a time T_v for the performance of the first MR&R action that not only optimizes the VI function but also provides the best option in the sense that it minimizes the number of MR&R actions to be performed. In most cases, the program can be used to identify T_v for **n**=2 (i.e. only two MR&R actions to be performed).

5.1.2 Selection of Bridge Life. One of the major input parameters that must be provided to run the computer software is bridge life (in years). Although bridge life is, in most cases, determined by the rate of deterioration of the bridge and its components, one may select a desired life and guarantee this life by identifying a MR&R plan that would be optimal in ensuring that the bridge rating will remain above the R_{min} condition at all times. For the purpose of optimizing the VI function, various options for the desired bridge life must be considered. Upon running the optimization program for each option, a close examination of the outcome for each bridge life option will reveal which bridge life option (among those initially selected) is likely to be the most economically viable one. The decision to select the various options for bridge life is left to the analyst. As a first trial, the analyst may wish to select the desired bridge life based on experience, existing bridge condition or on the limits of the bridge rating, i.e. R_{min} and T_{max}. The latter approach is explained below.

Suppose, as shown in Fig. 5.3, there are only two MR&R works to be performed in a single life cycle. Furthermore, suppose that the deterioration curve is R(t). Hence, the permissible maximum value of the life cycle T_c is:

$$(T_c)_{max} = T_{3max} = 3\,\frac{(9 - R_{min})}{k} \qquad [5.5]$$

Notice that the term $(9-R_{min})/k$ is based on a simple linear deterioration curve. If more than 2 MR&R works are planned, then Eq. [5.5] may be modified accordingly. It is evident that the number of MR&R works is dependent upon bridge life duration. At the same time, bridge life can be selected independently of the number of times MR&R works are to be performed. This means that the final decision on bridge life duration and an accompanying plan for the number and timing of the MR&R works to be performed can only be made based on many iterations. The computer program that has been developed for optimization of the VI permits this type of analysis to be made. However, the computer program includes only provisions for linear deterioration function R(t).

5.1.3 Other Input Data Needed to Run the Computer Program. The program also requires the following additional data in order to run:

- Historical bridge data records
- Structural type
- Roadway type

The needed data may be obtained from such computer systems as the Illinois Structure Information System (ISIS), or the Maintenance Management Information System (MMIS) (22). Both of these systems can be interrogated to acquire historical bridge inspection data.

The following is a detailed description of the data needed to run the computer program. A sample input file is given in Chapter VI Section 6.5.

(i) **Deterioration function for bridge elements.** This information may be obtained from the records of prior bridge inspections and the repair history. If such data for a bridge similar to that under consideration is available, then an appropriate bridge element deterioration function can be selected and used in the computer program. If such data is not available or is not adequate, then linear models (as described in Chapter IV) can be selected and calibrated for use in running the computer program. The computer program also has a built-in default option that can be invoked in the absence of any relevant information on the deterioration function.

(ii) **Average daily traffic (ADT).** The ADT value and its rate of growth are needed to run the computer program. The rate of growth can be obtained by observing past trends. Also, the ISIS and MMIS systems (22) can be consulted to obtain such data.

(iii) **Cost data.** Cost data includes: (a) the original cost of construction, (b) interest and inflation rates, and (c) the relation between bridge rating improvement and maintenance, repair and rehabilitation costs. The latter information is often difficult to find. Accordingly, the computer program, by default, uses a simplified approach as described by the linear functions shown in Fig. 5.4. From this figure, if the condition rating improvement due to any maintenance, rehabilitation and replacement (MR&R) action at $t=t_i$ is $k(t_i-t_{i-1})$, then with the original cost C_0, the interest rate *IR* and inflation rate *FR*, a cost function for the MR&R cost $C_i(t_i)$ at time $t=t_i$ is,

$$C_i(t_i) = C_0 \left(\frac{1+IR}{1+FR}\right)^{t_i} \frac{K(t_i - t_{i-1})}{9} \qquad [5.6]$$

in which the value 9 appearing in the denominator is the maximum bridge rating.

5.1.4 Description of Output. The computer program's output consists of the following:

- MR&R actions and their corresponding schedules as identified by the optimization process.
- Condition ratings prior to any MR&R action.
- Cost associated with each MR&R action.
- The optimum VI value for the various options investigated.
- Estimates of the extension of bridge life corresponding to the various planning options investigated.

5.2 Development of the Life-Cycle Activity Profile

The results of the VI optimization process may be used to develop a comprehensive life-cycle activity profile. As described earlier the life-cycle activity profile may be developed based on the bridge MR&R records and/or based on the engineer's judgment. The results obtained from running the computer program will allow the user to develop a projected life-cycle activity profile that is an effective tool in

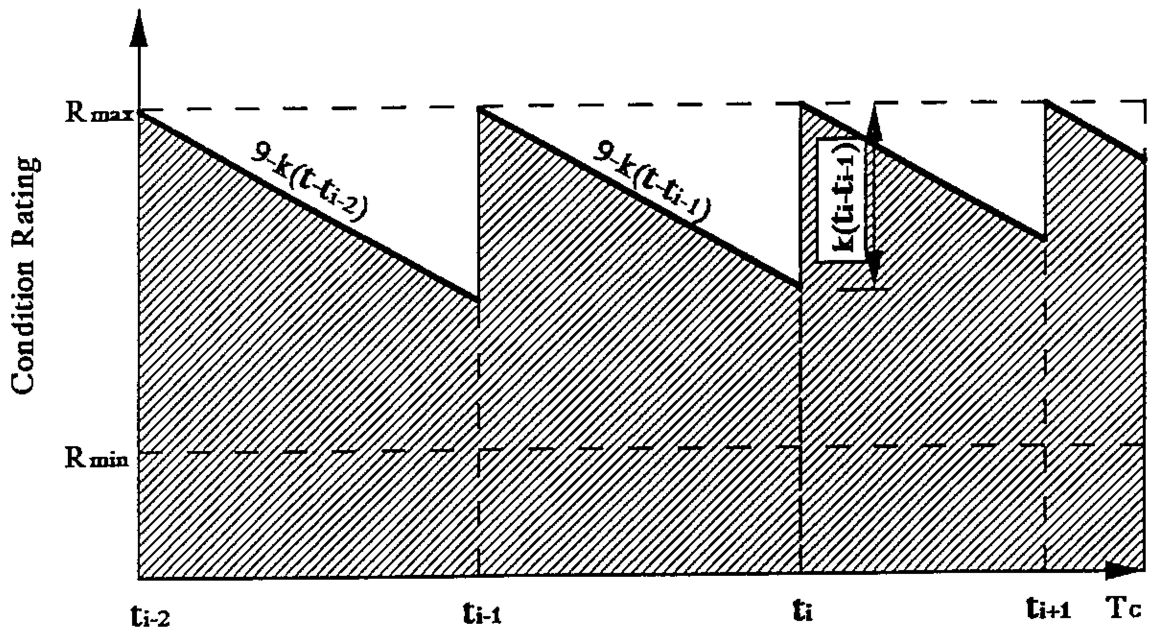

Figure 5.4 Computation of Rating Improvement

bridge planning and management. The following example demonstrates the process by which the life-cycle activity profile can be developed. Using the example cited in Chapter IV, a bridge was built in 1980 with a deck construction cost of $150,000. It is a steel girder bridge with a length of 250 feet and a width of 30 feet. It carries Interstate highway 55 with an average constant daily traffic ADT=25,000 vehicles per day. The minimum rating requirement R_{min} is 4. Two MR&R actions are considered: (A) deck replacement; and (B) redecking. Redecking costs less than total deck replacement and involves the restoration of deck through major repair. Thus, in this example, deck replacement and redecking constitute two different bridge MR&R alternatives with the following different costs:

Action A: Deck replacement with a unit cost of $61.29/feet^2.

Action B: Redecking with a unit cost of $55.30/feet^2.

The interest and inflation rates are IR=7% and FR=4%, respectively. The planning horizon is 30 years.

Deterioration function for deck is defined as:

$$R(t) = 9 - 0.119\,(AGE) - 2.158\times10^{-6}\,(ADTAGE)$$

Gradual age-related rating degradation function is:

$$R_u(t) = 9$$

With the help of the computer program, the following four options for the MR&R actions in one life cycle (30 year) have been investigated:

(i) Deck replaced twice:

$(VI)_{max1}$=16.426

t_1=4, t_2=7

The costs of deck replacement in 1984 and 1987 are $20,498 and $16,743 respectively.

(ii) Redecking twice:

$(VI)_{max2}$=16.897

t_1=4, t_2=8

The costs of redecking in 1984 and 1988 are $18,495 and $20,723, respectively.

(iii) Deck replacement first, then redecking:

$(VI)_{max3}$=16.696

t_1=3, t_2=8

The costs of deck replacement in 1983 and redecking in 1988 are $14,494 and $25,904, respectively.

(iv) Redecking first, then deck replacement:

$(VI)_{max4}$=16.677

t_1=5, t_2=8

The costs of redecking in 1985 and deck replacement in 1988 are $23,785 and $17,226, respectively.

Comparing the four values obtain for $(VI)_{max}$ in the respect four options, one finds that $(VI)_{max}$=$(VI)_{max2}$=16.897. Hence, option (ii) thus is selected. The other options, in their orders of priority, are: (iii), (iv) and (i), respectively. The projected life-cycle activity profiles for these options are shown in Fig. 5.5.

Once the life-cycle activity profile has been developed, decisions consistent with the specific objective outlined for each option may be made. For example, either the equivalent uniform annual cost (EUAC) method or the cost-effective improvement analysis can be performed.

The computer program is also capable of performing a cost analysis for a single bridge. This is done without considering the importance of the bridge in relation to a group or network of bridges. As described earlier, this type of analysis is classified as the project level. To conduct this type of analysis, the computer program includes the constraints specific only to the bridge under consideration. These include the required rating, the ADT, current condition rating of the bridge and a selection of the target times for major repair or rehabilitation actions. The analysis makes no reference to other bridges in the system or priorities that may exist among those other bridges. The result of this analysis can be used in future planning exercises when the specific needs of individual bridges are of concern.

Table 5.1 lists the results on five candidate bridges for a network level analysis. All bridges have equal importance to the network, and all costs are adjusted to present worth values considering the relevant interest and inflation rates. From the results of this table, it is evident that in 1993 an

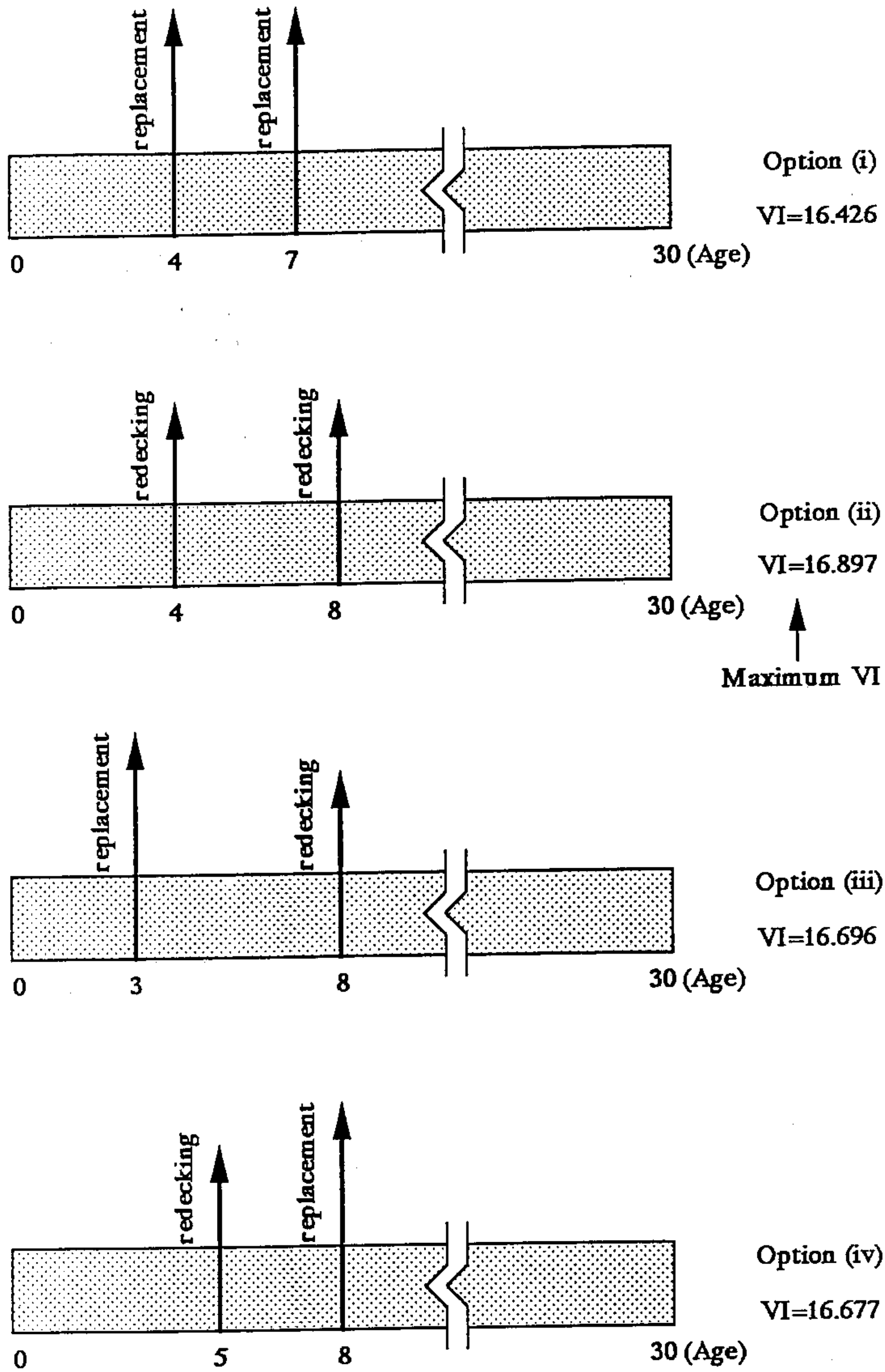

Figure 5.5 Projected Life Cycle Activity Profiles Derived from Computer Output

Table 5.1 Sample Alternatives Selection in Network Level Analysis

Bridges	VI Value	MR&R Alternative Action Years				
		1993	1994	1995	2010	2015
A	20	$50,000				$100,000
B	18			$25,000		$200,000
C	17		$265,000			$100,000
D	14		$100,000			
E	10	$60,000			$38,000	

MR&R work is required for bridges **A** and **E**. This is the case regardless of the amount of money that may be allocated to **A** and **E**. However, when the priorities for bridge rehabilitation work are being decided, the cost associated with each MR&R action in relation to the funds allocated to each bridge must be considered.

5.3 Limitations of the Computer Program

The VI model developed herein is based on a linear deterioration function. This must be modified when reliable data, sufficient to establish other types of functions, becomes available. Furthermore, the deterioration function is assumed to be consistent in each time period. In other words, the bridge is assumed to possess the same deterioration function in one or more time intervals. This feature is depicted in Fig. 5.6. As may be seen from this figure, although the curves start at different times, they all show the identical variation with time as well as the same confining area.

The gradual age-related rating degradation curve $R_u(t)$ is used to investigate the limits for the improvements that can be achieved by maintenance, rehabilitation and replacement actions. The VI computer program employs a constant value for $R_u(t)$, that is,

$$R_u(t) = R_{max}$$

where R_{max} is the maximum rating used the bridge condition rating system. An alternative form is a straight line function for $R_u(t)$ as given by (see Fig. 5.7):

$$R_u(t) = 9 - K' t$$

in which k' is a constant.

The computer program distinguishes between MR&R actions and an improvement action. The MR&R activities are geared to keeping a bridge in the best possible condition but at its current level of service. An improvement action, on the other hand, is expected to result in an increased the level of service (8). Hence, the input data must reflect whether the

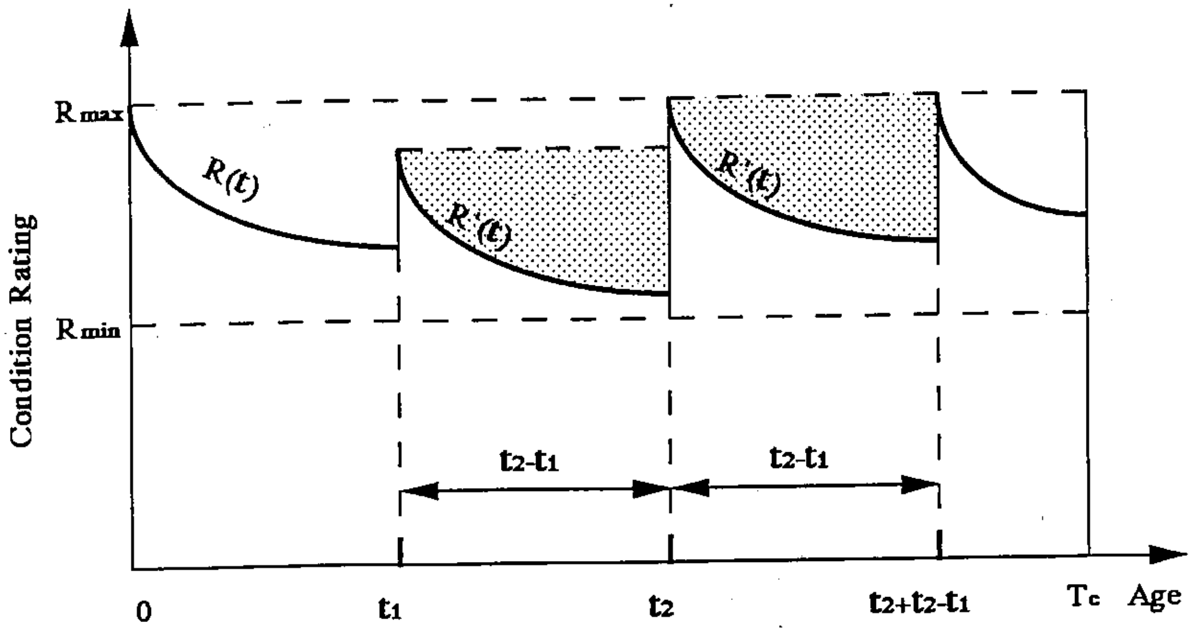

Figure 5.6 Consistency of Deterioration Functions

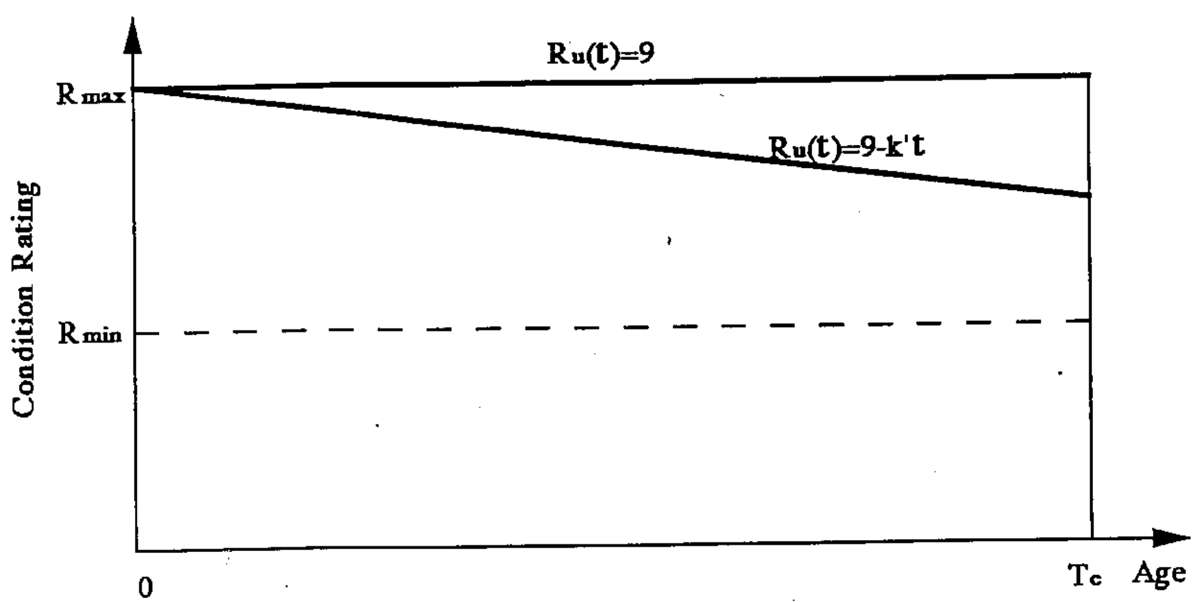

Figure 5.7 Two Simple Cases for Rating Degradation Function Ru(t)

contemplated actions are of the MR&R type or the improvement type.

The computer program does not include routine maintenance. Such actions are often performed on bridges to maintain the required daily level of service. No major change in the structural rating of a bridge is expected to result from the performance of routine maintenance work. Figure 5.8 depicts the difference between routine maintenance activities (B) and a specific MR&R action (A).

The computer program permits analysis to be made for the deck, superstructure and substructure as the three main components of a bridge. Additional modules for the analysis of other components (such as channels, approaches, joints, etc.) may to be added to the program. Each additional component, of course, will require a separate deterioration function.

Finally, the computer program is limited to agency costs only. User costs can be added when the relevant data becomes available, specifically, relationships between such cost items as wear and tear caused by vehicles, increase or reduction in insurance costs, accident rates, etc. Only when such relationships are established, can the computer program be extended to incorporate user costs in the analysis.

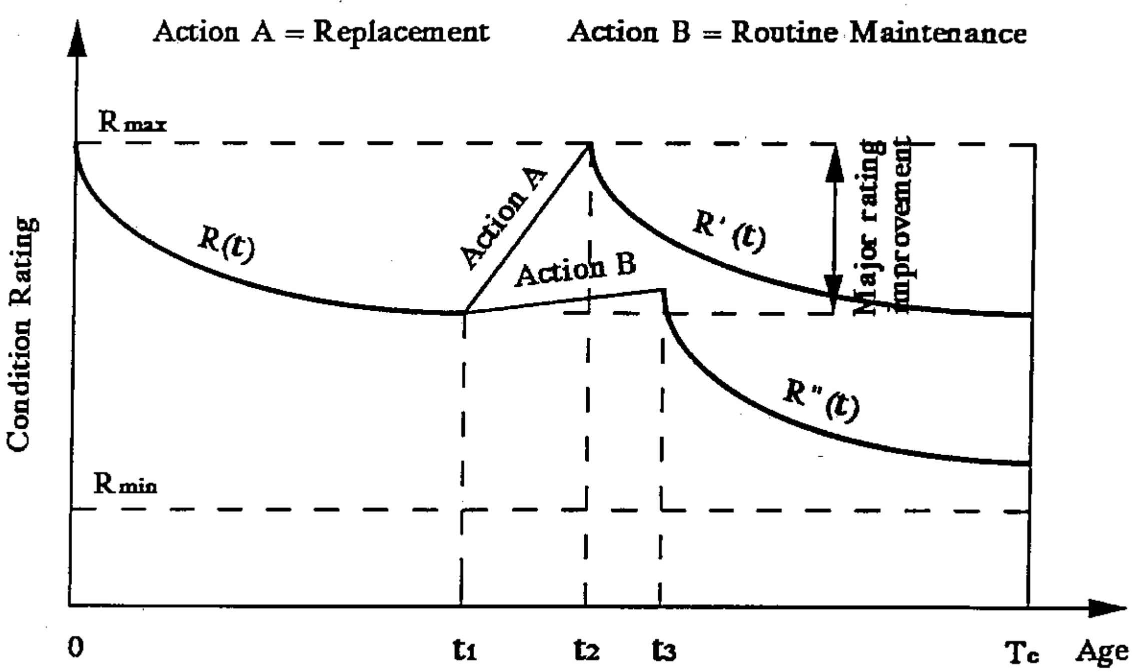

Figure 5.8 MR&R Action and Routine Maintenance

CHAPTER VI

ILLUSTRATIVE CASE STUDIES

6.1 Examples Used in the Illustration

Three bridges in Illinois were selected for life-cycle cost analysis to demonstrate the applicability of the VI model. The selection was based on bridge structural type. A recent study shows that bridges with different structural types exhibit different deterioration rates (23). The types selected are: (i) steel girder/beam; (ii) prestressed precast concrete girders; and (iii) concrete culvert bridge. The selection was made in consultation with IDOT engineers from a list of 35 potential bridges.

The VI model can be applied to the deck as well as to the super- and substructure. However, each will require a model that represents the deterioration of rating specific to the bridge component being analyzed. In this study, only the deck was analyzed in case studies A and superstructure in case studies B and C presented in this chapter. Information regarding structural design was acquired from the actual bridge drawings. Data on past records of bridge repair, maintenance and replacement was supplied by IDOT through the Illinois Structure Inventory System (ISIS) and the Maintenance Management Information System (MMIS).

6.2 Case Study A: Steel Wide Flange Beam Bridge

Bridge **A** (Bridge #0840088), built in 1963 and located on

County Highway 1 over Interstate 55 at the east city limits of Sherman, Illinois, is a four-span continuous wide flange steel beam bridge on open abutments and solid hammer head type piers (24) with an overall length of 227.33 feet back to back of abutments and a total deck width of 31.67 feet. The average daily traffic (ADT) on this bridge is 1750 (1987 data). The estimated ADT in year 2007 is expected to be 2100. The original deck was removed and a new one was built utilizing composite beam-slab action in 1989 as reported in Ref. (25). A routine inspection conducted on September 25, 1986, resulted in the following ratings: the deck 4 (poor condition), superstructure and substructure 7 (good condition) and overall structural condition 5 (fair condition) (24). The overall structural condition rating, which reflects both physical condition and load carrying capacity, has been reduced from good to fair as result of the poor inventory load rating. For the superstructure (including deck), the original 7-inch bare reinforced concrete deck has an additional 1/2 inch A-3 surface constructed by the county to improve a very rough surface created by spalling. This spalling was so severe that it suggested that a replacement was necessary without further analysis. No significant structural deterioration was noted in the other superstructure elements except for some minor transverse or craze cracks in the abutments. The recommendation to replace the deck was supported by FHWA personnel and by the Bureau of Bridges and Structures of IDOT.

The narrow deck width was cited as a problem and a recommendation to widen the deck was also made.

In addition to the above, the information on the planning period and number of desired times for repair work is also needed. Several factors affect the selection of the planning period. These are: (i) the long-range bridge rehabilitation plan by the state; (ii) the overall conditions of bridges being analyzed; (iii) changes in the ADT and usage of bridges, etc. Considering these factors, a time period that appears to be a reasonable estimate can be used to begin the optimization model. Changes in this estimate can then be made as the results of the optimization model indicate that a shorter or a longer time period may be desirable. The starting time can be entered as the year the bridge was built. Also, the initial cost of the structure when it was built (parameter C) needs to be entered. This cost can be estimated based on current year cost data rated back to the year the bridge was built. This cost was estimated as $272,450 for this bridge. Also, a planing period of 35 years was selected. It was then assumed that two repair actions are to be undertaken within the 35-year period. In the absence of a more definite set of data, a linear deterioration function (see Chapter IV and V) was used. However, the function was calibrated using the information on the changes in the condition rating of the bridge provided by IDOT. The input variables used are: T_c (planning time period) = 35 years; R_{min} = minimum rating requirement = 5; ADT = 1330 (based on 1963 statistics); ΔADT (Annual rate of ADT increase) = 1.32% (based on 1963 ADT value); IR (interest rate) = 7%; FR (inflation rate) = 1%; and the initial 1963 cost for the new deck, C=$272,450. The values of IR and FR were assumed for this study. These values change periodically with time. For more accurate estimates, the data on IR and FR over several years should be used as a means to project future changes. The results of the optimization model will be sensitive to changes in IR and FR especially if these changes are dramatic from year to year and also especially if an MR&R plan involves delaying an action over an extended time period. The data on IR and FR can be found in government publications on economic indices and consumer reports.

The VI optimization process (with first reconstruction in 1989) yields the following results for planning deck repair for a life cycle time of 35 years:

(i) The rating assigned to the deck in 1998 is 8.0. To upgrade this to 9, the <u>best</u> option is to repair the deck in 1998 (9 years after the first reconstruction) for a cost of $75,176 (1998 dollars). With a reconstruction cost of $129,195 in 1989, the present worth of this option is $239,419 (1993 dollar amount). This takes the inflation and interest rates into the account. The optimum VI achieved for this option is VI=11.963. The <u>next</u> best option using is to repair deck in 1997 (8 years after the first reconstruction). Since total bridge deterioration is smaller within a 8-year period than it is within an 9-year period, the cost to upgrade its deck to a rating of 9 will be smaller. The estimated cost for this option is $63,076 (1997 dollars) with VI=11.200. The 1993 present worth is $253,505 which indicates that the method is sensitive to the precise timing of the repairs.

(ii) If the inflation and interest rates are changed, the outcome of the optimization process will be affected accordingly. For example, if the inflation rate is increased to 5% and the interest rate remains at 7%, the following results will be obtained.

The rating assigned to the deck in 1997 is 8.2. To upgrade this to 9, the best option is to repair the deck in 1996 (7 years after the first reconstruction) at a cost of $41,269 (1996 dollars). With the reconstruction cost of $134,312 in 1989, the present worth of this option is $196,526 (1993 dollars). The optimum VI achieved for this option is VI=14.330. The next best option is to repair the deck in 1995 (6 years after the first reconstruction). The estimated cost for this option is $34,710 (1995 dollars) and VI=14.320. The 1993 present worth for this option is $197,301.

6.3 Case Study B: Precast Concrete Slab Bridge

Bridge B (Bridge #0860013), built in 1936 on FA route 76 section 1-L, is a two-span precast concrete slab (Nelsen Beam) bridge which rests on closed abutments with a solid hammerhead pier (26). It has an overall length of 76 feet a width of

33.9 feet. It carries Illinois Route 106 over Little Sandy Creek 1.5 miles north of Alsey in Scott County. It was reconstructed in 1981 as FA 566, Section IBR-2. This segment of Illinois Route 106 is functionally classified as an "Minor Arterial" highway. The 1989 ADT is 1400 vehicles with a projected ADT count of 1750 by 2009. The condition report for this bridge states that (26): (i) all existing substructure elements, existing abutments and piers, be recommended for reuse; and (ii) complete removal and replacement of the existing superstructure is recommended.

A routine inspection conducted on August 3, 1989, rated the superstructure and overall structural condition as 4 (marginal condition) and the substructure as 7 (generally good condition) (27).

The input variables used in the study are: T_c = 60 years; R_{min} (minimum rating requirement) = 5; ADT = 473 (1936 data) ΔADT = 3.7% (based on 1936 ADT value); IR = 7%; FR = 1%; and C = $275,000. With the first reconstruction done in 1981, the following represents the planning for bridge repair for a life cycle time of 60 years using the VI optimization model.

(i) The rating assigned to the superstructure in 1995 is 7.3. To upgrade this to 9, the <u>best</u> option is to repair the bridge in 1995 (14 years after the first reconstruction) at a cost of $29,976 (1995 dollars). With the reconstruction cost of $42,953 in 1981, the present worth of this option is $210,102 (1993 dollars) and the optimum VI is 21.587. The next best option using the VI method is to repair the bridge in 1994 (13 years after the first reconstruction). The estimated cost for this option is $26,274 (1994 dollars) and the VI is 13.587. The 1993 present worth is $305,737.

(ii) If the inflation rate is increased to 5% and interest rate remains at 7%, the following results will be obtained.

The rating assigned to the superstructure in 1995 is 7.3. To upgrade this to 9, the best option, according to the VI model, is to repair the bridge in 1995 at a cost of $24,685 (1995 dollars). With a reconstruction cost of $60,927 in 1981, the present worth of this option is $110,838 (1993 dollars). The optimum VI achieved for this option VI is 42.088. The next best option using the VI method is to repair the bridge in 1994. The estimated cost for this option is $22,494 (1994 dollars) and the VI is 38.613. The 1993 present worth is $119,799.

6.4 Case Study C: Concrete Culvert Bridge

Bridge C (Bridge #0162522), built in 1983, is a three-span concrete culvert structure (see Appendix A). It has an overall length of 42 feet and a width of 108 feet. It carries US 30 (Lincoln highway) across Butterfield Creek at 0.6 mile east of Cicero Avenue in Cook County. Average daily traffic (ADT) in 1990 was 36,400 and predicted ADT by 2012 is 14,580 (note that this is a negative ADT growth). This bridge has never been rehabilitated. The initial cost is assumed to be $253,381, this can be estimated by means of a unit cost of $55.86 (Appendix B) times the total bridge surface area.

A complete listing of input variables is provided below:

T_c = planning time period = 30 years

R_{min} = minimum rating requirement = 5

ADT = 43343 (for year 1983)

ΔADT = -2.29% (based on 1983 ADT value)

IR = interest rate = 7%

FR = inflation rate = 1%

C = the initial cost for the superstructure = $253,381

The following represents the planning for bridge repair for a life cycle time of 30 years.

(i) The <u>best</u> option, according to the VI model, is to repair the bridge in 1998 and 2010 for a cost of $79,710 (1998 dollars) and $127,454 (2010 dollars) respectively. The present worth of this option is $125,415 (1993 dollars). The optimum VI achieved for this option is VI=9.378. The <u>next</u> best option using the VI method is to repair the bridge in 1999 and 2010 at a cost of $90,075 (1999 dollars) and $116,833 (2010 dollars) respectively. The present worth of this option is $125,415 (1993 dollars). The optimum VI achieved for this option is VI=9.369.

(ii) If the inflation rate is increased to 5% and interest rate remains at 7%, the following results will be obtained.

The best option, according to the VI model, is to repair the bridge in 1995 and 2007 at a cost of $44,165 (1995 dollars) and $55,387 (2007 dollars) respectively. The present worth of this option is $109,334 (1993 dollars). The optimum VI achieved for this option is VI=18.578. The next best option using the VI method is to repair the bridge in 1995 and in 2006 at a cost of $44,165 (1995 dollars) and $49,823 (2006 dollars) respectively. The present worth of this option is $109,836 (1993 dollars). The optimum VI achieved for this option VI=18.576.

6.5 Sample Input File for the VI Model Computer Program

The computer program described in Chapter V was used to run the above three case studies. The input data is supplied interactively. Depending on the specific bridge component for which the analysis is required, one of several programs (i.e. DECK2V1.FOR) is selected and used for the analysis. A sample input file for case study **A** is provided below. A complete listing of the program appears in Appendix C.

A. ENTER THE BRIDGE NUMBER:

#0840088*

B. ENTER BRIDGE LOCATION:

S.A.Rte.IA over F.A.I.Rte 55 at East City Limits of Sherman, IL.

C. ENTER NUMBER FOR BRIDGE TYPE:

---

* All underlined items are inputs for sample bridge **A**.

1. STEEL I-BEAM/PLATE GIRDER

2. REINFORCED CONCRETE GIRDER/T-BEAM

3. PRESTRESSED PRECAST CONCRETE GIRDER/DECK BEAM

4. OTHERS (SPECIFY THE BRIDGE AND ENTER)*

1

D. ENTER NUMBER FOR ROADWAY:

1. INTERSTATE

2. STATE

3. COUNTY/LOCAL

3

E. ENTER THE LENGTH AND WIDTH (IN FEET) OF THE BRIDGE, SEPARATE YOUR ENTRIES BY A SPACE (I.E. 123.0 45.0):

227.33 31.67

F. ENTER THE YEAR BRIDGE WAS CONSTRUCTED: 1963

G. ENTER AVERAGE DAILY TRAFFIC (ADT) IN THE YEAR THE BRIDGE WAS BUILT: 1330

H. ENTER AVERAGE YEARLY RATE (WITH DECIMAL, I.E. 4.0) OF ADT INCREASE IN PERCENTAGE (USE A NEGATIVE VALUE IF ADT DECREASES): 1.32

I. ENTER THE MINIMUM DESIRED RATING (SCALES OF 1 TO 9, 9 BEING BEST):

5

J. ENTER YOUR BEST ESTIMATE FOR THE LIFE CYCLE OF DECK IN

---

* A reinforced concrete slab bridge, for example, is included in this category

YEARS. ENTER 0 IF YOU WISH THIS TO BE DETERMINED BY PROGRAM:

35

K. ENTER THE INITIAL COST (IN $ AND WITHOUT COMMA, I.E. 4726742.40) FOR DECK CONSTRUCTION IN YEAR:

272450

L. ENTER CURRENT INTEREST RATE IN PERCENTAGE:

7

M. ENTER CURRENT INFLATION RATE IN PERCENTAGE:

1

N. ENTER WHAT YEAR IS IT NOW (I.E. 1993):

1993

O. HAS THE BRIDGE WORK ALREADY PLANNED TO BE CONDUCT ON SPECIFIC YEARS? ENTER YES OR NO:

NO

P. HAS THIS BRIDGE DECK EVER BEEN REHABILITATED? ENTER YES OR NO:

YES

Q. WHAT WAS THE YEAR THE 1ST REHABILITATION WAS DONE:

1989

R. DO YOU WISH TO SEE NEXT BEST OPTION? ENTER YES OR NO:

YES

DONE! YOU MAY CHECK THE RESULTS IN FILE DECK2V1.OUT

CHAPTER VII

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

This study presents an analytical approach for highway bridge life-cycle cost analysis and the selection of the most cost-effective bridge maintenance, rehabilitation and/or replacement strategy. A parameter, which incorporates age, condition rating and cost, called the "value index" (VI), is used as a basis for comparing various bridge maintenance, rehabilitation and replacement strategies. This enables rational decisions to be made regarding the type of work to be performed that best suits a bridge's needs within the constraints of available funds. Information on the past records of inspection, maintenance and repair of various types of bridges is especially critical to this decision-making process. Bridges in Illinois are regularly inspected and rated on a routine basis. The rating data can be used as a basis to develop models to predict deterioration as a function of time of a bridge or bridge component. These models can then be utilized in bridge life-cycle cost analysis for the purpose of estimating the variation in the condition of a bridge over its service lifetime. This study presents an optimization approach which employs the value index (VI) and bridge deterioration as a function of time to permit rational decisions to be make about scheduling and the type of bridge work to be executed.

7.2 Conclusions

The decision on the number and timing of bridge works to be made depends on many factors of which the available funding level is perhaps the most important one. The objective of this study is to develop a procedure that can provide a rational means to analyze the most significant variables affecting bridge life-cycle costs in the decision-making process.

The model developed in this study uses only a limited number of variables in the analysis. These variables are, however, considered to be those most critical ones in bridge life-cycle planning. The concept described herein makes use of the value index (VI) and the total present worth value (PW). Using this concept, the option with the greatest VI and the smallest PW is taken to be the most desirable one. The model developed in this investigation is based on optimization of the value index in the decision-making process. It is also based on the notion that the value index is directly related to the magnitude of the present worth. Generally speaking the optimum VI value corresponds to the minimum PW; however such constraints as the number of bridge work options planned for the bridge, the anticipated service life and the desired minimum condition rating may give rise to several different optima. The advantage of using both VI and the PW over the PW alone in decision-making is that the VI also includes the optimum time schedule for the selected bridge work options as well as the cost in the analysis. The model developed in this study can also be used to make decisions on the timing of bridge works within a designated life cycle. In most applications, the scheduling of bridge works can be used as the most critical decision-making step in minimizing the cost. The results from the case studies presented in this study indicate that a minimum cost option is not necessarily the most desirable one. In fact, in certain applications it may be desirable to increase the cost so that the time between consecutive bridge works can be lengthened. In a network level analysis, this is especially important because individual bridges can be evaluated and compared for their repair/rehabilitation needs in terms of overall costs. If a particular bridge appears to engender higher costs, then the allocation of funds to the other bridges in the network can be adjusted to reflect this.

In long-term planning, the significance of early bridge repair and rehabilitation works can be compared with delayed ones by means of the life-cycle cost approach. Although delaying any particular bridge works may be expedient, and perhaps more expensive in the long term, the functional condition of the bridge and its adherence to safety requirements may be decisive in setting priorities for bridge works.

7.3 Recommendations

The following recommendations are made for possible continuation of the present study:

- Further investigations are needed to develop more specific and accurate deterioration models for three major types of bridges in Illinois, i.e (i) steel; (ii) prestressed precast concrete; and (iii) reinforced concrete bridges. Furthermore, reliable deterioration models for all major elements in each type of bridge are needed for a more refined life-cycle cost analysis.

- An extension of the program developed herein to cover network level analysis is needed. This requires a module that can be used to develop an allocation-of-fund process based on input from the user and specific requirements of the individual bridges in the network.

- User costs need to be implemented in the analysis. This requires a mechanism through which user costs can be estimated on a bridge-by-bridge basis. Development of a series of empirical functions is recommended for this purpose.

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APPENDIX A

ILLINOIS STRUCTURE INFORMATION SYSTEM REPORTS

RIS-S105, DTGB94FG, RIS-R105

ILLINOIS DEPARTMENT OF TRANSPORTATION
ILLINOIS STRUCTURE INFORMATION SYSTEM
INVENTORY TURNAROUND REPORT

DATE: 07/30/93

STRUCTURE NUMBER: 016 - 2522 DIST: 1 MAINTENANCE COUNTY: COOK
MUNICIPALITY: MATTESON
STATUS: OPEN - NO RESTRICT
STATUS DATE: 04 / 88

KEY RTE ON: FEDERAL-AID PRIMARY 0353 STA: 3.600 SEG: APRT: MAIN ROUTE 0.000 SUFFICIENCY RATING: 089.8
KEY RTE UN: 0000 STA: 0.000 SEG: APRT: 0.000 HBRRP ELIGIBLE: NO

************************ SCREEN 1 ****************************

ITEM #	ITEM NAME	EXISTING VALUES	REVISIONS
(7)	FACILITY CARRIED:	LINCOLN HWY US 30	
(6)	FEATURE CROSSED:	BUTTERFIELD CREEK	
(9)	LOCATION:	.6MI E OF CICERO AVE	
(7A)	BRIDGE NAME:		
(3B)	MAINTENANCE COUNTY:	016	
(21)	MAINTENANCE RESPONSIBILITY:	01	
(42)	SERVICE ON/UNDER:	1 5	
(22A)	REPORTING AGENCY:	1	
(20)	TOLL FACILITY:	0	
(35)	STRUCTURE FLARED:	0	
(31)	DESIGN LOAD:	02	
(31A)	STRUCT STEEL WEIGHT(LBS):	0	
(8A1)	BRIDGE REMARKS (EXISTING):		
	BRIDGE REMARKS (REVISED):		

ITEM #	ITEM NAME	EXISTING VALUES	REVISIONS
(101)	PARALLEL DESIGNATION:	N	
(8E)	REPLACED BY STRUCT NUMBER:	000 - 0000	
(8D)	REPLACES STRUCTURE NUMBER:	000 - 0000	
(49)	STRUCTURE LENGTH (FT):	42.0	
(112)	AASHTO BRIDGE LENGTH (FT):	42.0	
(51)	BRIDGE ROADWAY WIDTH (FT):	86.0	
(32)	APPROACH ROADWAY WIDTH (FT):	92.0	
(52)	DECK WIDTH (FT):	108.0	
(107/A)	DECK TYPE/THICKNESS (IN):	0.0	/
(48)	LENGTH OF LONGEST SPAN (FT):	14.0	
(45/6)	NBR SPANS MAIN/APPROACH:	03 0	/
(43A/B)	MAIN SPAN MATERIAL/TYPE:	1 19	/
(44AN/BN)	NEAR APPR SPAN MATRL/TYPE: #1		/
	#2		/
(44AF/BF)	FAR APPR SPAN MATRL/TYPE: #1		/
	#2		/

************************** SCREEN 2 *****************************

ITEM #	ITEM NAME	EXISTING VALUES	REVISIONS
(34/A)	SKEW DIR/ANGLE(DG-MN-SEC):	R / 20 0 0	/
(33)	BRIDGE MEDIAN TYPE:	2	
(33A)	BRIDGE MEDIAN WIDTH (FT):	14	
(38)	NAVIGATION CONTROL:	0	
(39)	NAVIGATION VERT CLEARANCE (FT):	0	
(40)	NAVIGATION HORZ CLEARANCE (FT):	0	
(50A)	SIDEWALK WIDTH ON - RIGHT (FT):	0.0	
(50B)	SIDEWALK WIDTH ON - LEFT (FT):	0.0	
(50C)	SIDEWALKS UNDER STRUCTURE:	0	
(36E)	GUARDRAILS ON - RIGHT:	1	
(36F)	GUARDRAILS ON - LEFT:	1	
(8C)	RR CROSSING NUMBERS:		
(55B1)	RR LATERAL UNDERCLEARANCE (FT):	0.0	
(54B3)	RR VERT UNDERCLEAR (FT-IN):	0 - 0	

ITEM #	ITEM NAME	EXISTING VALUES	REVISIONS
(202)	TRAFFIC PERMITS RTE SEC NBR:		
(8B)	MULTI-LEVEL STRUCTURE NUMBER:		
(62A)	CULVERT CELLS (COUNT):	0	
(62B)	CULVERT CELL WIDTH (FT):	0.00	
(62C)	CULVERT CELL HEIGHT (FT):	0.00	
(62D)	CULVERT OPENING AREA (SQ FT):	0.0	
(62E)	CULVERT FILL DEPTH (FT):	6.0	
(16A)	STATE PLANE ZONE:	E	
(16B)	NORTH COORDINATE:	1763300	
(17)	EAST-WEST COORDINATE:	668000	
(98A)	BORDER BRIDGE STATE NUMBER:		
(98B)	BORDER BRIDGE ADJ STATE (% RESP):	0	
(99)	BORDER BRIDGE NUMBER EXISTING:		
	BORDER BRIDGE NUMBER REVISED:		

RIS-S110,DTGB94FT,RIS-R111

ILLINOIS DEPARTMENT OF TRANSPORTATION
ILLINOIS STRUCTURE INFORMATION SYSTEM
KEY ROUTE TURNAROUND REPORT

DATE: 07/30/93

STRUCTURE NUMBER: 016 - 2522 DIST: 1 MAINTENANCE COUNTY: COOK
MUNICIPALITY: MATTESON

SUFFICIENCY RATING: 089.8
HBRRP ELIGIBILITY: NO

FACILITY CARRIED: LINCOLN HWY US 30 BRIDGE NAME:
FEATURE CROSSED: BUTTERFIELD CREEK LOCATION: .6MI E OF CICERO AVE
BRIDGE REMARKS:

BRIDGE STATUS: OPEN - NO RESTRICT BRIDGE STATUS DATE: 04/88
STATUS REMARKS:

K E Y R O U T E O N

ITEM #	ITEM NAME	VALUE	REVISION
(1A,B,C)	KEY ROUTE NUMBER:	2 0353	
(1D)	APPURTENANCE TYPE:	0	
(1E)	KEY ROUTE SEGMENT:		
(1F)	APPURTENANCE NUMBER:	00.000	
(1G)	KEY ROUTE STATION:	003.600	
(1H)	DIR OF INVENTORY:	E	
(3A)	INVENTORY COUNTY:	016	
(3A1)	INV TOWNSHIP/RD DIST:	28	
(4)	MUNICIPALITY:	3620	
(26)	FUNCTIONAL CLASS:	30	
(104)	HIGHWAY SYSTEM:	04	
(19)	BYPASS LENGTH:	03	
(30)	ESTIMATED AADT YEAR:	90	
(29)	ESTIMATED AADT:	036400	
(28)	NUMBER OF LANES:	06	
(102)	ONE OR TWO WAY TRAFFIC:	2	
(109)	ESTIMATED % TRUCKS:	05	
(115)	FUTURE AADT YEAR:	12	
(114)	FUTURE AADT:	014580	
(110)	DESIG. NAT'L TRUCK RTE:	2	

K E Y R O U T E U N D E R

ITEM #	ITEM NAME	VALUE	REVISION
(1A,B,C)	KEY ROUTE NUMBER:	0000	
(1D)	APPURTENANCE TYPE:		
(1E)	KEY ROUTE SEGMENT:		
(1F)	APPURTENANCE NUMBER:	00.000	
(1G)	KEY ROUTE STATION:	000.000	
(1H)	DIR OF INVENTORY:		
(3A)	INVENTORY COUNTY:	000	
(3A1)	INV TOWNSHIP/RD DIST:		
(4)	MUNICIPALITY:	0000	
(26)	FUNCTIONAL CLASS:		
(104)	HIGHWAY SYSTEM:		
(19)	BYPASS LENGTH:	00	
(30)	ESTIMATED AADT YEAR:	00	
(29)	ESTIMATED AADT:	000000	
(28)	NUMBER OF LANES:	00	
(102)	ONE OR TWO WAY TRAFFIC:		
(109)	ESTIMATED % TRUCKS:	00	
(115)	FUTURE AADT YEAR:	00	
(114)	FUTURE AADT:	000000	
(110)	DESIG. NAT'L TRUCK RTE:		

C L E A R A N C E I N F O R M A T I O N

	SOUTH OR EAST VALUE	SOUTH OR EAST REVISION	NORTH OR WEST VALUE	NORTH OR WEST REVISION
(47) MAX. RDWY WIDTH (FT):	0.0			
(47A/B) HORIZONTAL (FT):	090.0		000.0	
(53A/B) MIN VERT (FT-IN)	99 11		00 00	
(10A/B) 10 FT VERT (FT IN)	99 11		00 00	

	SOUTH OR EAST VALUE	SOUTH OR EAST REVISION	NORTH OR WEST VALUE	NORTH OR WEST REVISION
(47) MAX. RDWY WIDTH (FT):	0.0			
(47A/B) HORIZONTAL (FT):	000.0		000.0	
(54B1/2) MIN VERT (FT IN)	00 00		00 00	
(10A/B) 10 FT VERT(FT IN)	00 00		00 00	
(55B/56) MIN LATERAL (FT):	00.0		00.0	

M A R K E D R O U T E I N F O R M A T I O N

	ROUTE #1 VALUE	ROUTE #1 REV.	ROUTE #2 VALUE	ROUTE #2 REV.	ROUTE #3 VALUE	ROUTE #3 REV.
(5B) KIND:	2					
(5C) DESIG:	1					
(5D) NUMBER:	0030					

	ROUTE #1 VALUE	ROUTE #1 REV.	ROUTE #2 VALUE	ROUTE #2 REV.	ROUTE #3 VALUE	ROUTE #3 REV.
(5B) KIND:						
(5C) DESIG:						
(5D) NUMBER:						

RIS-S104
DTGB94FE
RIS-R104

ILLINOIS DEPARTMENT OF TRANSPORTATION
ILLINOIS STRUCTURE INFORMATION SYSTEM
INSPECTION / APPRAISAL REPORT

07/29/93

STRUCTURE NUMBER: 016 - 2522 DISTRICT: 1 MAINTENANCE COUNTY: COOK
MUNICIPALITY: MATTESON

BRIDGE STATUS: OPEN - NO RESTRICT BRIDGE STATUS DATE: 04/88
SUFFICIENCY RATING: 089.8 HBRRP ELIGIBILITY: NO
KEY ROUTE ON: FAP 0353 STA: 003.600 SPUR/ALT: MAIN RT. SEG:
KEY RT UNDER: 0000 STA: 000.000 SPUR/ALT: SEG:
INVENTORY RATING: 253 OPERATING RATING: 289

ALLOWABLE POSTINGS (TONS):
SINGLE UNIT VEHICLE-- COMBINATION VEHICLE(TYPE 3S-1)-- (TYPE 3S-2)--

---------------------- COMPUTER GENERATED APPRAISAL ITEMS -----------------

ITEM #	ITEM NAME	LAST RATING
(67)	STRUCTURAL EVALUATION:	6 EQUAL TO PRESENT MINIMUM CRITERIA
(68)	DECK GEOMETRY:	6 EQUAL TO PRESENT MINIMUM CRITERIA
(69)	UNDERCLEARANCE:	N NOT APPLICABLE

ITEM #	ITEM NAME	LAST INSPECTION	CURRENT INSPECTION
(90)	INSPECTION DATE:	02/11/92	__/__/__
(90C)	INSPECTION TEMPERATURE (FAHRENHEIT):	+031	____
(90A)	INSPECTION BY NAME:	J TIPPETT	________
(108A-C)	WEARING SURFACE AND PROTECTIVE SYSTEM:	A F A	__ __
(108D)	TOTAL DECK THICKNESS (IN):	7.0	___.__
(58)	DECK CONDITION:	N	____
(36)	RAILING APPRAISAL:	1 1 3 3	_ _ _ _
(59C)	UTILITIES ATTACHED TO STRUCTURE:	N N N	_ _ _
(59A)	LAST PAINT DATE (MM/YY):	00/00	__/__
(59B)	LAST PAINT TYPE:		_ _ _ _
(59)	SUPERSTRUCTURE CONDITION:	N	____
(60)	SUBSTRUCTURE CONDITION:	N	____
(61)	CHANNEL AND CHANNEL PROTECTION CONDITION:	7	____
(111)	PIER NAVIGATION PROTECTION CONDITION:	N	____
(62)	CULVERT CONDITION:	6	____
(71)	WATERWAY ADEQUACY APPRAISAL:	8	____
(72)	APPROACH ROADWAY ALIGNMENT APPRAISAL:	8	____

--------------------- ACTUAL POSTED VEHICLE RESTRICTIONS ------------------

(70D2) POSTED ONE TRUCK AT A TIME: ____
(70A2) SINGLE UNIT VEHICLE WEIGHT LIMIT (TONS): ____
(70B2) COMBINATION VEHICLE TYPE 3S-1 WT. LIMIT (TONS): ____
(70C2) COMBINATION VEHICLE TYPE 3S-2 WT. LIMIT (TONS): ____

(93C) SPECIAL INSPECTION DATE: 00/00/00 __/__/__
(90B) REMARKS (LAST INSPECTION):

REMARKS (CURRENT INSPECTION):

APPENDIX B

BRIDGE STRUCTURE SQUARE FOOT CONSTRUCTION COST

REVISED STRUCTURE MATERIAL, TYPE CODES, GROUPS, DESCRIPTION

BRIDGE SQUARE FOOT COST REPORT

MATERIAL GROUP	STRUCTURE TYPE CODE	STRUCTURE TYPE PRINT	SUPER STRUCTURE DESCRIPTION (MAIN LOAD CARRYING MEMBERS)
Structural Steel	01	SSG	Plate Girder, Wide Flange Beam, I-Beam or other structural steel members including special steel.
Precast Prestressed Concrete	02	PPC	Precast Prestressed Concrete Girders or Deck Beams.
Reinforced Concrete	03	RCS	Reinforced Concrete Slab, T-Beam, Girder or other cast-in-place R/C bridges.
Precast Concrete	04	PCS	Precast Reinforced Concrete Slab/Beam (Nonprestressed)
Misc.	31	*MTS	Multiple Type, Special, Unusual Construction
Misc.	32	*MAJ	Major Structures, River Crossings
Misc.	33	*RR	Structure Designed For Railroad Loading
Misc.	34	*PED	Pedestrian Bridges
Misc.	35	*DRR	Deck Repair & Rehabilitation
Misc.	36	*CAS	Structures with Closed Abutments
Misc.	37	*WES	Widening Existing Structures with similar material.

*Costs of miscellaneous group structures and deck repairs are not included in the average square foot cost determination.

DEPARTMENT OF TRANSPORTATION
BRIDGE STRUCTURE SQUARE FOOT CONSTRUCTION COST

RUN DATE 06/26/91

PRIMARY SYSTEM

GROUP SUMMARY NEW STRUCTURES REPORTING PERIOD DEC 89-DEC 90

		DISTRICT	SQ FT	SUPERSTR COST SQ FT	SUPERSTR COST TOTAL	SUBSTR COST SQ FT	SUBSTR COST TOTAL	SUP-SUB SQFT COST	INCID COST	TOTAL AWARDED	NO OF BRDGS
	STR STE	1	19,534	51.70	1,009,976	28.21	550,964	79.91	70,000	1,630,940	1
	PSTRES		11,245	37.69	423,850	21.71	244,084	59.40	64,807	732,742	2
	REINF C		10,695	33.59	359,261	24.15	258,237	57.74	117,738	735,236	2
DIST TOTAL			41,474	43.23	1,793,088	25.40	1,053,286	68.63	252,545	3,098,920	5
	STR STE	2	13,985	45.34	634,118	24.58	343,794	69.93	155,631	1,133,544	6
	PSTRES		43,833	28.96	1,269,553	21.21	929,688	50.17	380,125	2,579,366	9
	REINF C		13,339	31.02	413,777	25.05	334,194	56.07	119,950	867,922	2
DIST TOTAL			71,157	32.57	2,317,449	22.59	1,607,676	55.16	655,706	4,580,832	17
	STR STE	3	38,624	45.87	1,771,582	30.67	1,184,763	76.54	161,640	2,410,234	6
	PSTRES		31,317	28.37	888,417	22.21	695,433	50.57	443,693	2,027,544	8
	REINF C		5,500	21.74	119,594	23.49	129,211	45.24	24,999	273,804	2
DIST TOTAL			75,441	36.84	2,779,594	26.64	2,009,408	63.48	630,333	4,711,583	16
	STR STE	4	20,397	39.30	801,572	20.80	424,337	60.10	83,223	1,309,133	3
	PSTRES		14,818	42.30	626,795	30.60	453,479	72.90	266,699	1,346,974	6
DIST TOTAL			35,215	40.56	1,428,368	24.93	877,816	65.49	349,923	2,656,108	9
	STR STE	5	27,189	30.93	840,880	9.62	261,653	40.55	258,415	1,360,949	1
	PSTRES		3,248	44.56	144,734	38.93	126,455	83.49	60,727	331,917	1

ELC-RO48 ELC-SO38 ELC38

DEPARTMENT OF TRANSPORTATION
BRIDGE STRUCTURE SQUARE FOOT CONSTRUCTION COST

RUN DATE 06/26/91

PRIMARY SYSTEM

GROUP SUMMARY   NEW STRUCTURES

REPORTING PERIOD DEC 89-DEC 90

		DISTRICT		SQ FT	SUPERSTR COST SQ FT	SUPERSTR COST TOTAL	SUBSTR COST SQ FT	SUBSTR COST TOTAL	SUP-SUB SQFT COST	INCID COST	TOTAL AWARDED	NO OF BRDGS
		REINF C		3,817	36.18	138,117	35.72	136,338	71.90	71,577	346,033	2
DIST	TOTAL			34,254	32.81	1,123,733	15.31	524,448	48.12	390,719	2,038,901	4
		STR STE	6	82,297	33.07	2,721,179	18.95	1,559,512	52.02	468,138	4,748,821	9
		PSTRES		38,045	28.70	1,091,794	22.88	870,555	51.58	585,068	2,547,418	6
DIST	TOTAL			120,342	31.68	3,812,973	20.19	2,430,068	51.88	1,053,207	7,296,239	15
		STR STE	7	3,306	37.71	124,676	26.76	88,468	64.47	50,476	263,621	1
		PSTRES		5,954	34.64	206,225	10.78	64,172	45.41	36,000	306,397	1
DIST	TOTAL			9,260	35.73	330,902	16.48	152,640	52.22	86,476	570,018	2
		STR STE	8	36,597	44.69	1,635,663	23.10	845,480	67.80	293,362	2,774,506	8
		PSTRES		3,537	28.18	99,669	26.60	94,095	54.78	115,730	309,494	1
		REINF C		4,469	31.02	138,631	19.04	85,083	50.06	00	223,714	1
DIST	TOTAL			44,603	42.01	1,873,964	22.97	1,024,658	64.99	409,092	3,307,715	10
		STR STE	9	3,024	54.48	164,735	16.36	49,482	70.84	33,400	247,617	1
		PSTRES		4,255	28.96	123,227	13.01	55,338	41.97	114,749	293,315	1
DIST	TOTAL			7,279	39.56	287,962	14.40	104,820	53.96	148,149	540,932	2
		STR STE		244,953	39.62	9,704,386	21.67	5,308,456	61.29	1,574,288	15,879,368	36
		PSTRES		156,252	31.19	4,874,267	22.61	3,533,301	53.81	2,067,601	10,475,171	35

DEPARTMENT OF TRANSPORTATION

ELC-RO48 ELC-SO38 ELC38 BRIDGE STRUCTURE SQUARE FOOT CONSTRUCTION COST RUN DATE 06/26/91

PRIMARY SYSTEM GROUP SUMMARY NEW STRUCTURES REPORTING PERIOD DEC 89-DEC 90

	DISTRICT	SQ FT	SUPERSTR COST SQ FT	SUPERSTR COST TOTAL	SUBSTR COST SQ FT	SUBSTR COST TOTAL	SUP-SUB SQFT COST	INCID COST	TOTAL AWARDED	NO OF BRDGS
	REINF C	37,820	30.92	1,169,381	24.94	943,065	55.86	334,264	2,446,712	9
STATE TOTAL		439,025	35.87	15,748,036	22.29	9,784,823	58.16	3,976,154	28,801,252	80

ELC-RO48 ELC-SO38 ELC38

DEPARTMENT OF TRANSPORTATION
BRIDGE STRUCTURE SQUARE FOOT CONSTRUCTION COST

RUN DATE 06/28/91

PRIMARY SYSTEM

GROUP SUMMARY REDECKINGS AND WIDENINGS

REPORTING PERIOD DEC 89-DEC 90

		DISTRICT	SQ FT	SUPERSTR COST SQ FT	SUPERSTR COST TOTAL	SUBSTR COST SQ FT	SUBSTR COST TOTAL	SUP-SUB SOFT COST	INCID COST	TOTAL AWARDED	NO OF BRDGS
	STR STE	1	165,381	40.94	6,771,420	9.30	1,537,941	50.24	2,321,866	10,319,272	9
	PSTRES		1,717	30.53	52,424	41.29	70,893	71.82	7,782	131,082	1
DIST TOTAL			167,098	40.84	6,823,844	9.63	1,608,834	50.47	2,329,649	10,450,354	10
	STR STE	2	104,938	33.36	3,500,640	7.22	757,597	40.58	185,545	4,443,783	12
DIST TOTAL			104,938	33.36	3,500,640	7.22	757,597	40.58	185,545	4,443,783	12
	STR STE	3	63,771	32.94	2,100,307	17.34	1,106,081	50.28	70,000	3,276,388	5
	PSTRES		19,770	29.58	584,738	10.65	210,497	40.22	34,600	829,836	2
DIST TOTAL			83,541	32.14	2,685,045	15.76	1,316,579	47.90	104,600	4,106,225	7
	STR STE	4	7,013	29.30	205,481	4.12	28,861	33.42	8,000	242,342	1
	PSTRES		4,256	83.68	356,144	47.11	200,485	130.79	202,882	759,512	3
DIST TOTAL			11,269	49.84	561,625	20.35	229,346	70.19	210,882	1,001,854	4
	STR STE	5	221,234	52.04	11,512,079	11.83	2,616,871	63.86	588,217	14,717,167	9
	REINF C		15,724	40.53	637,368	16.43	258,303	56.96	91,761	987,433	5
DIST TOTAL			236,958	51.27	12,149,447	12.13	2,875,174	63.41	679,978	15,704,601	14
	STR STE	6	6,095	48.99	298,585	9.64	58,745	58.63	22,909	380,240	2
DIST TOTAL			6,095	48.99	298,585	9.64	58,745	58.63	22,909	380,240	2
	STR STE	7	47,672	23.83	1,136,129	3.49	166,299	27.32	88,528	1,390,957	5

ELC-RO48 ELC-SO38 ELC38

DEPARTMENT OF TRANSPORTATION
BRIDGE STRUCTURE SQUARE FOOT CONSTRUCTION COST

RUN DATE 06/28/91

PRIMARY SYSTEM

GROUP SUMMARY REDECKINGS AND WIDENINGS

REPORTING PERIOD DEC 89-DEC 90

		DISTRICT	SQ FT	SUPERSTR COST SQ FT	SUPERSTR COST TOTAL	SUBSTR COST SQ FT	SUBSTR COST TOTAL	SUP-SUB SOFT COST	INCID COST	TOTAL AWARDED	NO OF BRDGS
	REINF C		2,075	42.10	87,351	5.28	10,950	47.37	17,260	115,561	1
DIST TOTAL			49,747	24.59	1,223,480	3.56	177,249	28.16	105,788	1,506,518	6
	STR STE	8	401,399	53.52	21,481,818	7.08	2,842,203	60.60	1,167,467	25,491,489	12
	PSTRES		4,714	47.58	224,312	10.56	49,766	58.14	22,175	296,253	1
DIST TOTAL			406,113	53.45	21,706,130	7.12	2,891,970	60.57	1,189,642	25,787,742	13
	STR STE	9	15,374	49.87	766,727	15.04	231,273	64.91	116,519	1,086,568	2
DIST TOTAL			15,374	49.87	766,727	15.04	231,273	64.91	116,519	1,086,568	2
	STR STE		1032,877	46.25	47,773,188	9.05	9,345,875	55.30	4,569,054	61,348,210	57
	PSTRES		30,457	39.98	1,217,619	17.46	531,641	57.43	267,440	2,016,683	7
	REINF C		17,799	40.72	724,719	15.13	269,253	55.84	109,021	1,102,994	6
STATE TOTAL			1081,133	45.98	49,715,527	9.39	10,146,770	55.37	4,945,515	64,467,888	70

ELC-R048 ELC-S038 ELC38

DEPARTMENT OF TRANSPORTATION
BRIDGE STRUCTURE SQUARE FOOT CONSTRUCTION COST

RUN DATE 06/06/91.

LOCAL SYSTEM

GROUP SUMMARY NEW STRUCTURES

REPORTING PERIOD DEC 89-DEC 90

		DISTRICT	SQ FT	SUPERSTR COST SQ FT	SUPERSTR COST TOTAL	SUBSTR COST SQ FT	SUBSTR COST TOTAL	SUP-SUB SQFT COST	INCID COST	TOTAL AWARDED	NO OF BRDGS
	STR STE	1	16,603	45.80	760,351	13.48	223,763	59.27	233,691	1,358,306	2
	PSTRES		9,560	36.54	349,344	70.69	675,758	107.23	115,035	1,140,138	3
DIST TOTAL			26,163	42.41	1,109,695	34.38	899,521	76.80	348,727	2,498,444	5
	STR STE	2	11,600	52.28	606,486	30.28	351,210	82.56	1,085,068	2,042,765	1
	PSTRES		16,457	31.68	521,346	28.99	477,084	60.67	193,548	1,191,978	4
DIST TOTAL			28,057	40.20	1,127,832	29.52	828,295	69.72	1,278,616	3,234,744	5
	PSTRES	3	12,027	32.49	390,807	40.30	484,742	72.80	176,962	1,052,511	2
	REINF C		5,332	30.07	160,335	17.32	92,352	47.39	44,225	296,912	2
DIST TOTAL			17,359	31.75	551,142	33.24	577,094	64.99	221,187	1,349,423	4
	PSTRES	4	21,444	29.29	628,130	18.49	396,415	47.78	227,258	1,251,804	8
DIST TOTAL			21,444	29.29	628,130	18.49	396,415	47.78	227,258	1,251,804	8
	PSTRES	5	17,698	25.84	457,290	13.70	242,460	39.54	179,689	879,440	8
	REINF C		4,470	22.74	101,636	16.12	72,062	38.86	45,888	219,587	2
DIST TOTAL			22,168	25.21	558,926	14.19	314,522	39.40	225,578	1,099,027	10
	PSTRES	6	30,322	25.55	774,869	11.78	357,167	37.33	200,390	1,332,427	7
DIST TOTAL			30,322	25.55	774,869	11.78	357,167	37.33	200,390	1,332,427	7
	STR STE	7	8,866	36.93	327,464	11.11	98,460	48.04	71,488	497,413	2

ELC-RO48 ELC-SO38 ELC38

DEPARTMENT OF TRANSPORTATION
BRIDGE STRUCTURE SQUARE FOOT CONSTRUCTION COST

RUN DATE 06/06/91

LOCAL SYSTEM   GROUP SUMMARY   NEW STRUCTURES   REPORTING PERIOD DEC 89-DEC 90

		DISTRICT	SQ FT	SUPERSTR COST SQ FT	SUPERSTR COST TOTAL	SUBSTR COST SQ FT	SUBSTR COST TOTAL	SUP-SUB SOFT COST	INCID COST	TOTAL AWARDED	NO OF BRDGS
	PSTRES		16,227	33.33	540,904	19.32	313,459	52.65	407,499	1,261,862	7
	REINF C		2,891	28.44	82,231	13.89	40,148	42.33	23,604	145,983	1
DIST TOTAL			27,984	33.97	950,599	16.15	452,067	50.12	502,591	1,905,259	10
	PSTRES	8	7,723	28.85	222,842	19.52	150,759	48.38	141,428	510,030	4
DIST TOTAL			7,723	28.85	222,842	19.52	150,759	48.38	141,428	510,030	4
	PSTRES	9	12,396	34.90	432,660	22.22	275,408	57.12	179,023	887,092	7
DIST TOTAL			12,396	34.90	432,660	22.22	275,408	57.12	179,023	887,092	7
	STR STE		37,069	45.71	1,694,301	18.17	673,434	63.87	1,390,248	3,898,485	5
	PSTRES		143,854	30.02	4,318,195	23.45	3,373,255	53.47	1,820,836	9,507,287	50
	REINF C		12,693	27.12	344,202	16.12	204,562	43.23	113,717	662,482	5
STATE TOTAL			193,616	32.83	6,356,699	21.96	4,251,252	54.79	3,324,803	14,068,255	60

RIS-S107,DTGB94FI,RIS-R107

ILLINOIS DEPARTMENT OF TRANSPORTATION
ILLINOIS STRUCTURE INFORMATION SYSTEM
MASTER REPORT
INVENTORY DATA

DATE: 07/29/93

STRUCTURE NUMBER: 016 - 2522 DIST: 1

FACILITY CARRIED: LINCOLN HWY US 30
FEATURE CROSSED: BUTTERFIELD CREEK
BRIDGE REMARKS:
BRIDGE STATUS: OPEN - NO RESTRICT
STATUS REMARKS:
MAINT COUNTY: COOK
MAINT RESPONSIBILITY: I.D.O.T.
SERVICE ON/UNDER: HIGHWAY / WATERWAY

BRIDGE NAME:
LOCATION: .6MI E OF CICERO AVE
BRIDGE STATUS DATE: 04 / 88

SUFFICIENCY RATING: 089.8
HBRRP ELIGIBLE: NO
REPLACED BY: 000 - 0000
REPLACES: 000 - 0000
LAST UPDATE DATE: 06/16/92
PARALLEL STRUCTURE: NONE
MULTI-LEVEL STRUC NUMBER:
SKEW DIR: RIGHT
SKEW ANGLE: 20 00 00
STRUCTURE FLARED: NO
HISTORICAL SIGNIFICANCE: NO
BORDER BRIDGE STATE:
BDR STATE SN:
BDR STATE % RESPONSIBILITY: 00
STRUCTURAL STEEL WT: 000000000

REPORTING AGENCY: I.D.O.T. - BUREAU OF MAINTENANCE
MAIN SPAN MAT'L/TYPE: CONCRETE / CULVERT
NUMBER OF SPANS: (MAIN SPANS) - 03 (APPROACH SPANS) - 00
*** APPROACHES ***
NEAR #1 MAT'L/TYPE: /
NEAR #2 MAT'L/TYPE: /
FAR #1 MAT'L/TYPE: /
FAR #2 MAT'L/TYPE: /

MEDIAN WIDTH/TYPE: 14 FT. MOUNTABLE, ALL TYPES
GUARDRAILS L/R: STEEL PLATE BEAM STEEL PLATE BEAM
TOLL FACILITY: NO TOLL
STATE PLANE COORDS: 1763300 668000 EAST ZONE
STRUCTURE LENGTH: 42.0 SIDEWALKS UNDER STRUCTURE: NONE
AASHTO BRIDGE LENGTH: 42.0 SIDEWALK WIDTH RIGHT: 0.0 CULVERT FILL DEPTH: 6.0
LENGTH OF LONG SPAN: 14.0 SIDEWALK WIDTH LEFT: 0.0 CULVERT CELLS(COUNT): 0
BRIDGE ROADWAY WIDTH: 86.0 NAVIGATION CONTROL: NO CULVERT OPENING AREA: 0.0
APPR ROADWAY WIDTH: 92.0 NAVIGATION HORZ CLEAR: 0000 CULVERT CELL HEIGHT: 0.00
DECK WIDTH: 108.0 NAVIGATION VERT CLEAR: 000 CULVERT CELL WIDTH: 0.00
DECK STRUCTURE TYPE: DECK STRUCTURE THICKNESS: 0.0

RATED BY: N/A RATING DATE: 04/17/85
INVENTORY RATING: HS 29.4 (253)
OPERATING RATING: HS 49.4 (289)
DESIGN LOAD: HS20

*** RAILROAD CROSSING INFO ***
CROSSING 1 NBR:
CROSSING 2 NBR:
RR LATERAL UNDERCLEAR: 0.0
RR VERT UNDERCLEAR: 00 FT 00 IN

* * * KEY ROUTE ON DATA * * *

KEY ROUTE NBR: FEDERAL-AID PRIMARY 0353 STA: 3.600
APPURTENANCES: MAIN ROUTE 0.000 SEG:
INVENTORY COUNTY: COOK
TOWNSHIP/ROAD DIST: RICH
MUNICIPALITY: MATTESON
FUNCTIONAL CLASS: OTHER PRINCIPAL ARTERIAL
HIGHWAY SYSTEM: FA PRIMARY, URBAN

	SOUTH/EAST	NORTH/WEST		
** CLEARANCES **			AADT YR/COUNT:	90 / 036400
MAX. RDWY WIDTH:	0.0 FT			
HORIZONTAL:	90.0 FT	0.0 FT	TRUCK PERCENTAGE:	5
MIN VERTICAL:	99 FT 11 IN	00 FT 00 IN	NUMBER OF LANES:	06
10 FT VERTICAL:	99 FT 11 IN	00 FT 00 IN	ONE OR TWO WAY:	TWO-WAY
LATERAL:			BYPASS LENGTH:	03
			FUTURE AADT YR/COUNT:	12 / 14580
			DESIG NAT'L TRUCK ROUTE:	CLASS 2
			DEFENSE HIGHWAY DESIGNATION:	YES

* * KEY ROUTE UNDER DATA * * *

0000 STA: 0.000
0.000 SEG:

SOUTH/EAST	NORTH/WEST		
		AADT YR/COUNT:	00 / 000000
0.0 FT			
0.0 FT	0.0 FT	TRUCK PERCENTAGE:	0
00 FT 00 IN	00 FT 00 IN	NUMBER OF LANES:	00
00 FT 00 IN	00 FT 00 IN	ONE OR TWO WAY:	
0.0 FT	00.0 FT	BYPASS LENGTH:	00
		FUTURE AADT YR/COUNT:	00 / 000
		DESIG NAT'L TRUCK ROUTE:	
		DEFENSE HIGHWAY DESIGNATION:	

*** MARKED ROUTE ON DATA ***

	DESIGNATION	KIND	NUMBER
ROUTE #1	MAINLINE	U.S. HIGHWAY	0030
ROUTE #2			
ROUTE #3			

*** MARKED ROUTE UNDER DATA ***

DESIGNATION	KIND	NUMBER

ILLINOIS DEPARTMENT OF TRANSPORTATION
ILLINOIS STRUCTURE INFORMATION SYSTEM
MASTER REPORT
INSPECTION/IMPROVEMENT DATA

DATE: 07/29/93
PAGE: 2 OF 2

STRUCTURE NUMBER: 016 - 2522 DIST: 1

*** DATA RELATED TO INSPECTION INFORMATION ***

*** INSPECTION INTERVALS ***
ROUTINE NBIS: 24 MOS UNDERWATER: 00 MOS
FRACTURE CRITICAL: 00 MOS SPECIAL: 00 MOS

*** MAXIMUM ALLOWABLE POSTING LIMITS ***
ONE TRUCK AT A TIME:
SINGLE UNIT VEHICLES: TONS
BRIDGE POSTING LEVEL: NO POSTING REQUIRED
COMBINATION TYPE 3S-1: TONS
COMBINATION TYPE 3S-2: TONS

*** INSPECTION/APPRAISAL INFORMATION ***

INSPECTION DATE 02/11/92 SPECIAL INSPECTION DATE: 00/00/00
INSPECTION TEMPERATURE: +31 DEG. F.
DECK: N NOT APPLICABLE
BRIDGE RAILING APPRAISAL: 1 NO BRIDGE RAILING
APPROACH GUARDRAIL: 1 3 3 DOES NOT EXIST ACCEPTABLE ACCEPTABLE
SUPERSTRUCTURE: N NOT APPLICABLE
SUBSTRUCTURE: N NOT APPLICABLE
CHANNEL AND PROTECTION: 7 GOOD CONDITION - SOME MINOR PROBLEMS
CULVERT: 6 SATISFACTORY CONDITION - MINOR DETERIORATION
STRUCTURAL EVALUATION: 6 EQUAL TO PRESENT MINIMUM CRITERIA
DECK GEOMETRY: 6 EQUAL TO PRESENT MINIMUM CRITERIA
UNDERCLEARANCE-VERT,LAT: N NOT APPLICABLE
WATERWAY ADEQUACY: 8 EQUAL TO PRESENT DESIRABLE CRITERIA
APPROACH RDWY ALIGN: 8 EQUAL TO PRESENT DESIRABLE CRITERIA
PIER NAVIG PROTECTION: N N/A
INSPECTED BY (NAME): J TIPPETT
INSPECTION REMARKS:

*** ACTUAL POSTED LIMITS ***
SINGLE UNIT VEHICLES: TONS
COMBINATION TYPE 3S-1: TONS
COMBINATION TYPE 3S-2: TONS
POSTED ONE TRUCK AT A TIME:

UTILITIES ATTACHED:

DECK WEARING SURFACE: BARE DECK NO OVRLAY
DECK MEMBRANE: NONE
DECK PROTECTION: EPOXY COATED REINF
TOTAL DECK THICKNESS: 07.0 IN

LAST PAINT DATE	LAST PAINT TYPE
00/00	

*** UNDERWATER INSPECTION/APPRAISAL INFORMATION ***

INSPECTION DATE: 00/00/00 INSPECTION CATEGORY:
TEMPERATURE: +0 F. INSPECTION METHOD:
INSPECTED BY: APPRAISAL RATING:
INSPECTION REMARKS:

*** SCOUR CRITICAL INFORMATION ***

APPRAISAL RATING: 9 FNON ABOVE FLOOD EVALUATION METHOD: RATIONAL ANALYSIS
ANALYSIS DATE: 05/22/92 ANALYSIS BY (NAME): A.ELMER

*** MISCELLANEOUS ***

FRACTURE CRITICAL MEMBERS: NO
MICROFILM DATA RECORDED: YES

*** CONSTRUCTION INFORMATION ***

YEAR: 1983 ORIGINAL 0000 RECONSTRUCTED
ROUTE: FAP-848 STA: 252+40 STA:
SECTION NBR: 23B-I(82)
CONTRACT NBR:
FED AID PR #: IX- 8480080000
BUILT BY: I.D.O.T.

*** WATERWAY INFORMATION ***

FLOOD DESIGN FREQUENCY: 000 YRS DRAINAGE AREA: 00000000.0 ACRE
FLOOD DESIGN Q (CFS): 0000000
FLOOD DESIGN NAT H W E: 0.00 FLOOD BASE Q (C F S): 0000000
FLOOD DES OPEN PROP: 0000000 SF FLOOD BASE NAT H W E: 0.00

*** PROPOSED IMPROVEMENTS ***

COST ESTIMATE YEAR: 0000 LENGTH: 000000
TYPE OF WORK:

DONE BY:
REMARKS:

*** COSTS IN DOLLARS ***
BRIDGE IMPROVEMENT COST: $ 0
ROADWAY IMPROVEMENT COST: $ 0

TOTAL PROJECT COST: $ 0

APPENDIX C

PROGRAM CODE

PROGRAM DECK2V1.FOR

```
* PROGRAM IDENTIFICATION        DECK2V1.FOR
*       Bridge structure element: Deck.
*       Consider minimum rating condition.
*       The deterioration is:
*           R(t)=9-0.119*(AGE)-2.158*10**(-6)*(ADTAGE)
*           where ADTAGE=ADT*AGE/10
*       ----developed by Transportation System Center
*           U.S. Department of Transportation
*           Cambridge, Mass.
*       The Ru(t) curve: Ru(t)=Rmax=9 ( 100% recovery ).
*       Two times of action in one life cycle.
*       All actions are done within one year.
*       Consider the interest and inflation rates for money.
*       The initial cost is known.
*       The original PI has been amplified to 10000 times.
*       ----written by YAN, LI
*           reviewed by      . Jamshid Mohammadi.
*           Department of Civil Engineering
*
*

*
*
*
*
*

*


*DEFINITION OF VARIABLES
CHARACTER*35  CH1*52,CH2,CH3,CH4,CH5,CH6,CH7,CH8,CH9,CH10
CHARACTER*10  Q, Q1, Q2, A1, A2, A3, A4, CH11*52
INTEGER  ADT1,PASS,COUNT,COUNT1,COUNT2,COMP,I,K,L
INTEGER  Y1(10),Y2(10),Y4(10),Y5(10)
INTEGER  M1,M2,M1C,M2C,YB,YB1,YP,YBP,YE1,YE2
INTEGER  TT1,TT2,TT3,TY1,TY2, CASE1,CASE2
REAL  RMIN,IR,FR,B1,B2,B3,B4,B5,TEMP
REAL  TC,TC1,TC2,T1,T2,T1MAX,T2MAX,T3MAX
REAL  PI(2000),ST(2000),PI1(2000),PI2(2000),PI3(2000)
REAL  PI4(2000),CT1(4),CT2(4),CT3(4),CT(2000),J1(10),J2(10)
REAL  C1(10),C2(10),C3(10),C4(10),C5(10),C6(10),C7(10)
REAL  C8(10),PW1(10),PW2(10),R4(10),R5(10),R7(10),R8(10)
REAL  C,V,PC1,PC2, PC3,PCT,PIT,STT,ADT2,ADT01,ADT02,ADT03
REAL  CN,CRW,LE,WI,CO1,CO2,PIMAX1,PIMAX2,PIC1,PIC2
REAL  S1,S2,S3,R1,R2,R3
REAL  F1,F2,F3,F4,F5,F6,F7,F8,F9

*OPEN A FILE FOR OUTPUT FILE
OPEN(FILE='DECK2V1.OUT',UNIT=6,STATUS='UNKNOWN')
```

```
*INPUT OF BRIDGE INFORMATION
CH1='LIFE CYCLE COST ANALYSIS OF HIGHWAY BRIDGES PROGRAM'
CH2='DEVELOPED BY:'
CH3='YAN, LI'
CH4='DEPARTMENT OF CIVIL ENGINEERING'
CH5='ILLINOIS INSTITUTE OF TECHNOLOGY'
CH6='VERSION 1.0'
CH7='AUGUST 1993'
CH8='( PLEASE RETURN TO CONTINUE )'
      WRITE(5,1)CH1
      WRITE(6,1)CH1
 1    FORMAT(/////,15X,A,//)
      WRITE(5,3)CH2
 3    FORMAT(34X,A,//)
      WRITE(5,5)CH3
 5    FORMAT(36X,A)
      WRITE(5,7)CH4
 7    FORMAT(25X,A)
      WRITE(5,9)CH5
 9    FORMAT(24X,A,//)
      WRITE(5,11)CH6
 11   FORMAT(35X,A,/)
      WRITE(5,13)CH7
 13   FORMAT(35X,A,////)
      WRITE(5,15)CH8
 15   FORMAT(26X,A,///)
      READ*
      WRITE(5,17)
 17   FORMAT(/////)
      WRITE(5,19)
 19   FORMAT(//////20X,'THIS PROGRAM DETERMINES AT WHAT
      FUTURE YEAR',/)
      WRITE(5,21)
 21   FORMAT(19X,'A BRIDGE WORK SHOULD BE CONDUCTED TO
      OPTIMIZE',/)
      WRITE(5,23)
 23   FORMAT(30X,'COST AND BRIDGE SERVICE',//////)
      WRITE(5,15)CH8
      READ*
      WRITE(5,25)
 25   FORMAT(/////////////1X, '***************************
      BEGINNING OF PROGRAM**********************',//)
      WRITE(5,27)
 27   FORMAT(//////10X,'ENTER THE BRIDGE NUMBER:',//)
      READ(5,29)CH9
      WRITE(6,26)CH9
 26   FORMAT(//10X,'BRIDGE NUMBER:',1X,A,//)
 29   FORMAT(A)
      WRITE(5,31)
 31   FORMAT(/,10X,'ENTER BRIDGE LOCATION:',//)
      READ(5,29)CH10
      WRITE(6,28)CH10
```

```
28    FORMAT(/10X,'BRIDGE LOCATION:',1X,A,//)
32    WRITE(5,33)
33    FORMAT(/,10X,'ENTER NUMBER FOR BRIDGE TYPE:',/)
      WRITE(5,35)
35    FORMAT(10X,'1.',1X,'STEEL I-BEAM/PLATE GIRDER',/)
      WRITE(5,37)
37    FORMAT(10X,'2.',1X,'REINFORCED CONCRETE GIRDER
      /T-BEAM',/)
      WRITE(5,39)
39    FORMAT(10X,'3.',1X,'PRESTRESSED PRECAST CONCRETE
      GIRDER/DECK BEAM'1,/)
      WRITE(5,41)
41    FORMAT(10X,'4.',1X,'OTHERS ( SPECIFY THE BRIDGE AND
      ENTER IT )',/)
      WRITE(6,44)
44    FORMAT(////33X,'BRIDGE DATA INPUT',//)
      WRITE(6,46)
46    FORMAT(5X,'*************************************',//)
      READ(5,*)TY1
      IF(TY1.EQ.1) THEN
        WRITE(6,45)
45      FORMAT(6X,'BRIDGE TYPE: STEEL I-BEAM/PLATE
        GIRDER',/)
      ELSE IF(TY1.EQ.2) THEN
        WRITE(6,47)
47      FORMAT(6X,'BRIDGE TYPE: REINFORCED CONCRETE
        GIRDER/T-BEAM',/)
      ELSE IF(TY1.EQ.3) THEN
        WRITE(6,49)
49      FORMAT(6X,'BRIDGE TYPE: PRESTRESSED PRECAST CONCRETE
        GIRDER/DECK BEAM',/)
      ELSE IF(TY1.EQ.4) THEN
        WRITE(5,51)
51      FORMAT(10X,'SPECIFY THE BRIDGE TYPE AND ENTER IT',/)
        READ(5,53)CH11
53      FORMAT(/,A,/)
        WRITE(6,55)CH11
55      FORMAT(/6X,'BRIDGE TYPE IS:',1X,A,//)
        WRITE(5,57)
57      FORMAT(10X,'ENTER THE UNIT COST ( $/SQ.FT.) FOR
        THESE TWO CASES, SEPARATE'/10X,'BY A SPACE.'/10X,'1.
        NEW'/10X,'2. REDECKING & WIDENING')
        READ(5,*)CN,CRW
      ELSE
        WRITE(5,59)
59      FORMAT(/10X,'WRONG ENTRY, PLEASE ENTER 1,2,3,4,OR
        5',//)
        GO TO 32
      END IF
      WRITE(5,*)
      WRITE(6,*)
62    WRITE(5,61)
```

```
61    FORMAT(/,10X,'ENTER NUMBER FOR ROADWAY:',/)
      WRITE(5,63)
63    FORMAT(10X,'1.',1X,'INTERSTATE',/)
      WRITE(5,65)
65    FORMAT(10X,'2.',1X,'STATE',/)
      WRITE(5,67)
67    FORMAT(10X,'3.',1X,'COUNTY/LOCAL',/)
      READ(5,*)TY2
      IF(TY2.EQ.1) THEN
        WRITE(6,69)
69      FORMAT(/6X,'TYPE OF ROADWAY: INTERSTATE',/)
      ELSE IF(TY2.EQ.2) THEN
        WRITE(6,71)
71      FORMAT(/6X,'TYPE OF ROADWAY: STATE',/)
      ELSE IF(TY2.EQ.3) THEN
        WRITE(6,73)
73      FORMAT(/6X,'TYPE OF ROADWAY: COUNTY/LOCAL',/)
      ELSE
        WRITE(5,75)
75      FORMAT(/,10X,'WRONG ENTRY, PLEASE ENTER 1, 2 OR
        3',/)
        GO TO 62
      END IF
      WRITE(5,74)
74    FORMAT(/,10X,'ENTER THE LENGTH AND WIDTH (IN FEET) OF
      THE BRIDGE, SEPARATE YOUR'/10X,'ENTRIES BY A SPACE
      (I.E. 123.0 45.0).',/)
      READ(5,*)LE,WI
      WRITE(5,77)
77    FORMAT(/,10X,'ENTER THE YEAR BRIDGE WAS CONSTRUCTED:
      ',//)
      READ(5,78)YB
78    FORMAT(I4)
      WRITE(6,79)YB
79    FORMAT(/6X,'THE YEAR OF BRIDGE CONSTRUCTION IS:',1X,
      I4,/)
      WRITE(5,81)
81    FORMAT(/,10X,'ENTER AVERAGE DAILY TRAFFIC (ADT) IN THE
      YEAR THE BRIDGE WAS BUILT',//)
      READ(5,83)ADT1
83    FORMAT(I8)
      WRITE(5,85)
85    FORMAT(/10X,'ENTER AVERAGE YEARLY RATE ( WITH DECIMAL,
      I.E 4.0 ) OF ADT INCREASE'/10X,'IN PERCENTAGE ( USE A
      NEGATIVE VALUE IF ADT DECREASES ).',//)
      READ(5,87)ADT2
87    FORMAT(F6.2)
      WRITE(5,89)ADT1
      WRITE(6,89)ADT1
89    FORMAT(/6X,'ADT FOR BRIDGE CONSTRUCTION YEAR  IS:',4X,
      I8,//)
      WRITE(5,91)ADT2
```

```
      WRITE(6,91)ADT2
91    FORMAT(/6X,'YEARLY RATE OF THE ADT INCREASE OR
      DECREASES IS:',4X,F6.2,1X,'%',/)
      ADT2=ADT2*ADT1/100
      WRITE(5,*)'ADT2=',ADT2
      WRITE(5,93)
93    FORMAT(/10X,'ENTER THE MINIMUM DESIRED RATING ( SCALES
      OF 1 TO 9, 9 BEING BEST )',//)
      READ(5,*)RMIN
      WRITE(5,95)RMIN
      WRITE(6,95)RMIN
95    FORMAT(/6X,'THE MINIMUM DESIRED RATING IS:',4X,F6.2,
      //)
      WRITE(5,94)
94    FORMAT(/10X,'ENTER YOUR BEST ESTIMATE FOR THE LIFE
      CYCLE OF DECK IN YEARS.',/,10X,'ENTER 0 IF YOU WISH
      THIS TO BE DETERMINED BY PROGRAM.'//)
      READ(5,*)TC
      B1=2.158*10**(-6)/10*ADT1+0.119
      B2=2.158*10**(-6)/10*ADT2
      IF(B2.EQ.0) THEN
            B2=0.000001
      END IF
      B3=B1**2-4*B2*(RMIN-9)
      T1MAX=(SQRT(B3)-B1)/2/B2
      B4=(B1-B2*T1MAX)**2-4*B2*(RMIN-9-B1*T1MAX)
      IF(B4.LT.0) THEN
            T2MAX=(B2*T1MAX-B1)/2/B2
      ELSE
            T2MAX=(B2*T1MAX-B1+SQRT(B4))/2/B2
      END IF
      B5=(B1-B2*T2MAX)**2-4*B2*(RMIN-9-B1*T2MAX)
      IF(B5.LT.0) THEN
           T3MAX=(B2*T2MAX-B1)/2/B2
      ELSE
           T3MAX=(B2*T2MAX-B1+SQRT(B5))/2/B2
      END IF
      IF(TC.GT.T3MAX) THEN
         WRITE(5,99)TC,T3MAX
99    FORMAT(/10X,'YOUR ENTRY FOR LIFE CYCLE IS',1X,F5.0,1X,
      'YEARS.  BASE ON BRIDGE'/10X,'DATA YOU ENTERED, A
      SHORTER LIFE CYCLE COULD BE ENTERED.'/10X,'THE PROGRAM
      SUGGEST A MAXIMUM OF',1X,F5.0,1X,'YEARS FOR LIFE
      CYCLE.'/10X,'ENTER THE LIFE CYCLE OR 0 IF YOU LIKE THE
      PROGRAM TO DETERMINE IT.'//)
         READ(5,*)TC
      END IF

*LIFE CYCLE DETERMINED BY PROGRAM
      IF(TC.EQ.0) THEN
      WRITE(5,97)T1MAX+2,T3MAX
97    FORMAT(/10X,'THE PROGRAM SUGGEST THE LIFE CYCLE FOR
```

```
      THE DECK IS BETWEEN:'/10X,F6.0,1X,'YEARS', 2X,F6.0,1X,
      'YEARS.  ENTER THE LIFE CYCLE AGAIN'/)
      READ(5,*)TC
      END IF
      IF(T1MAX.GT.TC-2) THEN
        WRITE(5,98)TC,T1MAX+2
98    FORMAT(/10X,'YOUR ENTRY FOR LIFE CYCLE IS',1X,F5.0,1X,
      'YEARS.  BASE ON BRIDGE'/,10X,'DATA YOU ENTERED, A
      LONGER LIFE CYCLE COULD BE ENTERED.'/10X,'THE PROGRAM
      SUGGEST A MINIMUM OF',1X,F5.0,1X,'YEARS ENTER NEW'
      /10X, 'LIFE CYCLE IN YEARS OR ENTER 0 IF YOU WISH TO
      KEEP YOUR'/10X,'INITIAL ENTRY.',//)
      READ(5,*)TC1
        IF(TC1.NE.0) THEN
         TC=TC1
        END IF
      END IF
      WRITE(5,101)TC
      WRITE(6,102)TC
101   FORMAT(/10X,'THE ESTIMATED LIFE CYCLE OF DECK IN YEARS
      IS:',4X,F5.0,1X,'YEARS'//)
102   FORMAT(/6X,'THE ESTIMATED LIFE CYCLE OF DECK IN YEARS
      IS:',4X,F5.0,1X,'YEARS'//)
      IF(T1MAX.GT.(TC-2)) THEN
         T1MAX=TC-2
      END IF
      IF(T2MAX.GT.(TC-1)) THEN
         T2MAX=TC-1
      END IF
      WRITE(5,103)YB
103   FORMAT(/10X,'ENTER THE INITIAL COST (IN $ AND WITHOUT
      COMMA, I.E. 4726742.40)'/10X,'FOR DECK CONSTRUCTION IN
      YEAR:',4X,I4,//)
      READ(5,*)C
      WRITE(5,105)C
      WRITE(6,105)C
105   FORMAT(/6X,'THE INITIAL COST FOR DECK CONSTRUCTION:',
      4X,'US$',F11.2,//)
      WRITE(5,107)
107   FORMAT(/10X,'ENTER CURRENT INTEREST RATE IN
      PERCENTAGE. '//)
      READ(5,*)IR
      WRITE(6,109)IR
109   FORMAT(/6X,'CURRENT INTEREST RATE:',4X,F6.2,'%',//)
      IR=IR/100
      WRITE(5,111)
111   FORMAT(/10X,'ENTER CURRENT INFLATION RATE IN
      PERCENTAGE.',//)
      READ(5,*)FR
      WRITE(6,113)FR
113   FORMAT(/6X,'CURRENT INFLATION RATE:',4X,F6.2,'%'//)
      FR=FR/100
```

```
      V=(1+IR)/(1+FR)
      IF(((TY2.EQ.1).OR.(TY2.EQ.2)).AND.(TY1.EQ.1)) THEN
         CO1=LE*WI*61.29/V**(1990-YB)
         CO2=LE*WI*55.30/V**(1990-YB)
      ELSE IF(((TY2.EQ.1).OR.(TY2.EQ.2)).AND.(TY1.EQ.2))
      THEN
         CO1=LE*WI*55.86/V**(1990-YB)
         CO2=LE*WI*55.84/V**(1990-YB)
      ELSE IF(((TY2.EQ.1).OR.(TY2.EQ.2)).AND.(TY1.EQ.3))
      THEN
         CO1=LE*WI*53.81/V**(1990-YB)
         CO2=LE*WI*57.43/V**(1990-YB)
      ELSE IF(((TY2.EQ.1).OR.(TY2.EQ.2)).AND.(TY1.EQ.4))
      THEN
         CO1=LE*WI*CN/V**(1990-YB)
         CO2=LE*WI*CRW/V**(1990-YB)
      ELSE IF((TY2.EQ.3).AND.(TY1.EQ.1)) THEN
         CO1=LE*WI*63.87/V**(1990-YB)
         CO2=LE*WI*34.01/V**(1990-YB)
      ELSE IF((TY2.EQ.3).AND.(TY1.EQ.2)) THEN
         CO1=LE*WI*43.23/V**(1990-YB)
         CO2=LE*WI*43.23/V**(1990-YB)
      ELSE IF((TY2.EQ.3).AND.(TY1.EQ.3)) THEN
         CO1=LE*WI*53.47/V**(1990-YB)
         CO2=LE*WI*47.10/V**(1990-YB)
      ELSE IF((TY2.EQ.3).AND.(TY1.EQ.4)) THEN
         CO1=LE*WI*CN/V**(1990-YB)
         CO2=LE*WI*CRW/V**(1990-YB)
      END IF
      A1='YES'
      A2='NO'
      A3='yes'
      A4='no'
      WRITE(5,114)
114   FORMAT(/10X,'ENTER WHAT YEAR IS IT NOW (I.E. 1993)./)
      READ(5,116)YP
116   FORMAT(I4)
      YBP=YP-YB
118   WRITE(5,115)
115   FORMAT(/10X,'HAS THE BRIDGE WORK ALREADY PLANNED TO BE
      CONDUCT ON SPECIFIC',/10X,'YEARS?  ENTER YES OR NO.')
      READ(5,117)Q1
117   FORMAT(A)
      IF((Q1.EQ.A1).OR.(Q1.EQ.A3)) THEN
        WRITE(5,119)
119   FORMAT(/10X,'ENTER THE TWO DIFFERENT YEARS IN WHICH
      YOU PLAN TO CONDUCT THE'/10X,'WORK.  SEPARATE YOUR
      ENTRIES BY A SPACE.',//)
      READ(5,121)TT1,TT2
121   FORMAT(I4,I5)
      WRITE(6,123)TT1,TT2
123   FORMAT(/6X,'YOUR INPUT FOR ACTION YEARS ARE:',4X,I4,
```

```
4X,I4,//)
T1=TT1-YB
T2=TT2-YB
  IF(TC.LE.T2) THEN
    TC=T2+1
  END IF
B5=(B1-B2*T2)**2-4*B2*(RMIN-9-B1*T2)
  IF(B5.LT.0) THEN
    T3MAX=(B2*T2-B1)/2/B2
  ELSE
    T3MAX=(B2*T2-B1+SQRT(B5))/2/B2
  END IF
  IF((T3MAX.GE.TC).OR.(T3MAX.LE.T2))  THEN
    T3MAX=TC
  END IF
ADT01=ADT1+ADT2*T1
ADT02=ADT1+ADT2*T2
ADT03=ADT1+ADT2*T3MAX
S1=F1(T1,ADT01)
S2=F2(T2,T1,ADT02)
S3=F3(T3MAX,T2,ADT03)
STT=S1+S2+S3
CT1(1)=F4(CO1,V,T1,ADT01)
CT2(1)=F5(CO1,V,T2,T1,ADT02)
CT3(1)=F6(C,V,T3MAX,T2,ADT03)
CT(1)=CT1(1)+CT2(1)+CT3(1)
PI1(1)=ABS(STT/CT(1)*10000)
CT1(2)=F4(CO1,V,T1,ADT01)
CT2(2)=F5(CO2,V,T2,T1,ADT02)
CT3(2)=F6(C,V,T3MAX,T2,ADT03)
CT(2)=CT1(2)+CT2(2)+CT3(2)
PI2(2)=ABS(STT/CT(2)*10000)
CT1(3)=F4(CO2,V,T1,ADT01)
CT2(3)=F5(CO1,V,T2,T1,ADT02)
CT3(3)=F6(C,V,T3MAX,T2,ADT03)
CT(3)=CT1(3)+CT2(3)+CT3(3)
PI3(3)=ABS(STT/CT(3)*10000)
CT1(4)=F4(CO2,V,T1,ADT01)
CT2(4)=F5(CO2,V,T2,T1,ADT02)
CT3(4)=F6(C,V,T3MAX,T2,ADT03)
CT(4)=CT1(4)+CT2(4)+CT3(4)
PI4(4)=ABS(STT/CT(4)*10000)
  IF(PI1(1).LE.PI2(2)) THEN
    PIT=PI2(2)
    L=2
  ELSE
    PIT=PI1(1)
    L=1
  END IF
  IF(PIT.LE.PI3(3)) THEN
    PIT=PI3(3)
    L=3
```

```
          END IF
          IF(PIT.LE.PI4(4)) THEN
            PIT=PI4(4)
            L=4
          END IF
        R1=F7(T1,ADT01)
        R2=F8(T2,T1,ADT02)
        R3=F9(T3MAX,T2,ADT03)
        TT3=T3MAX+YB
        PC1=CT1(L)/V**(TT1-YP)
        PC2=CT2(L)/V**(TT2-YP)
        PC3=CT3(L)/V**(TT3-YP)
        PCT=PC1+PC2+PC3
        PIMAX1=PIT
        PIMAX2=0
        WRITE(6,122)TT1,TT2
122     FORMAT(/6X,'THE BRIDGE WORK HAS BEEN PLANNED TO BE
        CONDUCT ON THESE TWO YEARS:',/6X,I4,1X,I4,//)
        WRITE(6,124)
124     FORMAT(/6X,'*****************************RESULTS OF
        PROGRAM*********************',//)
        WRITE(6,125)
125     FORMAT(/6X,'YEAR1',3X,'COST1',4X,'YEAR2',3X,'COST2',
        4X,'TOTAL-COST,/)
        WRITE(6,127)TT1,CT1(L),TT2,CT2(L),CT(L)
127     FORMAT(/6X,I4,3X,F11.2,4X,I4,3X,F11.2,4X,F15.2,//)
        WRITE(6,126)PCT
126     FORMAT(/6X,'THE TOTAL COST FOR THE PRESENT WORTH VALUE
        IS:',4X,F15.2//)
        WRITE(6,129)R1,R2
129     FORMAT(/6X,'THE RATING FOR THESE YEARS:',4X,F5.2,2X,
        F5.2/)
        WRITE(5,128)
128     FORMAT(/10X,'YOU MIGHT COMPARE THE RESULT WITH RUNNING
        THE PROGRAM WITHOUT'/10X,'ENTER ACTION YEARS
        DIRECTLY.'//)
        WRITE(5,*)
        GO TO 510
        ELSE IF((Q1.EQ.A2).OR.(Q1.EQ.A4)) THEN
          GO TO 132
        ELSE
          WRITE(5,131)
131     FORMAT(/10X,'ENTER YES OR NO ONLY!',//)
        WRITE(5,*)
          GO TO 118
        END IF
        WRITE(5,*)
        WRITE(6,*)
132     WRITE(5,133)
133     FORMAT(/10X,'HAS THIS BRIDGE DECK EVER BEEN
        REHABILITATED?  ENTER YES OR NO.',//)
        READ(5,135)Q
```

```
 135  FORMAT(A)
      IF((Q.EQ.A1).OR.(Q.EQ.A3)) THEN
          CASE1=1
          CASE2=0
      ELSE IF((Q.EQ.A2).OR.(Q.EQ.A4)) THEN
          CASE1=0
          CASE2=1
      ELSE
          WRITE(5,131)
          GO TO 132
      END IF
      I=0
      COUNT=0

*CALCULATION OF CASE1
      IF(CASE1.EQ.1) THEN
        WRITE(5,137)
 137  FORMAT(/10X,'WHAT WAS THE YEAR THE 1ST REHABILITATION
      WAS DONE?',//)
      READ(5,*)YB1
      WRITE(6,139)YB1
 139  FORMAT(/6X,'THE YEAR THE 1ST REHABILITATION WAS DONE
      IS:',4X,I4,//)
      T1=YB1-YB
        IF(T1.GT.TC-2) THEN
           WRITE(5,141)T1+2
 141  FORMAT(/10X,'BASED ON ENTRY OF THE YEAR THE 1ST
      REHABILITATION, A LONGER'/10X,'LIFE CYCLE COULD BE
      ENTERED.  THE PROGRAM SUGGEST A LONGER'/10X,'LIFE:',
      1X,F4.0,1X,'YEARS.  ENTER THE LIFE CYCLE IN YEARS.'/)
      READ(5,*)TC2
           IF(TC2.GE.(T1+2)) THEN
               TC=TC2
           ELSE
               WRITE(5,138)T1+2
 138  FORMAT(/10X,'A LONGER LIFE AT LEAST:',1X,F5.0,1X,
      'YEARS MUST BE ENTERED.  ENTER'/10X,'THE LIFE CYCLE IN
      YEARS AGAIN.',//)
               READ(5,*)TC2
               TC=TC2
            END IF
        END IF
      B4=(B1-B2*T1)**2-4*B2*(RMIN-9-B1*T1)
      IF(B4.LT.0) THEN
               T2MAX=(B2*T1-B1)/2/B2
      ELSE
               T2MAX=(B2*T1-B1+SQRT(B4))/2/B2
      END IF
      IF(T2MAX.GE.(TC-1)) THEN
               T2MAX=TC-1
      END IF
      DO  10  T2=T1+1, T2MAX
```

```
B5=(B1-B2*T2)**2-4*B2*(RMIN-9-B1*T2)
  IF(B5.LT.0) THEN
         T3MAX=(B2*T2-B1)/2/B2
  ELSE
         T3MAX=(B2*T2-B1+SQRT(B5))/2/B2
  END IF
  IF((T3MAX.GE.TC).OR.(T3MAX.LE.T2MAX)) THEN
         T3MAX=TC
  END IF
I=I+1
YE1=YB+T1
YE2=YB+T2
ADT01=ADT1+ADT2*T1
ADT02=ADT1+ADT2*T2
ADT03=ADT1+ADT2*T3MAX
ST(I)=F1(T1,ADT01)+F2(T2,T1,ADT02)+F3(T3MAX,T2,ADT03)
CT1(1)=F4(CO1,V,T1,ADT01)
CT2(1)=F5(CO1,V,T2,T1,ADT02)
CT3(1)=F6(C,V,T3MAX,T2,ADT03)
CT(1)=CT1(1)+CT2(1)+CT3(1)
PI1(I)=ABS(ST(I))/CT(1)*10000
CT1(2)=F4(CO1,V,T1,ADT01)
CT2(2)=F5(CO2,V,T2,T1,ADT02)
CT3(2)=F6(C,V,T3MAX,T2,ADT03)
CT(2)=CT1(2)+CT2(2)+CT3(2)
PI2(I)=ABS(ST(I))/CT(2)*10000
CT1(3)=F4(CO2,V,T1,ADT01)
CT2(3)=F5(CO1,V,T2,T1,ADT02)
CT3(3)=F6(C,V,T3MAX,T2,ADT03)
CT(3)=CT1(3)+CT2(3)+CT3(3)
PI3(I)=ABS(ST(I))/CT(3)*10000
CT1(4)=F4(CO2,V,T1,ADT01)
CT2(4)=F5(CO2,V,T2,T1,ADT02)
CT3(4)=F6(C,V,T3MAX,T2,ADT03)
CT(4)=CT1(4)+CT2(4)+CT3(4)
PI4(I)=ABS(ST(I))/CT(4)*10000
  IF(PI1(I).LE.PI2(I)) THEN
         PI(I)=PI2(I)
         L=2
  ELSE
         PI(I)=PI1(I)
         L=1
  END IF
  IF(PI(I).LE.PI3(I)) THEN
         PI(I)=PI3(I)
         L=3
  END IF
  IF(PI(I).LE.PI4(I)) THEN
         PI(I)=PI4(I)
         L=4
   END IF
WRITE(6,142)YE1,CT1(L),YE2,CT2(L),PI(I)
```

```
 142   FORMAT(I4,2X,F11.2,4X,I4,2X,F11.2,4X,F7.3)
       COUNT=I
 10    CONTINUE
       GO TO 500

*CALCULATION OF CASE2
       ELSE IF(CASE2.EQ.1) THEN
         WRITE(6,*)
       DO  20  T1=1,T1MAX
       B4=(B1-B2*T1)**2-4*B2*(RMIN-9-B1*T1)
         IF(B4.LT.0) THEN
                T2MAX=(B2*T1-B1)/2/B2
         ELSE
                T2MAX=(B2*T1-B1+SQRT(B4))/2/B2
         END IF
         IF(T2MAX.GE.(TC-1)) THEN
                T2MAX=TC-1
         END IF
       DO  30  T2=T1+1, T2MAX
       B5=(B1-B2*T2)**2-4*B2*(RMIN-9-B1**T2)
         IF(B5.LT.0) THEN
                T3MAX=(B2*T2-B1)/2/B2
         ELSE
                T3MAX=(B2*T2-B1+SQRT(B5))/2/B2
         END IF
         IF((T3MAX.GE.TC).OR.(T3MAX.LE.T2MAX)) THEN
                T3MAX=TC
         END IF
       I=I+1
       YE1=YB+T1
       YE2=YB+T2
       ADT01=ADT1+ADT2*T1
       ADT02=ADT1+ADT2*T2
       ADT03=ADT1+ADT2*T3MAX
       ST(I)=F1(T1,ADT01)+F2(T2,T1,ADT02)+F3(T3MAX,T2,ADT03)
       CT1(1)=F4(CO1,V,T1,ADT01)
       CT2(1)=F5(CO1,V,T2,T1,ADT02)
       CT3(1)=F6(C,V,T3MAX,T2,ADT03)
       CT(1)=CT1(1)+CT2(1)+CT3(1)
       PI1(I)=ABS(ST(I))/CT(1)*10000
       CT1(2)=F4(CO1,V,T1,ADT01)
       CT2(2)=F5(CO2,V,T2,T1,ADT02)
       CT3(2)=F6(C,V,T3MAX,T2,ADT03)
       CT(2)=CT1(2)+CT2(2)+CT3(2)
       PI2(I)=ABS(ST(I))/CT(2)*10000
       CT1(3)=F4(CO2,V,T1,ADT01)
       CT2(3)=F5(CO1,V,T2,T1,ADT02)
       CT3(3)=F6(C,V,T3MAX,T2,ADT03)
       CT(3)=CT1(3)+CT2(3)+CT3(3)
       PI3(I)=ABS(ST(I))/CT(3)*10000
       CT1(4)=F4(CO2,V,T1,ADT01)
       CT2(4)=F5(CO2,V,T2,T1,ADT02)
```

```
      CT3(4)=F6(C,V,T3MAX,T2,ADT03)
      CT(4)=CT1(4)+CT2(4)+CT3(4)
      PI4(I)=ABS(ST(I))/CT(4)*10000
        IF(PI1(I).LE.PI2(I)) THEN
               PI(I)=PI2(I)
               L=2
        ELSE
               PI(I)=PI1(I)
               L=1
        END IF
        IF(PI(I).LE.PI3(I)) THEN
               PI(I)=PI3(I)
               L=3
        END IF
        IF(PI(I).LE.PI4(I)) THEN
               PI(I)=PI4(I)
               L=4
        END IF
      WRITE(6,142)YE1,CT1(L),YE2,CT2(L),PI(I)
      COUNT=I
   30 CONTINUE
   20 CONTINUE
      END IF

*SORTING FOR THE CORRESPONDING CASE RESULT
 500  DO  40  PASS=1, COUNT-1, 1
      DO  50  COMP=1, COUNT-PASS, 1
        IF ( PI(COMP) .GT. PI(COMP+1) )  THEN
               TEMP=PI(COMP)
               PI(COMP)=PI(COMP+1)
               PI(COMP+1)=TEMP
        END IF
   50 CONTINUE
   40 CONTINUE
      PIMAX1=PI(COUNT)
      PIMAX2=PI(COUNT-1)

*LIST THE SORTING RESULTS
      WRITE(6,*)
      WRITE(6,*)'THE SORTED LIST OF PI:'
      WRITE(6,*)
      IF(COUNT.LE.4) THEN
        WRITE(6,1000)(PI(J),J=1,COUNT,1)
1000    FORMAT(F7.3)
        GO TO 1020
      END IF
      COUNT1=(COUNT/5)*5
      COUNT2=COUNT-COUNT1
      IF(COUNT1.GT.4) THEN
        WRITE(6,1002)(PI(J),J=1,COUNT1,1)
1002    FORMAT(F7.3,6X,F7.3,6X,F7.3,6X,F7.3,6X,F7.3)
      END IF
```

```
      IF(COUNT2.NE.0) THEN
        GO TO(1004,1008,1012,1016)COUNT2
1004    WRITE(6,1006)PI(COUNT)
1006    FORMAT(F7.3)
        GO TO 1020
1008    WRITE(6,1010)PI(COUNT-1),PI(COUNT)
1010    FORMAT(F7.3,6X,F7.3)
        GO TO 1020
1012    WRITE(6,1014)PI(COUNT-2),PI(COUNT-1),PI(COUNT)
1014    FORMAT(F7.3,6X,F7.3,6X,F7.3)
        GO TO 1020
1016    WRITE(6,1018) (PI(J),J=COUNT-3,COUNT,1)
1018    FORMAT(F7.3,6X,F7.3,6X,F7.3,6X,F7.3)
        GO TO 1020
      END IF
1020  WRITE(6,*)
      WRITE(6,*)'COUNT=',COUNT
      WRITE(5,1022)COUNT
1022  FORMAT('THERE ARE:',3X,I6,3X,'CHOICES')
      IF(COUNT.LE.2) THEN
        WRITE(6,1024)
1024  FORMAT(/10X,'THE PROBLEM NEED NOT TO BE SOLVED BY THIS
      PROGRAM.')
      GO TO 510
      END IF

*FIND THE MAXIMUM PI AND THE CORRESPONDING YEARS
      WRITE(6,144)
 144  FORMAT(/6X,'************************BEGINNING OF
      RESULTS************************',//)
      WRITE(6,145)
 145  FORMAT(6X,'THE BEST STRATEGIES ARE LISTED BELOW, YOU
      CAN SELECT ANY ALTERNATIVE',//)
      WRITE(6,147)
 147  FORMAT(/15X,'REHABILITATION INFORMATION')
      WRITE(6,149)
 149  FORMAT(/6X,'------------------------------------',//)
      WRITE(6,151)
 151  FORMAT(/6X,'ALT#',3X,'YEAR',2X,'COST',2X,'RATING',
      3X,'YEAR',2X,'COST',2X,'RATING',3X,'TOTAL COST',/)
      WRITE(6,149)
      K=0
      M1=0
      M2=0
      M1C=0
      M2C=0

*CASE1
      IF(CASE1.EQ.1) THEN
        IF(T2MAX.GE.(TC-1)) THEN
              T2MAX=TC-1
        END IF
```

```
DO  70   T2=T1+1, T2MAX
K=K+1
B5=(B1-B2*T2)**2-4*B2*(RMIN-9-B1*T2)
  IF(B5.LT.0) THEN
         T3MAX=(B2*T2-B1)/2/B2
  ELSE
         T3MAX=(B2*T2-B1+SQRT(B5))/2/B2
  END IF
  IF((T3MAX.GE.TC).OR.(T3MAX.LE.T2MAX)) THEN
         T3MAX=TC
  END IF
ADT01=ADT1+ADT2*T1
ADT02=ADT1+ADT2*T2
ADT03=ADT1+ADT2*T3MAX
CT1(1)=F4(CO1,V,T1,ADT01)
CT2(1)=F5(CO1,V,T2,T1,ADT02)
CT3(1)=F6(C,V,T3MAX,T2,ADT03)
CT(1)=CT1(1)+CT2(1)+CT3(1)
PI1(K)=ABS(ST(K))/CT(1)*10000
CT1(2)=F4(CO1,V,T1,ADT01)
CT2(2)=F5(CO2,V,T2,T1,ADT02)
CT3(2)=F6(C,V,T3MAX,T2,ADT03)
CT(2)=CT1(2)+CT2(2)+CT3(2)
PI2(K)=ABS(ST(K))/CT(2)*10000
CT1(3)=F4(CO2,V,T1,ADT01)
CT2(3)=F5(CO1,V,T2,T1,ADT02)
CT3(3)=F6(C,V,T3MAX,T2,ADT03)
CT(3)=CT1(3)+CT2(3)+CT3(3)
PI3(K)=ABS(ST(K))/CT(3)*10000
CT1(4)=F4(CO2,V,T1,ADT01)
CT2(4)=F5(CO2,V,T2,T1,ADT02)
CT3(4)=F6(C,V,T3MAX,T2,ADT03)
CT(4)=CT1(4)+CT2(4)+CT3(4)
PI4(K)=ABS(ST(K))/CT(4)*10000
  IF(PI1(K).LE.PI2(K)) THEN
         PI(K)=PI2(K)
         L=2
  ELSE
         PI(K)=PI1(K)
         L=1
  END IF
  IF(PI(K).LE.PI3(K)) THEN
         PI(K)=PI3(K)
         L=3
  END IF
  IF(PI(K).LE.PI4(K)) THEN
         PI(K)=PI4(K)
         L=4
  END IF
R1=F7(T1,ADT01)
R2=F8(T2,T1,ADT02)
R3=F9(T3MAX,T2,ADT03)
```

```
      PIC1=PI(K)-PIMAX1
      PIC2=PI(K)-PIMAX2
        IF((PIC1.LE.0.0005).AND.(PIC1.GE.(-0.0005))) THEN
               WRITE(6,*)
               M1=M1+1
               Y1(M1)=YB+T1
               Y2(M1)=YB+T2
               C1(M1)=CT1(L)
               C2(M1)=CT2(L)
               C3(M1)=CT3(L)
               C4(M1)=CT(L)
               PW1(M1)=CT1(L)/V**(T1-YBP)+CT2(L)/V**(T2-YBP)
                       +CT3(L)/V**(T3MAX-YBP)
               R4(M1)=R1
               R5(M1)=R2
               M1C=M1
               J1(M1)=L
        ELSE IF((PIC2.LE.0.0005).AND.(PIC2.GE.(-0.0005)))
        THEN
               WRITE(6,*)
               M2=M2+1
               Y4(M2)=YB+T1
               Y5(M2)=YB+T2
               C5(M2)=CT1(L)
               C6(M2)=CT2(L)
               C7(M2)=CT3(L)
               C8(M2)=CT(L)
               PW2(M2)=CT1(L)/V**(T1-YBP)+CT2(L)/V**(T2-YBP)
                       +CT3(L)/V**(T3MAX-YBP)
               R7(M2)=R1
               R8(M2)=R2
               M2C=M2
               J2(M2)=L
        END IF
 70   CONTINUE

*CASE2
      ELSE IF(CASE2.EQ.1) THEN
      DO  80  T1=1,T1MAX
      B4=(B1-B2*T1)**2-4*B2*(RMIN-9-B1*T1)
        IF(B4.LT.0) THEN
               T2MAX=(B2*T1-B1)/2/B2
        ELSE
               T2MAX=(B2*T1-B1+SQRT(B4))/2/B2
        END IF
        IF(T2MAX.GE.(TC-1)) THEN
               T2MAX=TC-1
        END IF
      DO  90  T2=T1+1, T2MAX
      B5=(B1-B2*T2)**2-4*B2*(RMIN-9-B1*T2)
        IF(B5.LT.0) THEN
               T3MAX=(B2*T2-B1)/2/B2
```

```
   ELSE
           T3MAX=(B2*T2-B1+SQRT(B5))/2/B2
   END IF
   IF((T3MAX.GE.TC).OR.(T3MAX.LE.T2MAX)) THEN
           T3MAX=TC
   END IF
K=K+1
ADT01=ADT1+ADT2*T1
ADT02=ADT1+ADT2*T2
ADT03=ADT1+ADT2*T3MAX
CT1(1)=F4(CO1,V,T1,ADT01)
CT2(1)=F5(CO1,V,T2,T1,ADT02)
CT3(1)=F6(C,V,T3MAX,T2,ADT03)
CT(1)=CT1(1)+CT2(1)+CT3(1)
PI1(K)=ABS(ST(K))/CT(1)*10000
CT1(2)=F4(CO1,V,T1,ADT01)
CT2(2)=F5(CO2,V,T2,T1,ADT02)
CT3(2)=F6(C,V,T3MAX,T2,ADT03)
CT(2)=CT1(2)+CT2(2)+CT3(2)
PI2(K)=ABS(ST(K))/CT(2)*10000
CT1(3)=F4(CO2,V,T1,ADT01)
CT2(3)=F5(CO1,V,T2,T1,ADT02)
CT3(3)=F6(C,V,T3MAX,T2,ADT03)
CT(3)=CT1(3)+CT2(3)+CT3(3)
PI3(K)=ABS(ST(K))/CT(3)*10000
CT1(4)=F4(CO2,V,T1,ADT01)
CT2(4)=F5(CO2,V,T2,T1,ADT02)
CT3(4)=F6(C,V,T3MAX,T2,ADT03)
CT(4)=CT1(4)+CT2(4)+CT3(4)
PI4(K)=ABS(ST(K))/CT(4)*10000
  IF(PI1(K).LE.PI2(K)) THEN
          PI(K)=PI2(K)
          L=2
  ELSE
          PI(K)=PI1(K)
          L=1
  END IF
  IF(PI(K).LE.PI3(K)) THEN
          PI(K)=PI3(K)
          L=3
  END IF
  IF(PI(K).LE.PI4(K)) THEN
          PI(K)=PI4(K)
          L=4
  END IF
R1=F7(T1,ADT01)
R2=F8(T2,T1,ADT02)
R3=F9(T3MAX,T2,ADT03)
PIC1=PI(K)-PIMAX1
PIC2=PI(K)-PIMAX2
  IF((PIC1.LE.0.0005).AND.(PIC1.GE.(-0.0005))) THEN
          WRITE(6,*)
```

```
          M1=M1+1
          Y1(M1)=YB+T1
          Y2(M1)=YB+T2
          C1(M1)=CT1(L)
          C2(M1)=CT2(L)
          C3(M1)=CT3(L)
          C4(M1)=CT(L)
          PW1(M1)=CT1(L)/V**(T1-YBP)+CT2(L)/V**(T2-YBP)
                  +CT3(L)/V**(T3MAX-YBP)
          R4(M1)=R1
          R5(M1)=R2
          M1C=M1
          J1(M1)=L
   ELSE IF((PIC2.LE.0.0005).AND.(PIC2.GE.(-0.0005)))
   THEN
          WRITE(6,*)
          M2=M2+1
          Y4(M2)=YB+T1
          Y5(M2)=YB+T2
          C5(M2)=CT1(L)
          C6(M2)=CT2(L)
          C7(M2)=CT3(L)
          C8(M2)=CT(L)
          PW2(M2)=CT1(L)/V**(T1-YBP)+CT2(L)/V**(T2-YBP)
                  +CT3(L)/V**(T3MAX-YBP)
          R7(M2)=R1
          R8(M2)=R2
          M2C=M2
          J2(M2)=L
   END IF
90  CONTINUE
80  CONTINUE
    END IF
    DO  100  M1=1,M1C
    WRITE(6,153)M1,Y1(M1),C1(M1),R4(M1),Y2(M1),C2(M1),
    R5(M1),PW1(M1)
153 FORMAT(/6X,I2,3X,I4,2X,F11.2,2X,F5.2,3X,I4,2X,F11.2,
    2X,F5.2,3X,F15.2,/)
    WRITE(6,149)
    WRITE(6,154)YP
154 FORMAT(6X,'THE TOTAL COST HAS ALREADY ADJUSTED TO THE
    PRESENT WORTH VALUE IN:',1X,I4/)
    IF(J1(M1).EQ.1) THEN
      WRITE(6,155)Y1(M1),Y2(M1)
155 FORMAT(/6X,'REPLACE THE BRIDGE DECK IN YEARS:',1X,I4,
    1X,'AND',1X,I4,/)
    ELSE IF (J1(M1).EQ.2) THEN
      WRITE(6,157)Y1(M1),Y2(M1)
157 FORMAT(/6X,'REPLACE THE DECK IN YEAR:',1X,I4,1X,'AND
    REDECKING OR WIDENING IN YEAR:',1X,I4,/)
    ELSE IF (J1(M1).EQ.3) THEN
      WRITE(6,159)Y1(M1),Y2(M1)
```

```
159   FORMAT(/6X,'REDECKING OR WIDENING IN YEAR:',1X,I4,1X,
      'AND REPLACE THE DECK IN YEAR:',1X,I4,/)
      ELSE IF (J1(M1).EQ.4) THEN
           WRITE(6,161)Y1(M1),Y2(M1)
161   FORMAT(/6X,'REDECKING OR WIDENING IN YEARS:',1X,I4,1X,
      'AND',1X,I4,/)
      END IF
100   CONTINUE
      WRITE(5,163)
163   FORMAT(/10X,'DO YOU WISH TO SEE NEXT BEST ALTERNATIVE?
      ENTER YES OR NO',//)
165   READ(5,117)Q2
      IF((Q2.EQ.A1).OR.(Q2.EQ.A3)) THEN
        WRITE(6,149)
      WRITE(6,167)
167   FORMAT(/15X,'THE NEXT BEST ALTERNATIVE',//)
      WRITE(6,149)
      DO  110  M2=1,M2C
      WRITE(6,153)M2,Y4(M2),C5(M2),R7(M2),Y5(M2),C6(M2),
      R8(M2),PW2(M2)
        IF(J2(M2).EQ.1) THEN
               WRITE(6,155)Y4(M2),Y5(M2)
        ELSE IF (J2(M2).EQ.2) THEN
               WRITE(6,157)Y4(M2),Y5(M2)
        ELSE IF (J2(M2).EQ.3) THEN
               WRITE(6,159)Y4(M2),Y5(M2)
        ELSE IF (J2(M2).EQ.4) THEN
               WRITE(6,161)Y4(M2),Y5(M2)
        END IF
110   CONTINUE
      WRITE(6,149)
      ELSE IF((Q2.EQ.A2).OR.(Q2.EQ.A4)) THEN
        GO TO 510
      ELSE
        WRITE(5,131)
      GO TO 165
      END IF
      WRITE(6,169)

*STOP THE RUNNING
510   WRITE(5,*)
      WRITE(6,*)
      WRITE(5,169)
169   FORMAT(/10X,'DONE!  YOU MAY CHECK THE RESULTS IN FILE
      DECK2V1.OUT',//)
      WRITE(6,171)
171   FORMAT(/6X,'THIS IS THE RESULTS IN FILE DECK2V1.OUT',)
      WRITE(5,173)
173   FORMAT(1X,'*******************************END OF
      PROGRAM*****************************',//)
      WRITE(6,175)
175   FORMAT(1X,'*******************************END OF
```

```
     RESULTS****************************',//)
     WRITE(6,177)
177  FORMAT(/6X,'THE FOLLOWING INFORMATION SHOWS THE PROFIT
     INDEX (PI) VALUES'/6X,'CORRESPONDING TO THE BEST AND
     SECOND ALTERNATIVES SELECTED IN ABOVE.',//)
     WRITE(6,179)PIMAX1,PIMAX2
179  FORMAT(/6X,'THE PROFIT INDEX VALUE FOR THE BEST
     ALTERNATIVE IS:',1X,F9.4//6X,'THE PROFIT INDEX VALUE
     FOR THE SECOND ALTERNATIVE IS:',1X,F9.4//)

*CLOSE THE OUTPUT FILE
        CLOSE(UNIT=6)

*DONE FOR RUNNING
        STOP
        END

* FUNCTIONS
FUNCTION F1(V1,ADT)
REAL     F1,V1,ADT
F1=(9-0.119*V1-2.158*10**(-6)*ADT/10*V1+9)*V1/2
RETURN
END
FUNCTION F2(V2,V1,ADT)
REAL     F2,V2,V1,ADT
F2=(9-(0.119+2.158*10**(-6)*ADT/10)*(V2-V1)+9)*(V2-V1)/2
RETURN
END
FUNCTION F3(V3,V2,ADT)
REAL     F3,V3,V2,ADT
F3=(9-(0.119+2.158*10**(-6)*ADT/10)*(V3-V2)+9)*(V3-V2)/2
RETURN
END
FUNCTION F4(C0,V0,V1,ADT)
REAL     F4,C0,V0,V1,ADT
F4=C0*(V0**V1)*(0.119+2.158*10**(-6)*ADT/10)*V1/9
RETURN
END
FUNCTION F5(C0,V0,V2,V1,ADT)
REAL     F5,C0,V0,V2,V1,ADT
F5=C0*(V0**V2)*(0.119+2.158*10**(-6)*ADT/10)*(V2-V1)/9
RETURN
END
FUNCTION F6(C0,V0,V3,V2,ADT)
REAL     F6,C0,V0,V3,V2,ADT
F6=C0*(V0**V3)*(0.119+2.158*10**(-6)*ADT/10)*(V3-V2)/9
RETURN
END
FUNCTION F7(V1,ADT)
REAL     F7,V1,ADT
F7=9-(0.119+2.158*10**(-6)*ADT/10)*V1
RETURN
```

```
END
FUNCTION F8(V2,V1,ADT)
REAL      F8,V2,V1,ADT
F8=9-(0.119+2.158*10**(-6)*ADT/10)*(V2-V1)
RETURN
END
FUNCTION F9(V3,V2,ADT)
REAL      F9,V3,V2,ADT
F9=9-(0.119+2.158*10**(-6)*ADT/10)*(V3-V2)
RETURN
END
```