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AN APPROACH DOCUMENT ON WHOLE LIFE COSTING FOR BRIDGES IN INDIA

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AN APPROACH DOCUMENT

ON

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AN APPROACH DOCUMENT ON WHOLE LIFE COSTING (WLC) FOR BRIDGES IN INDIA

Background

The Bridge Maintenance and Rehabilitation Committee (B-9) at its meeting held on 4.7.1997, constituted a Sub-group consisting of Dr. T.N. Subba Rao (Convenor) and S/Shri A.G. Borkar, S.R. Tambe, A.K. Harit, D.K. Kanhere & Dr. H. Subba Rao as members for drafting an Approach Document on Whole Life Costing for Bridges in India. The draft prepared by the Sub-group was discussed in a number of meetings by the B-9 Committee. As the subject matter is new and needed wider interaction, B-9 Committee decided that the entire document should be discussed in the IRC Session as a Paper, comments obtained and thereafter the document finalised.

Accordingly, the Paper appeared as Paper No. 439, in Vol.57-2 of IRC Journal. The Paper was discussed at the IRC Session in Nagpur in January, 1997. Comments made by the participants were considered by the B-9 Committee in its meeting held on 20.12.1999 at Mumbai and the document was forwarded to the Bridges Specifications and Standards Committee. The personnel of B-9 Committe is given below:

A.G. Borkar	*Convenor*
CE (R&B), NH, Hyderabad (D. Sreerama Murthy)	*Co-Convenor*
D.K. Kanhere	*Member-Secretary*

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M.C. Bhide
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Y.G. Patwardhan
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N.G. Thatte

The Bridges Specifications & Standards Committee reviewed and approved the document in its meeting held on the 14th July, 2001 subject to modification in light of the comments offered by the members. Accordingly, the Convenor modified the document in light of the comments and later on the modified document was considered by the Executive Committee in its meeting held on the 5th May, 2002 with certain comments which were incorporated by Dr. T.N. Subba Rao. Finally, the draft was approved by the Council in its 166th meeting held at Panaji (Goa) on the 8th June, 2002 subject to modification in light of the comments of its members. As suggested by the Convenor, BSS Committee, the final document was sent to Dr. T.N. Subba Rao for modification in light of the comments offered.

The final modified document as received from Dr. T.N. Subba Rao after incorporating the comments offered by council members was sent to DG(RD) & Special Secretary, MORT&H for obtaining his approval before its publication. The Ministry of Road Transport & Highways vide their letter No. RW/NH-35075/2/2001-S&R (B) dated the 8th July, 2003 desired that after incorporating para 1.3 in the Introduction of the final document, the document may be got approved from the President, IRC as decided during the Mid-term Council Meeting held at Pondicherry in June, 2003. Accordingly, the document was sent to President, IRC who approved of the same for being published as a Special Publication of IRC.

1. INTRODUCTION

1.1. In the last two decades a large number of roads and bridges were built in India and majority of them were constructed in reinforced or prestressed concrete. There was a general and comfortable attitude that reinforced and prestressed elements were more durable than structural steel elements and hence economical in terms of lifetime maintenance. The past decade has indicated a somewhat different picture with damages due to extensive corrosion of reinforcement and prestressing steel used in bridge decks and substructures. Surveys in America and U.K. also have shown that the cost of repairs or replacement of such bridges is often more than the original capital cost of the bridge itself. As a result, there has been rapidly an increasing awareness of the importance of long term durability of bridges and its effect on the Whole Life Cost (WLC) of a bridge. In addition, in India, the future programme of bridge asset preservation is likely to be dominated by two major requirements:

- To strengthen a large number of existing bridges;
- To modify or replace a substantial number of existing bridges to accommodate widened roads.

With the large cost associated with any traffic disruption caused during the process of strengthening, modification or replacement, a new appreciation has arisen of the need to allow for such possible future operations, within the lifetime of a newly designed bridge.

Bridge designers are, therefore, faced with the idea of **'Whole Life' or 'Life Cycle Costs'**, defined as **'the costs of all activities associated with a bridge during its life'**. The useful life of a bridge is currently set at around 50 to 60 years in India. In that time span, the significant cost flows are:

- The high initial cost of design and construction including environmental cost.
- The regular inspection and maintenance costs over the bridge lifetime to ensure effective performance.
- The repairs, which could be expected during the lifetime, costs of which include those relating to traffic disruption.
- The possibility of one or more strengthening operations to cater for increased traffic loading or design code changes, including possible traffic disruption costs.
- The possibility of bridge modifications or replacement while in use due to widening of the road carried or crossed, with even greater traffic disruption costs.
- Cost of in service failure.
- Disposal cost.

It follows that bridge economy must be evaluated for the entire life span and any cost comparisons used by the owner ab-initio must go beyond the estimated initial design and construction costs. The costing must allow for planned lifetime inspection and maintenance operations, with commuted costs used to assist in the choice between, say, frequent low cost operations and infrequent more expensive operations and similar options. Some cost comparisons should also be made for the relative ease and economics of any future repairs, strengthening or modifications or replacements arising from road widening.

W.L.C., thus, involves putting the estimated capital, maintenance, operating, demolishing and replacement costs into a comparable form and coalescing them into a single cost value which recognises time value of money. The time value of money is explicitly taken into account, and the different operating costs over a number of years are reduced to a common base line using a financial instrument known as Present Value Theory (PVT). Effectively, it is possible to reduce the lifetime outgo and income to a single value in terms of current cost called Net Present Value (NPV).

Reference to IRC Special Publication 35[3] 'Guidelines for Inspection and Maintenance of Bridges' forms preliminary reading to this document. The need for WLC in the maintenance of bridges is implicitly addressed in Sections 2.5, 2.9.3, 2.9.5 of Special Publication 35. WLC becomes relevant to the bridge community when it is concerned with obtaining the best information on which to make choices between different forms of construction and different methods of widening or refurbishing bridge structures. Generally, choices are being made purely on the basis of initial costs without a detailed reference to maintenance and other costs. Legitimate concerns facing bridge authorities and owners are: How long will this particular bridge last? And how much will it cost to maintain it say for the next 30 years or more? WLC can be applied as a tool, at any point of the bridge's life cycle to assess which is the least cost option from a range of available maintenance alternatives.

Undertaking a WLC exercise for choosing between alternatives, will at the very least, emphasize the importance of planning and costing for maintenance/rehabilitation/replacement at the early design stage, since life cycle costs rather than initial capital costs alone will form the basis of evaluation for the owner. Again designing for WLC is a matter of resource allocation and deciding on priorities. Owners have previously tended to disregard the problems of maintenance of structures because of the lack of a simple method and the uncertainty of evaluations. It is essential that designers be aware of the future consequences of present actions. In the context of a WLC analysis, obvious implications for building for durability and constructibility not forgetting ease of maintenance, cannot be over-emphasized. It is suggested that bridges be designed that are inspectable, maintainable and if necessary, modifiable in the future with minimum interruptions to traffic.

1.2. **Fig.1** shows the asset life cycle of a typical public sector project which shows that except for the project initiation phase, WLC has potential application at every other phase throughout the life of the asset.

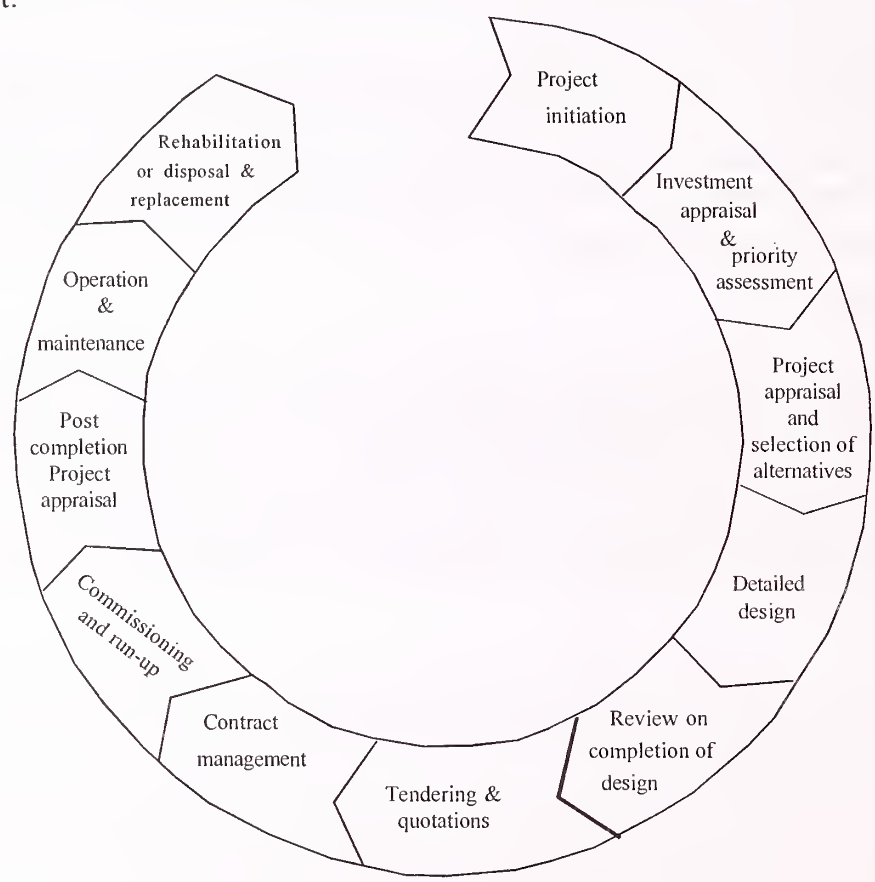


Fig. 1. Stages in the asset life cycle of a typical public sector project in which WLC has application[4]

The paucity of public resources for the construction of new highways or bridges forces owners to try to squeeze more out of the present infrastructure. All these focus attention onto devising maintenance strategies that cause minimal interruption to traffic and encourage use of WLC models. WLC can, thus, provide the basis for the most important part of the decision making module in a Bridge Management System – the financial module.

1.3. The approach brought out in these guidelines is only one of the many approaches available on Whole Life Costing of Bridges and it is purely at the discretion of the user whether to adopt the approach given in these guidelines or not. Further, the probabilistic approach adopted for deterioration modelling is also not the only approach available for the same and feedback from past experience can be vital.

2. SCOPE

2.1. This document provides a direction for evaluating the computed maintenance costs and to compare alternative designs of bridges either at the tender or design stage. It will also apply to alterations to existing structures at a later date. Whereas, the WLC technique proposed is generally applicable to all highway structures, it may require suitable interpretation of the methodology for major or unusual structures, e.g., cable-stayed and suspension bridges, movable bridges, steel deck bridges. and aluminium or timber structures.

To evaluate and compare the costs (including benefits, when they can also be expressed in monetary terms) of different alternatives, a financial analysis which is based on the Whole Life Approach, that takes into account all the costs and benefits associated with the bridge structure, is addressed in this document. This document emphasizes the need to develop WLC to provide a framework to assess the financial implications of new construction or alternative construction measures required to maintain, strengthen and/or widen existing bridges. The assessment of the physical residual life of the bridge, is an essential input for comparing different repair alternatives using WLC, but this aspect is covered in a separate IRC document. Similarly, in a new construction, the design service life of the bridge and its definition are essential inputs. This document addresses the four levels of application of WLC, all of which could co-exist:

- WLC used to aid the decision process for the management of the whole bridge stock in a road network.
- WLC used in the planning stage for a proposed new bridge.
- WLC used to aid decision making in evaluating foreseeable replacement or maintenance expenditure of elements of the bridge, within the lifetime of the bridge, e.g., bearings, waterproof membranes or joints which are known to have a poorer ‘performance profile’ since their design life is shorter than for other parts of the bridge.
- WLC used to aid decision making in evaluating unanticipated replacement or maintenance expenditure of substantial portions of a bridge, like, superstructures or substructures, within the life time of the bridge.

3. APPLICATION OF WLC TO BRIDGE MANAGEMENT

3.1. General

Due to the limited resources available for maintaining the existing stock of bridges, the owner is faced with a situation of getting the most for the monies available. In addition, the task encompasses allocating resources from a common budget for maintenance, rehabilitation and replacement of the existing stock of bridges, as also for the construction of new bridges. Faced with a scarcity of available resources, the need to prioritize their actions, and justify their ranking of overall bridge expenditure, through a financial technique, is evident.

3.2. Definition of 'Life' of a Bridge

The life of a bridge can be expressed or defined in various ways:

- The design life of a bridge span or component. This can be defined as the probable time period over which the bridge span or its component is expected to give the intended level-of-service (Performance) for the designed loads.

- Economic life of a bridge or any structures. This is the time over which the discounted value of the structure is adjudged to have reached a somewhat negligible small fraction of the initial cost of construction, and, therefore, provides an option for replacement with a 'cost certificate'.
- Physical life of a bridge. This can be more than the design life at a lower service level before the bridge collapses or is strengthened or demolished.
- The various uses of the WLC technique for Bridge Management are outlined in the following sub-sections.

3.3. **Planning and Prioritizing Allocation of Resources for Strengthening/Rehabilitation/ Replacement/Repairs of Existing Bridge Stock at Network Level**

At the national or network level available resources can be allocated on the basis of an established ranking of bridges. WLC can be incorporated into the prioritizing procedure **(Fig. 2).** The procedure followed in countries where a complete data base of all bridge stock exists is to rank the bridges on the basis of their importance, location, traffic density, military need, political sensitivity and other factors by a valid marking system. At times, a group of bridges along a certain track may qualify for this ranking in order to better optimise costs. Once the ranking is evaluated, specific rehabilitation and/or replacement strategy including the **'Do Nothing'** option is investigated for the prioritized ranked bridges. A WLC is carried out for the chosen ones, not forgetting the possibility of optimizing cost by grouping. Often, such grouping reduces cost of diversions, since closure of the road and diverting traffic through other arterial routes would be one such case. By simultaneously executing the repairs on all the grouped bridges at one time, cost saving can be meaningfully generated. Following this WLC operation, the funds available can be allocated in favour of those works where the maximum benefit is derived by society and the network decision can be taken. This operation can be substantially satisfactory if funds are assured and adequate to meet the prioritized repair activity. The entire strategy can be planned over a reasonable period of time in a ranked sequence so as to give maximum repair coverage in a planned manner.

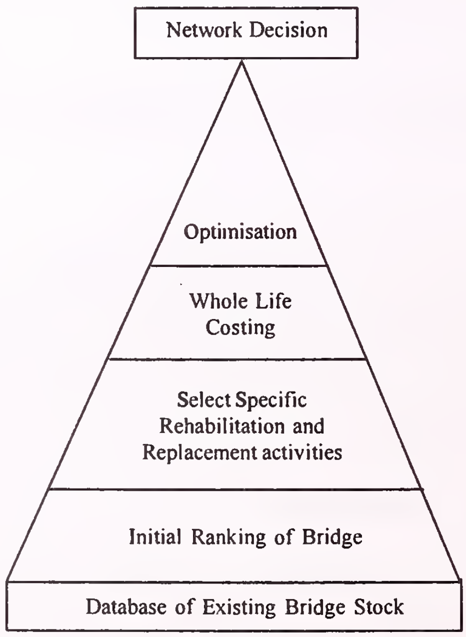


Fig. 2. Increasing complexity of decision-making associated with the selection of repair/replacement alternatives

3.4. Choosing between Alternative's Rehabilitation/Strengthening/Repair Schemes for an Existing Bridge

After inspection and evaluation of their load carrying capacity, bridges which are in need of repair, can be ranked according to the criteria in Section 2.8.4.3 of IRC Special Publication 35. Alternative repair plans are then considered for the bridge, which is at the top of the ranking list. Selection from among alternative repair plans is based on a WLC analysis including the **'Do Nothing'** options.

The broad guidelines for rehabilitation and strengthening of an existing bridge are dealt with in Section 2.8.4.2 of IRC Special Publication 35. It is implicitly mentioned in Clauses 2.8.4.2 (b) & (c), that the choice between competing schemes for rehabilitation and strengthening or replacement be evaluated taking into consideration the future costs and benefits accruing to each option on the basis of WLC analysis.

3.5. Comparative Assessment of Design/Construction Solutions for a New Bridge

WLC can be used to make comparative assessments of various alternative construction schemes at the tender/design stage before a bridge is built. All the life time costs (and benefits) associated with a particular scheme (refer Section 4) are taken into account and the alternatives are ranked according to their whole life costs. The construction scheme which results in the **least** whole-life cost is the preferred option for implementation.

Whole life costing is more often used in the evaluation of Privately Financed Projects of the Design, Build, Finance and Operate Schemes. The encouragement of private entrepreneurship in the road development programme and also for specific bridge projects, such as, major bridges with tolls urban flyovers and marine causeways, calls for special care in addressing the delicate interface between the private entrepreneur and the Government. Funds generated from profits accruing from operating revenues (such as, tolls or other such benefits), public safety and acceptable levels of risk, durability and serviceability levels of the construction during and at hand over and the residual life required of the bridge are likely to be assessed somewhat differently when seen through the eyes of the private entrepreneur and the Government[5].

The different permutations of finance, operation and transfer in design and build projects present a new opportunity in the use of WLC. Whereas, design standards will have to be met in the interest of public safety, there will be scope for designers to balance construction and maintenance costs, e.g., use of less expensive construction techniques and materials which would tend to maximize subsequent maintenance costs and vice-versa. Promoters are more inclined to adopt the first strategy, namely, minimum capital cost because they could defer some expenditure to a later stage, when there is a steady stream of income in place, and effectively reduce their expenditure in the initial phase which is financed by expensive borrowings from the public and banks. This strategy may not necessarily be acceptable to the owners.

With reference to **Fig. 3**, it can be seen that whole life costs associated with designing for low first cost followed by high maintenance costs would be lower in present value terms than in non-discounted terms. Promoters are likely to adopt Option B and design for a low initial cost followed by high maintenance costs. This approach increases risks as it would result in less durable bridges. Unexpectedly, expensive maintenance works and difficult to anticipate deterioration mechanisms will

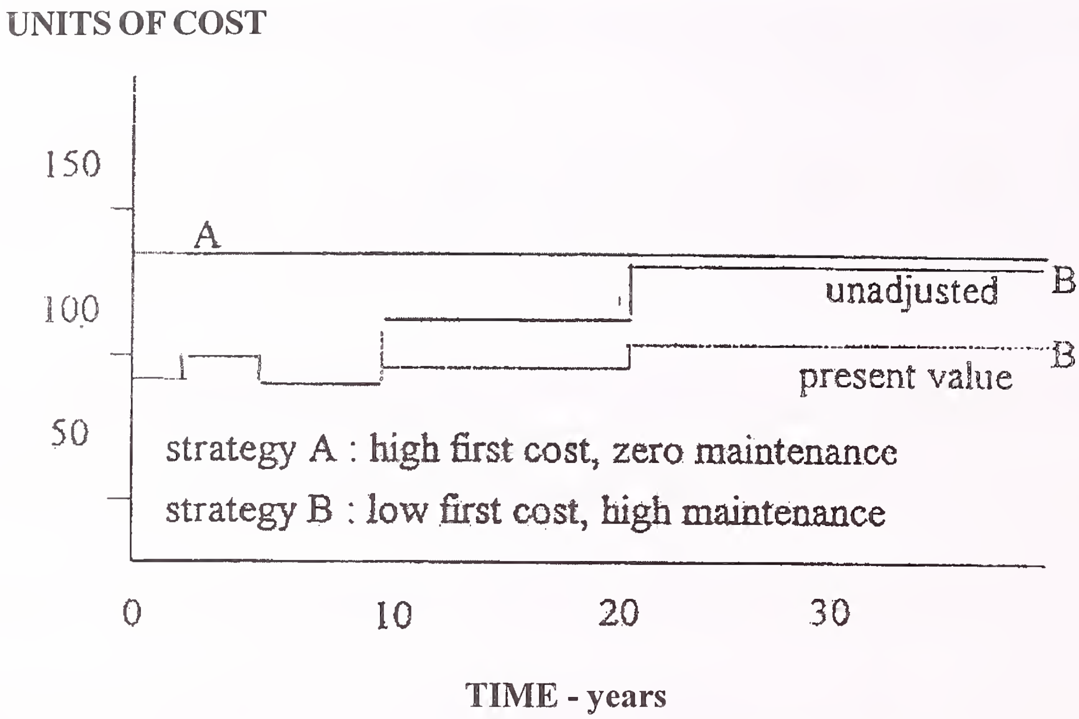


Fig. 3. Comparison of different strategies for whole life costing[5]

possibly require total closures and consequential loss of revenue. Inconvenience to motorists caused by maintenance works will be less important to project promoters than the possible loss of revenue. This would need to be incorporated in a traffic delay cost model **(Appendix B)**. The political climate and large variations in the discount rate during the operating period prior to hand over, are factors to be accommodated in the financial analysis.

In real practice, the WLC costing strategy for highway schemes in the private sector will be influenced by:

- Expected volumes of traffic; good traffic forecasting models are essential.
- The number of years the route will be operated before it is handed over.
- The specified condition at handing over as set down by the Government.
- Specified operational and maintenance requirements (with a special emphasis on safety) as set down by the Government.

The use of WLC[6] by the private sector for financial modelling of BOT schemes is discussed and the BOT approach is itself presented within the paradigm of risks.

3.6. WLC in Evaluating Foreseeable Replacement

All elements of a bridge have different life span and those with relatively poorer 'performance profiles' will need to be replaced within the designed lifetime of the bridge. Such replacement or maintenance expenditure is usually foreseeable and WLC is used to aid decision-making in evaluating such maintenance expenditure. The typical elements of limited life span include bearings, joints and waterproofing membranes.

4. COMPONENTS OF WLC FOR BRIDGES

WLC of a highway bridge concerns the evaluation of lifetime costs of construction, operation (tolls, etc.) maintenance, road user delay and benefits. The lifetime costs which should be taken into account are discussed in the following sections. The economic evaluation and ranking of alternative bridge designs will be at the tender/design stage, and for existing bridges evaluation and ranking will be for the various rehabilitation alternatives. The evaluation shall always be in terms of Net Present Value (NPV).

4.1. Costs

4.1.1. **Initial costs:** The initial costs to be taken into consideration are which envisage costs of planning, design and construction.

4.1.2. **Post-construction cost:** These will include operation and maintenance costs. The post-construction cost covers operational cost, such as, all the costs associated with inspections (access, labour, equipment and testing), providing services needed for toll collection arrangement and maintenance.

- All costs incurred on the bridge(s) to keep them in operation after commissioning (excluding engineering maintenance cost).
- Maintenance and inspection which has a bearing on costs (documented[3]).
- Strengthening/rehabilitation/repair activities which include structural assessment and structural repair costs, if these measures aim at restoring the structure to its original serviceability.
- Traffic management costs due to diversion, or traffic regulation costs in the interest of public safety which are incurred during maintenance.
- All operating benefits, like, revenues from tolls, etc.

4.1.3. **Indirect and other possible costs:** Road user (traffic) delay costs are seen by Highway authorities as an indirect cost. Traffic delay costs affect the user and as such are costs for which ‘real’ money does not have to be allocated from the available budget.

Various other possible costs which occur during the construction phase, operational phase and in the event of structure failure, are to be included in the whole life cost function. Such costs are listed in the next Section.

4.1.4. **Costing for environmental impact:** WLC involves the systematic identification of various events and activities and the manner in which they are carried out throughout the lifetime of the proposed bridge; a major benefit of adopting WLC is that it facilitates costing the impact of each of the events and activities over the estimated lifetime of the bridge. The environmental costs of various events and activities associated with bridge execution, operation, demolition, replacement and disposal, are examples.

4.2. Cost Function

The above lifetime costs and benefits are brought to a common denominator by discounting them to their present value as discussed in Section 5. For working out WLC, it is essential to define a cost function which is made up of the following:

Initial Costs

- Project study costs
- Detailed engineering costs
- Construction costs
- Testing costs

Post-Construction Costs

a) Operation cost
   - Cost of traffic management and regulation, security, lighting, collection of toll and other services

b) Inspection Costs (periodically)
   - Labour costs
   - Access costs
   - Testing costs
   - Equipment costs

c) Maintenance Costs (Periodical)

d) Repair Costs
   - Structural assessment costs
   - Design costs
   - Structural repair costs

Indirect and Other Possible Costs

Includes costs, which occur during construction phase, operational phase and contingent failure phase.

- Structure failure
- Bridge replacement
- Loss of lives and equipment
- Architectural/cultural/historical impacts
- Functional failure
- Traffic delay
- Traffic flow detour
- Heavy traffic detour
- Environmental management
- Blocking and clearing of navigation channel
- Lighting
- Traffic management
- Collection of tolls
- Security
- Other services

Benefits

- Saving in vehicle operating cost
- Saving in vehicle operating time
- Traffic delay benefits
- Traffic flow detour benefits
- Heavy traffic detour benefits

In the above benefits, a portion of the global benefits generated for the road on which the bridge is built, are deemed to also accrue for the bridge. The percentage of benefits of the road that is attributed to each bridge, is worked out on a prorata basis of the initial cost of the bridge *versus* the costs of all the bridges on the road.

5. METHODS OF EVALUATION

Three different methods are available to evaluate the financial worth or the return of an investment associated with a project or its various alternatives. These are simple Payback, Present Value, Net Present Value and Internal Rate of Return.

5.1. Simple Payback

Simple payback is the time taken for the return on an investment to repay the investment[1].

P = I/R
P = Payback period in years
I = Capital invested
R = Annual earning

The use of simple payback is limited by its result. An evaluation of the acceptable payback period is necessary for which no method or criterion is shown or established. A further drawback is that it makes no allowance for the following variables.

- Inflation
- Interest (payable or received)
- Cash flow
- Taxation

In the context of whole life costing of bridges, the net present value (NPV) is the most relevant method which has found universal acceptability and is described hereunder; a PV analysis precedes a NPV assessment.

Before we proceed with NPV analysis, it is necessary to understand PV analysis.

5.2. Present Value

The present value analysis technique involves the calculation of the cost of alternative schemes in present day monetary terms, i.e., **the amount that is required in today's value to obtain goods and services at any future date.** This is based on a simple investment principle.

A capital or principal (P) invested for (n) years at an interest rate (r), compounds to a sum (C) such that:

$$C = P\ (1+r)^n$$

Stated in another way the present value (P) of a sum (C) spent in year (n) at a discount rate (r) is:

$$P = \frac{C}{(1+r)^n}$$

This is the basis of present value analysis as it allows for the comparison of alternative schemes on an equitable basis. *In general, the alternative with the least present value is the preferred alternative.*

Discount rate can be based on Public Lending Rate (PLR), i.e., the current interest rate on borrowing. However, it is normal practice to use 12 per cent as the discount rate in India. The discount rates currently in the USA are 10 per cent, Portugal 8 per cent, Germany 3 per cent, Switzerland 2 per cent and elsewhere in developed countries it varies between 6 per cent to 8 per cent. In Germany, it is linked to the national growth rate. The current level of discount rate without any allowance for inflation, as used by the UK Department of Transport, is currently 8 per cent to the year of construction.

Discount rate can be based on Public Lending Rate (PLR) or on Current Interest Rate on borrowings. However, it is normal practice to use 12 per cent considering that it will reduce in the future.

Where there is a large difference between the rate of inflation and interest, this can be accounted by modifying the discount rate 'r' to a net of inflation discount rate (ndr) given by,

$$\text{ndr} = \left(\frac{1+\text{Interest rate} - 1}{1+\text{Inflation rate}} \right) \times 100 \text{ in per cent terms}$$

This method of adjusting future year's costs to allow for interest and inflation (when included) is called discounting. The technique is called Discounted Cash Flow (DCF). Annuity Tables for *ndr* help to ease the calculation.

Fig. 4 shows the relationship between economical residual value of an asset with time for different discount rates. It can be noticed that a higher discount rate has the effect of reducing the economic or residual value of the structure (asset) at a faster rate. An 8 per cent discount rate lends to numerically convenient value since it gives a discount factor of 0.1 at 30 years and 0.01 at 60 years. At a 12 per cent discount rate, the remnant value of the structure reaches 10 per cent of its original value after 20 years.

5.3. Net Present Value (NPV)

The NPV is defined as the sum of money that needs to be invested today to meet all financial implication as they arise throughout the life of the structure.

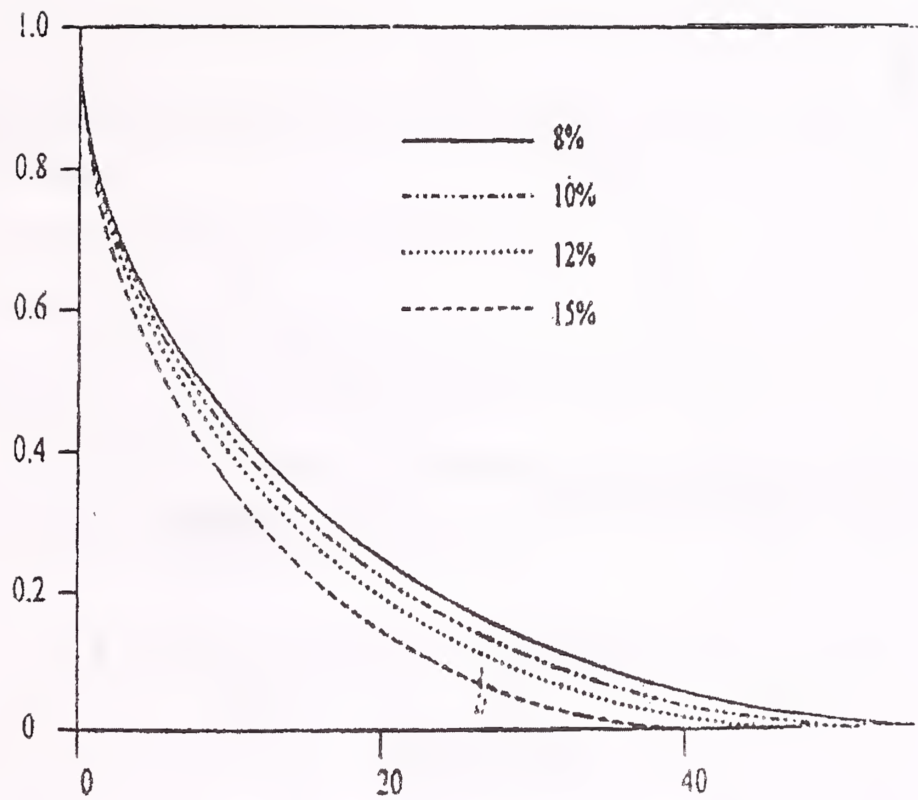


Fig. 4. Relationship between discount factors and time for different discount rates

If you wish to know how much one might have to invest today to meet the cost at some future year the formula is,

$$NPV = \sum_{t=0}^{t=n} \left[\frac{B_t - C_t}{(1+r)^t} \right]$$

Where

B_t	=	Estimated benefits in year 't'
C_t	=	Estimated costs in year 't'
r	=	Discount rate(the interest rate on borrowings based on Public Lending Rate)
N	=	Period of analysis in years

$$\frac{1}{(1+r)^t} = \text{Discount factor}$$

NPV *vs.* time curves provide a visual representation of the financial performance of competing options over a range of years as shown in **Fig. 5**. If a period of ten years is reckoned as the life of a specific structure or a component of it (e.g. water proofing), it will be seen that Option A which has the lowest capital investment today need not necessarily be more economical than Option B which has a slightly higher initial investment but a low NPV over this time scale. If the usable life is taken as twenty years, Options B and C merit equal choice but since Option B has a lower initial cost, it

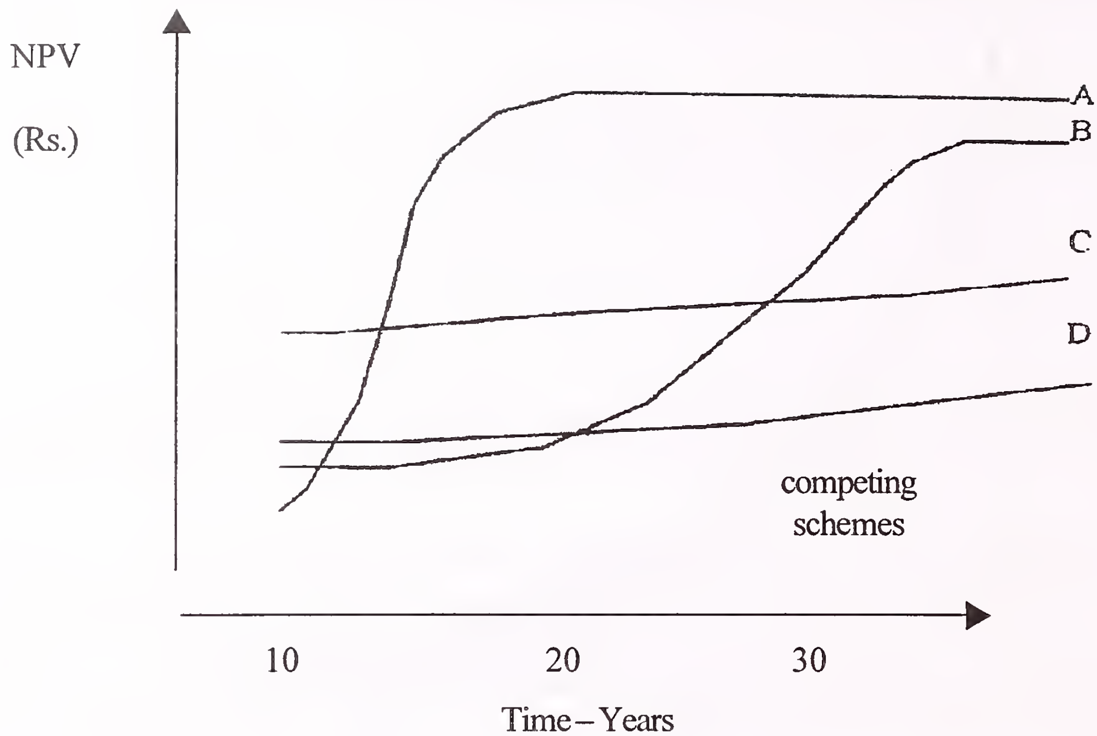


Fig. 5. NPV against time for competing schemes[1]

certainly deserves attention. Option D demands preference over A, B and C although it is somewhat higher in first cost. Option C does not merit much attention since it is more expensive than competing options at all periods of the usable life of thirty years but has a stable NPV. Depending on obsolescence and time scale chosen, a discrete solution invariably surfaces and invites preference.

The NPV can be negative when costs exceed benefits. However, when comparing alternative repair schemes at the design stage in which the benefits accruing are likely to be the same, the benefits may be disregarded. Similarly, it is possible to ignore any estimated regular annual maintenance costs if they are common to all the competing design options.

The use of the discounting method for financial evaluation of competing solutions will provide a list of various solutions each with a corresponding NPV (using the same discount rate for each alternative), similar to that shown in the example below:

Project Alternative	NPV (Rs. Lakhs)	Capital Cost (CC) (Rs. Lakhs)	Profit Index Pi
A	64	16	2.5
B	54	18	3.0
C	60	22	2.7
D	50	20	2.5

The lowest overall-cost NPV option will be project D and would normally be selected.

Ranking of projects on the basis of NPV gives the decision-maker a financial criteria to juxtapose with other ranking decisions, such as, Profitability Index, Cost-Effectiveness Index, Cost Benefit Ratio, etc.

However, if Profitability Index is defined as:

$$Pi = NPV/CC$$

Project B would yield the largest profitability index

Another useful indicator which may be used to compare alternative repair schemes is the Cost-Effectiveness Index (CEI). It is calculated for each scheme. The CEI indicates how well a particular repair action compares with the 'Do-nothing' option.

$$CEI = \frac{[C_{repair} + C_{failure} - B]_{\text{REPAIR}}}{[C_{failure} - B]_{\text{NO REPAIR}}}$$

Where,

B = Benefit
C = Cost

Present Value can also be used to discount the Cost Benefit Ratio (CBR),[4]

$$CBR = \frac{NPV + I}{I}$$

or

$$CBR = \frac{B - O - M - R + V}{I}$$

Where,

I = Present value of the investment costs of the project
B = Present value of monetary benefits
O = Present value of operating costs
M = Present value of maintenance costs
R = Present value of replacement costs
V = Present value of residual value

In the private sector, the costs used should be net of tax relief because capital expenditure usually attracts lower tax relief than recurrent expenditure. Thus, in the private sector, there may be preference for structures with low initial costs eventhough the maintenance costs may be higher.

For public sector projects taxation does not enter into the cash flow. This makes it easier to project the cash flow (over the life time), without having to guess at future changes in the tax structure.

Two worked examples with use of above formulae and accompanying commentary are given in **Appendix A.**

The first is for choosing between two options for a new bridge at the design stage. The second example is for choosing between three options for Repair/Rehabilitation of an existing bridge.

5.4. Internal Rate of Return

Internal Rate of Return (IRR) is defined as the percentage earned on the amount of capital invested in each year of the life of the project after allowing for the repayment of the sum originally invested[1].

This method while used, is not particularly amenable to public sector construction since it assumes that an investment will generate an income. It also assumes reinvestment at the IRR. In construction firm, nearly all cash flows are outward and there may be no guarantees of stable re-investment levels.

However, IRR is used in financial models in the context of BOT projects in the private sector[6].

5.5. Other Possible Ranking Decisions

Other ranking decisions may be more subjective, such as[1]:

- **Prestige** : the impression: the project gives to the corporate image.
- **Future** : potential: future changes and fall back plans.
- **Longevity** : the intended life span of the project.

6. SENSITIVITY ANALYSIS

While the mathematical model developed to carry out WLC would be rational and provides an auditable result, sensitivity analysis should be undertaken in order to assess the effects of variability in the uncertain parameters (or assumptions) over which the owner has least confidence or control. Thus, the sensitivity of the calculations to changes in such parameters will help to arrive at a range of present value costing. Engineering judgement in conjunction with other decision criteria are then used to arrive at the final decision. In general, an alternative with a low NPV, which is also least sensitive to uncertain parameters, justifies selection.

The problem that WLC faces when applied to longlife structures (bridges), is the appropriateness of any particular discount rate and the significant incidence and cost of repairs. Moreover, only a few parameters can be predicted with certainly due to the increasing nature of risk associated with increase in time. The extent of these problems are such that rather than take one unique answer from the WLC calculations, sensitivity analysis should be used to arrive at a range of costing by varying the input parameters by a fixed percentage from their estimated value, and the results compared thereafter.

- Financial parameters for bridges which are sensitive to the decision-making process and for which sensitivity analysis should be carried out are:
  - Cost
  - Residual life and value
  - Discount rate (includes the effects of inflation, consider a range between 8 per cent to 15 per cent, due to the uncertainty in predicting future economic trends).
  - Life cycle (not greater than 30 years).
  - Benefits to agency and the user.

In addition, sensitivity analysis may also be undertaken with regard to the possible financial implications of:

- Changes to the maintenance interval, i.e., the frequency of maintenance.
- Duration of maintenance activity.
- Possible changes to the road network.
- Variations in the envisaged future growth in traffic.
- Alterations to the prediction of remaining life of the bridge or a component of the bridge, due to adopting/carrying out specific repair strategy.

The sensitivity of future cost analysis can be developed for future values of the following[7]:

- Discount rate
- Inflation rate
- Initial cost
- Inspection costs
- Maintenance costs
- Repair costs
- Bridge deterioration rate
- Probability of structural collapse
- Traffic volume
- Detoured traffic volume

Despite all these exercises, a political decision which precipitates a crisis, such as, the 1973 petrol rate hike by OPEC, would affect the results and the need to revise and update the available discount rate data becomes necessary. While such extreme occurrences being random and rare in occurrence are difficult to project, they can happen and have happened.

6.1. Examples of Sensitivity Analysis

Sensitivity analysis is best illustrated graphically.

Fig. 6 shows the variation of net present costs with the asset life (a single variate analysis). It is presumed that net present costs do not vary with any other parameter and that the discount rate, in particular, is the same for all alternatives. The life-costs of all alternatives vary with the time scale. It can be seen that the time horizon adopted (life cycle period considered) in the analysis is crucial to the ranking alternative on the basis of least net present costs. Whereas, initially the cost of all alternatives are sensitive to the time horizon considered, with increasing time the net present costs are less sensitive as indicated by the reduction in slope of the curves. Alternative A is ranked higher than alternative B, and this ranking is not sensitive to asset life as alternative A is always more economical than alternative B. However, alternative A is only economical for products compared to alternative C.

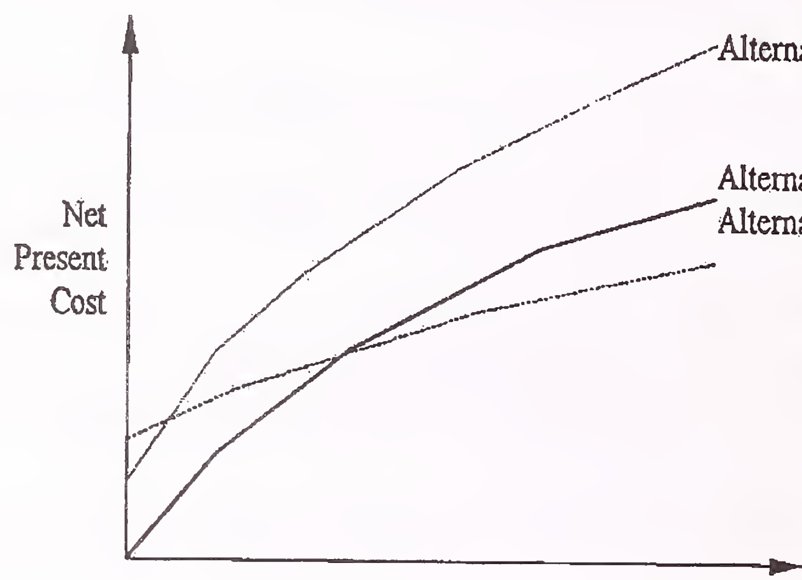


Fig. 6. Example of a single variate sensitivity analysis[4]

Fig. 7, illustrates a bivariate analysis in which the net present costs for a particular alternative (say Alternative C from Fig. 6 which has the lowest net present costs over the life period) vary with asset life in conjunction with the discount rate. At any given time net present costs vary to a greater extent with time. The high discount rate of 20 per cent tends to dampen the variation in net present costs with increasing time.

The above inferences are illustrated in greater detail in the **Figs. 8 & 9.**

Fig. 8 shows the results from an analysis of two structures. A has a cheaper initial cost but gradually becomes more expensive over time in terms of NPV as the life of the project continues. The centre line dictates the optimum solution in each case and is bordered by a band which represents the sensitivity of the calculation to the variables. This band broadens with time as unknown impact on the solution. It can be seen from the outer two distinct areas which structure should be built and a third, middle or 'intermediate' period where the ranges of variables are such that either A or B could be said to be viable within the limits of sensitivity analysis using assumed multiples of variables. The slope of the line is dictated by the size of the discount factor applied. A low discount factor results

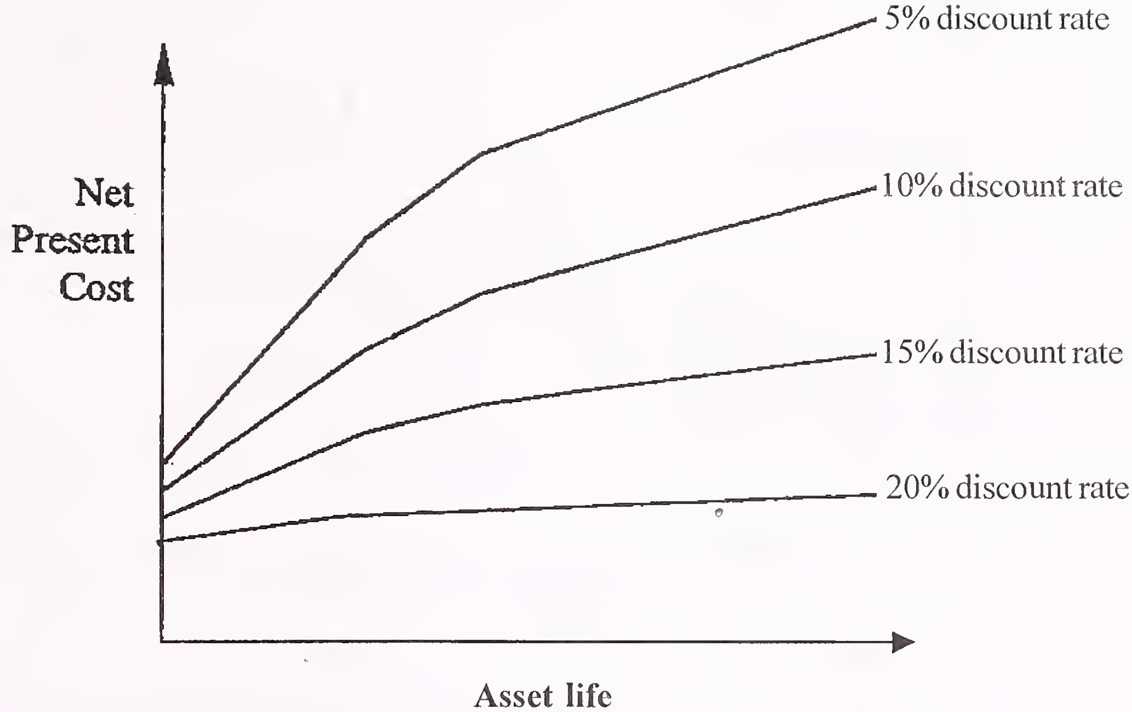


Fig. 7. Example of a bivariate sensitivity analysis[4]

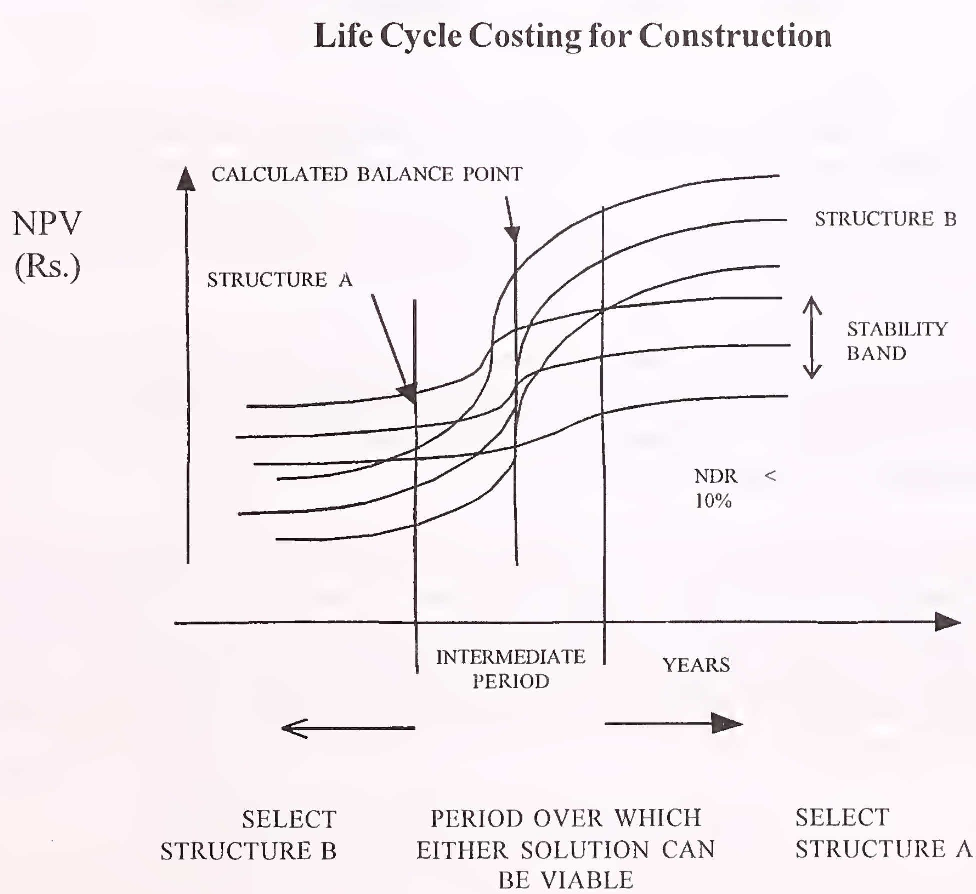


Fig. 8. Analysis of two structures A & B, using low discount factor

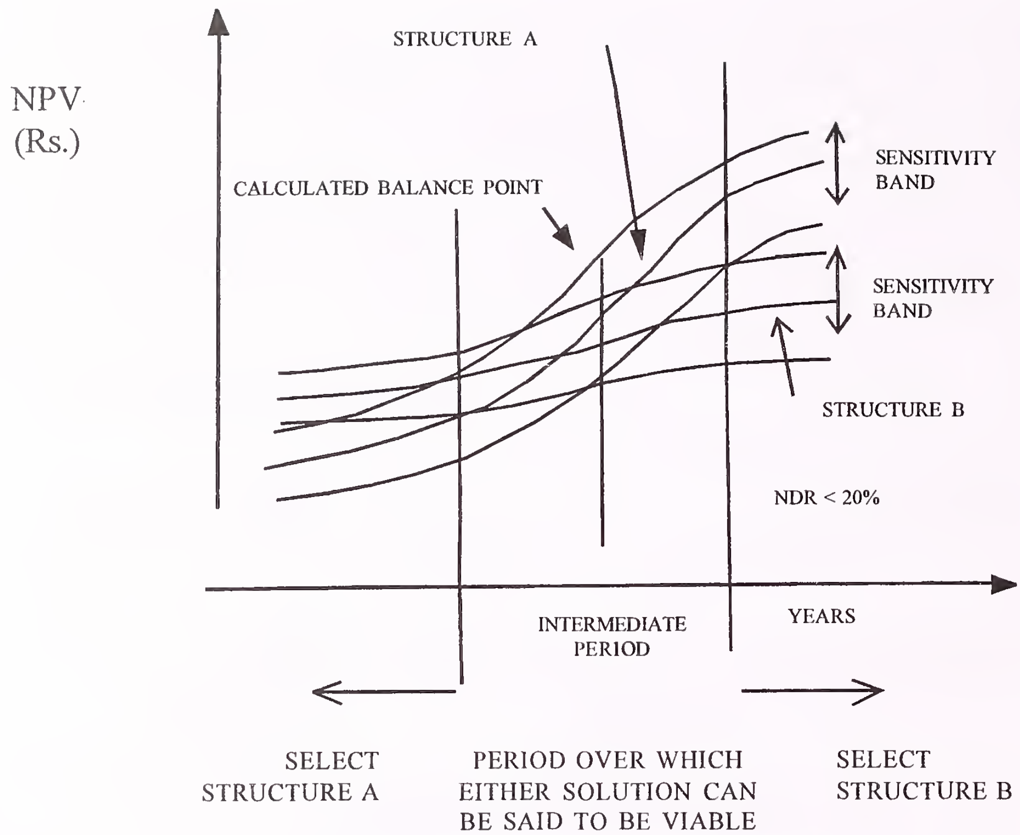


Fig. 9. Analysis of two structures A & B, using high discount factor

in a steeply sloping line. A high discount factor results in a less steep line, extending the time scale during which the calculated balance point is achieved and increases the intermediate period, as shown in **Fig. 9**. A view could be taken that it is sensible not to invest additional funds now which could be invested elsewhere. When the return is at such an investment drop, the lowest – cost selection system will tend to prevail on high discount – factor projects.

Such analysis help to identify the critical parameters (or assumptions) which underpin the cash flow forecast. They provide the means to test the sensitivity to forecast variations in the uncertain values of parameters (or assumptions). Rather than a single answer, a range of relative costing outputs need to be assessed before a final decision is made.

Despite sensitivity analysis, high interest, high inflation and uncertain funding availability, may cause erroneous influence over the long term predictions and render the working unstable. For this purpose, the analysis needs to be frequently updated and options re-evaluated, in order to route a most favourable solution under a set of prevailing circumstances and fresh anticipations. This approach will become more stable once fairly settled conditions prevail and market prices are steady, e.g., as in Japan, Germany, U.K. and U.S.A.

7. STEP-BY-STEP APPROACH TO THE USE OF WLC

The step-by-step approach to the use of WLC, as appropriate to bridges, is as under:

Step 1: Identify the objectives, constraints and alternatives to the whole life costing exercise

- The objective is to minimise the whole life costs or to choose the alternative, which results in the least WLC from a range of alternative schemes. WLC will be used to optimise and justify the financial decision.
- The constraints could be a limited budget and also recognition of the fact that subjective issues might influence the ranking of alternatives which are otherwise based on a purely financial decision.

Step 2 : Establish the basic assumptions and determine the whole life costing procedure to be adopted

- The NPV method is recommended for applying WLC to Bridges

Step 3 : Compile all the necessary data

- Most important financial parameters are:
  - Discount rate
  - Whole life period in years
- The most important components of life time costs for bridges stock are:
  - Construction
  - Maintenance
  - Operational
  - Road user (traffic) delay costs
  - Environment management costs

Where benefits are envisaged over the time period which reduce costs, and can be expressed in financial terms, they should be taken into account and discounted to their net present value.

Step 4: Compute and discount the whole life costs for each alternative using the NPV method

- Comparisons must be made in the light of the assumptions that underpin the analysis.
- Use can be made of spreadsheets or suitably modified proprietary software.

Step 5: Compare the results

- Prioritise the actions needed to be taken
- Rank the alternatives

Step 6: Evaluate the results for uncertainty by means of sensitivity analysis

- Arrive at a range of costing which shows the variation of NPV against time for a given scheme, or for the different alternatives under consideration, by varying the parameters for the WLC analysis within a suitable range.
- Engineering judgement should be exercised to choose the option for implementation. An awareness of uncertainly and risk which is endemic to whole life costing in the construction industry will need to be displayed (introducing WLC within the context of an effective risk management system is beyond the scope of the present document).

Step-7: Report on the findings and conclusions

- Where costs only are considered without consideration to benefits, the least NPV option is adopted.
- Where costs and benefits are considered, a positive NPV indicates that the benefits are greater than the costs.
- Where costs and benefits are considered, a negative NPV indicates that the proposed project, if taken-up, would yield a return, which is lower than the cost of capital to the owner. Unless the project can be justified on the grounds of some other essential criteria (e.g., strategic, defence, etc.) it should not be implemented.

8. WLC AND MANAGEMENT

In bridge management, WLC may be implemented as a management tool and invoked intermittently as a management system in which a continuum approach can be adopted throughout the lifetime the bridge.

8.1. WLC as a Management Tool

When used to plan expenditure in the public sector, it can be expected that whole life costing l be used for capital expenditure decisions only. As a management tool it can also be used at any e during the life cycle to minimise bridge management costs. In this approach, the WLC technique : only be used intermittently throughout the life cycle of the bridge in order to minimise costs. As ıanagement tool, WLC can be used most effectively to choose from a range of repair and ıbilitation alternatives for a highway structure.

8.2. WLC as a Management System

The approach is to introduce a continuum of WLC from the capital planning stage to ational maintenance, so that if at any time the actual costs are proving different from the budgeted a lesson can be learnt and future budgets modified in sufficient time. Used in this way WLC nes more effective, the estimates more realistic and costs can genuinely be controlled.

All the separate stages in the application of WLC over the bridge's life cycle need to be linked udgetary mechanism to create the desired continuum. Thus, when used as a management system, :-up which estimates the future costs and the set-up which is responsible for spending the money could be referenced on the basis of WLC[4]. This approach necessarily implies the development of a culture in which managements take on responsibility for the bridges under their control. It is obvious that such a working system would lead to better quality control and quality assurance methods being adopted.

The use of WLC as a management decision system is best addressed within the framework of a Bridge Management System (BMS), in which a cradle-to-grave approach is necessarily adopted for all the maintenance work of the existing and new bridgework. For an introduction to BMS and the roll of WLC within a BMS[2,3].

As part of a BMS, WLC provides a continuum approach in which it is used to help plan the prioritisation/ranking of bridges. As part of the decision making module of the BMS, it is best suited for choosing from a range of possible projects or for choosing from various alternative repair schemes within a single project. BMS is further discussed in Section 8.3.

8.3. Bridge Management System

With increasing road and highway infrastructure in place, the relative cost of maintenance and repair of existing bridges has been steadily growing. The problem facing bridge authorities worldwide is the need to balance available resources for new and existing bridges and maintenance costs, in a given time frame (budget time period). This requires prioritization of actions. As a consequence, management systems for bridges have been adopted in many countries.

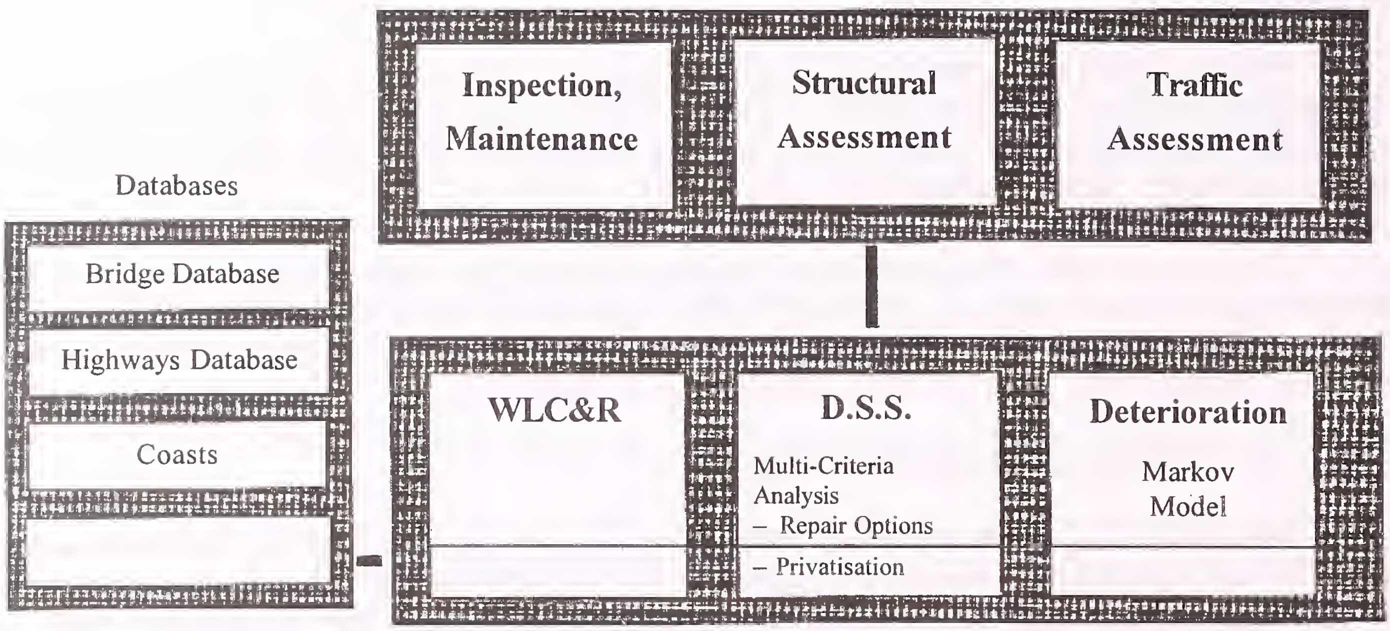
The development of a BMS is a major event and the following are meant to complement the already existing guidelines in IRC Special Publication 35[3].

Bridges need to be managed throughout their service life and the BMS does that by:

- Storing all the design, construction and field inspection data in a database.
- Standardizing procedures and reports in the form of Q&A software. This is to generate data in respect of personnel, equipment and previous inspections. Also, to track the processing of the reports from standpoint of quality control and on-time completion.
- Helping in decision-making. The decision system is divided into-
  - A non-structural in-expensive work to keep the bridges functionality upto the designed level (routine maintenance).
  - Prime structural works to improve the present capacity performance of the bridge (non-routine maintenance).
- Involving multi-criteria decision-making tools in overall decision modelling.
  - Primarily, a BMS must be appropriate to the prevailing state of engineering practice, apart from being cost effective to implement and maintain. Preference should be given to adopting/developing a computerized form of a BMS. A commonly used database software (Microsoft Access), corresponds the core bridge inventory module with other decision modules being added as shown in **Fig. 10.** This will allow various forms of 'query' to be posed to the BMS in the form of filters, and the outcome of these questions can be used either for

Bridge Management System

Systems and Prodcedures



R = Risk, D.S.S. = Decision Support System

Fig. 10. Overall framework of a bridge management system[2]

some form of decision–making or fed into a statistical software for estimating trends and processing. The successful development and use of a BMS for the inspection of a large number of bridges in Florida by a consulting company[12].

- It is appropriate to start with a simple BMS and gradually increase its sophistication as required with time, instead of adopting a complex BMS which might take several years to implement and operate at its full capacity, in view of the substantial input information not being readily available[14].

- Transport Research Laboratory (TRL), UK, have recently developed such an amenable computerised BMS. It comprises a central bridge inventory module to which are tied a relatively simple Markov model [**Appendix D**] for predicting the future deterioration rate and condition state (i.e. a durability module), as well as a financial module based on WLC to help rank the cost effectiveness of various bridge repair options.

- Needless to say that the bridge inventory database, the Markov model and the maintenance cost databases must be continuously updated on the basis of future inspection reports. From such stored data, deterioration rates can be derived from changes in condition state with time, data on the cost of maintenance options can be extracted from stored information on past maintenance work, improvement in condition state following maintenance as well as useful life of maintenance systems can be assessed[14].

- A three-level system methodology for a computerised BMS is a reliable administrative tool. In such a system[15] which employs a closed loop procedure to address budgetary and strategic concerns at the national, district and local levels, is addressed. The three level bridge rehabilitation and replacement management selection module, utilizes general wide-selection criteria applied to the full bridge inventory for that region, as extracted from the central data base maintained by the National Bridge Authority. Specific local criteria, regarding particular structures are taken into account at the local level taking full advantage of local engineering and planning knowledge about candidate bridge projects. This is feedback to the national level, thus ensuring valuable local and district level staff participation in the decision-making process. The basic system design and common data base could be used by any State in the country with any existing bridge stock. The flow-chart in **Fig. 11** is self-explanatory.

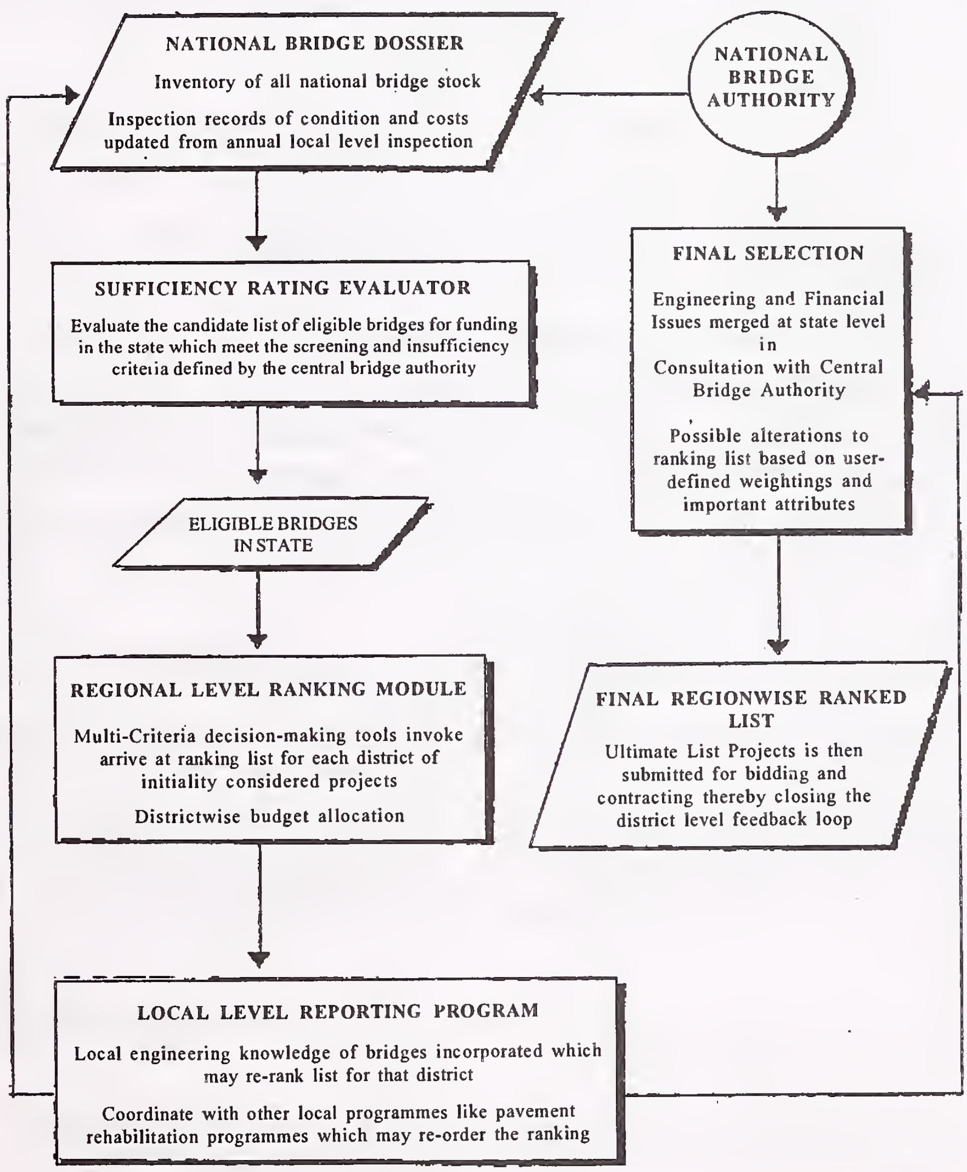


Fig. 11. Schematic flow-chart of bridge rehabilitation/replacement project selection module of a BMS, showing national, regional and local inter-relationships

This approach can be applied to national, district and local levels by choice.

The system is a good starting point for developing the basic maintenance, rehabilitation, and replacement sub-module within a BMS on a national and state-wise basis. A full BMS would cover the organization of bridge planning, design, construction, maintenance, evaluation, and research together with interaction with other infrastructure management systems, such as, that for pavements. Such an implementation of a BMS would be the ideal structure for evaluating the contributions made from techniques, materials, and systems designed to extend the life of bridges in the overall context of a nation's transport infrastructure.

9. PROBLEMS INVOLVED IN IMPLEMENTING AND USING WLC FOR BRIDGES

In general, what is needed for the bridge industry is a WLC approach to the purchase cost, maintenance cost, running cost, in-service failure cost, and the demolition and disposal cost associated with the structure.

With respect to estimating whole life costs for bridges, the following difficulties are currently envisaged:

- Difficulty in predicting bridge deterioration and the residual life and hence long-term maintenance costs.
- Difficulty in predicting long-term growth in traffic and hence traffic delay costs.
- Uncertainty in discount rate, inflation rate, etc.
- Difficulty in using subjective and qualitative criteria, which influence overall decision-making and which cannot be suitably expressed in monetary terms.
- Likely external influences altering resource allocation, ranking/prioritization established on the basis of WLC.
- Difficulty in predicting long-term economic conditions.
- Difficulty in assessing the life of various repairs and rehabilitation options.

10. STEPS REQUIRED FOR IMPLEMENTING WLC IN BRIDGES

In Section 6 of IRC Special Publication 35[3] some of the key allied areas of research and development aspects for bridge maintenance are identified. The section also highlights the need to 'study the economics of maintenance of bridges of various ages and types', thereby making an implicit reference to WLC.

A suitable framework to facilitate the use of WLC for bridge management is a pre-requisite in the following developmental referrals:

- A database of national bridge stock and their condition. The database to include increase bridge defects and maintenance, repair and strengthening costs.
- A bridge deterioration model on the basis of Markov probabilistic process **(Appendix D)**.

- A database of appropriate standard cost figures for bridge maintenance works and service lifes.

  In this context, suppliers of patented repair materials and techniques must be encouraged to provide a whole life cost for their products with special emphasis on guaranteed life expectancy of the repaired option using their product.

- Guidelines which set-out national procedures and methodology for bridge assessment, rating and deterioration monitoring.

  In this context, an 'Assessment Version' of the Bridge Code needs to be developed as distinct form the 'Standard' Bridge Code.

- A model to predict road user (traffic) delay costs.

  This might be done by making appropriate modifications to a model similar to the computerized model QUADRO used in the U.K. **(Appendix B)**.

- The following need to be considered in the development of a **Traffic Delay Cost Model**:
  - Traffic type, capacity and flow-rate
  - Sequence, number, timing and methodology of lane closures; working out and posting of vehicle speed and weight restrictions
  - Length and quality of diversion
  - Application of model to rural and/or urban areas or otherwise
  - Application of model to all categories of highways or otherwise
  - Application of model to major and/or minor bridges or otherwise
  - Hybrid maintenance schemes in which the bridge and the associated length of highway are both simultaneously closed during periods of future maintenance to minimise traffic delay costs. In such cases, depending on the circumstances, a major portion of the future traffic delay costs could be allocated to the highway/road as compared to the bridge
  - A single-lane closure or restriction of the carriageway might have the impact of demanding the simultaneous maintenance of a series of bridges/flyovers in close proximity, thus causing traffic delay costs to be apportioned equally to all the bridges in the series. For heavily used routes, maintenance, including painting of steel bridges/ elements, should be carried out at night time. However, in assessing the traffic delay costs, it may be necessary to ascertain whether it is required to maintain some carriageway restrictions during the daytime, which inturn would cause increase in journey time, vehicle operating costs and Queuing

  Appropriate traffic forecasting models

  In the context of construction of major National Highways, and keeping in mind the phenomenal annual expected growth in traffic volumes at the current rate of 20-36 per cent, its significance is self-evident

- Appropriate economic forecasting models

  These to take into account a construction price index (CPI), as distinct from a retail price index. The CPI to reflect the real financial environment within the construction industry and help the average cost of capital for construction to be more realistically incorporated in the discount rate

- Adoption of a realistic discount rate

  However, for the present an indicative Test Discount Rate (including inflation) of 7 per cent can be assumed and a sensitivity analysis undertaken for a variation in the discount rate of between 8-15 per cent, to arrive at a range of costing on which a decision can be taken. This action for evaluating alternative maintenance schemes for new and for the repair of existing bridges.

  (It is likely that on the basis of the present Indian economy, and an assessment of its future economic trend, a 12 per cent discount rate with a time horizon of 30 years could prove to be appropriate for bridges in the Indian context).

- Adoption of a computerized BMS to greatly facilitate the move towards WLC for bridges, as WLC is central to the prioritizing/ranking process.

  Whereas, adopting a WLC approach is conditional to spending more on initial feasibility and detailed design costs, it is nonetheless justifiable on the grounds that such an approach will give much better long term value for money and must, therefore, be encouraged.

  Maximum benefit from the WLC approach for bridges will be obtained by incorporating it as a part of a comprehensive Bridge Management System with the focus on a rolling, medium-term maintenance strategy.

  There is also a clear case for adopting a simple BMS and gradually increasing its sophistication with time, as compared with adopting a complex BMS at the outset with consequent delays in implementation.

  Further research/development work and data-base preparation as an index for probabilistic deterioration prediction and related cost studies, are pre-requisite to enhance the use of WLC in decision-making, and for the development of a Bridge Management System.

Appendix-A

SAMPLES OF WHOLE LIFE COSTING FOR BRIDGE PROJECTS

Example 1: Whole Life Costing to choose between 2 options for a New Bridge at the Design Stage

A three span continuous concrete slab carrying a dual two-lane all-purpose carriageway with footpaths is to be built. Two possible options are available: a composite steel beam with concrete deck or an 'all-concrete' deck. A whole life cost approach will determine the option to be adopted.

The use of spreadsheets shown in Tables 1 and 2 greatly facilitate this comparison; the bridge properties are entered in the shaded portions.

The bridge element, area/length/number of each elements; and their capital cost are entered in the first three columns respectively in the spreadsheets. The capital costs are based on prevailing costs in the construction market.

Similarly, the repair/replacement rates and costs and expected life before replacement are entered in Columns 5, 6 & 7.

The figures for piers, steel beams and concrete deck are taken from historical records. The remaining figures are gathered from various sources but cannot be regarded as authoritative.

A assumed expected long term inflation rate of **8 per cent** and a long-term market cost of capital (interest rate of **13.5 per cent**) are used to calculate the discount rate as under:

$$\text{Discount Rate \%} \quad \left(\frac{1 + \text{interest \%}}{1 + \text{inflation \%}} - 1 \right) \times 100$$

$$\left(\frac{1 + 13.5\,\%}{1 + 8\,\%} - 1 \right) \times 100 = 5.09\,\%$$

The repair/replacement rate is obtained by multiplying the repair/replacement cost with the value in area/length/number column.

$$\text{NPV} = \sum_{t=0}^{t=n} \frac{B_t - C_t}{(1 + r)^t} =$$

$$B_t = 0;\ C_t = C : \text{Capital Cost}$$

The Net Present Value for a typical bridge element is calculated based upon the formula given below:

Where,

N = Whole life period considered
C = Capital cost
t = Year in which the expenditure is envisaged
r = Discount rate in per cent

The years to be considered (t) is obtained by dividing life before replacement for that particular element by the design life of the bridge (N). In this example N=120 years.

For example, the NPV for 'Bearings', for the concrete bridge option in Table 1 at today's Capital Cost of Rs.4,12,500 and life replacement every 25 years, with a whole life period of 120 years is given below:

$$NPV = 412500 + \frac{30,00,000}{(1+5.09\%)^{25}} + \frac{30,00,000}{(1+5.09\%)^{50}} + \frac{30,00,000}{(1+5.09\%)^{75}} + \frac{30,00,000}{(1+5.09\%)^{100}}$$

$$= 1,622,650$$

Note that the initial capital cost (n=0) is also part of this NPV calculation.

It is interesting to compare the percentage cost of each bridge element in terms of capital cost and Net Present Value. This is facilitated by Pie Charts for each of the options. The results appear to back-up intuitive understanding that replacement of 'soft' bridge elements, like, bearing, expansion joints and waterproofing membranes figure much larger in whole life costs than in capital costs. This is not surprising, as these require more work in removal and replacement and require possibly more frequent replacements during the life of the bridge.

It is clear that the composite steel and concrete bridge option has a Net Present Value that is greater than the concrete bridge option. **The concrete bridge option with the lower NPV is the preferred option.**

Sensitivity Analysis can be carried out.

(1) By varying the expected long-term inflation and the long-term market cost of capital to generate discount rate for values other than what has been adopted in this specific example: 8 per cent, 13.5 per cent and 5.09 per cent respectively.

(2) By varying repair/replacement rates over a range to study the effect of various repair and replacement strategies.

(3) By varying the design life of 120 years.

(4) By varying the life expectancy for one or many bridge elements and observing the effect on the repair/replacement options.

Table 1. Three Span all Concrete Deck Bridge over River XYZ

SPANS 14, 26.5 & 14 Mtrs.

7.3 m C'Way Width, 1.5+2.0 FOOTPATHS, 2 X 0.5 PARAPETS
8.00 = EXPECTED LONG-TERM INFLATION PER CENT
13.50 = LONG-TERM MARKET COST OF CAPITAL PER CENT
5.09 = DISCOUNT RATE PER CENT

Bridge Element	Area or Length OR No.	Capital Cost (Rs.)	Per cent	Repair/ Replace Rate (Rs.)	Repair/ Replace Rate (Rs.)	Life Years	Total Life Cost (Rs.)	Per cent
Minor Inspection	1	0	0.00	5000	5000	6	16650	0.10
Principle Inspection	1	0	0.00	25000	25000	6	71800	0.42
Abutments		1725000	12.90	–	–	120	1725000	10.08
Piers	116	1650000	12.34	75	8700	20	1655100	9.67
Steel Beams	–	–	–	–	–	15	–	0.00
Concrete Deck	752	7211250	53.92	80	60150	20	7246550	42.32
Bearing	24	412500	3.08	125000	3000000	25	1622650	9.48
Waterproofing Membrane	698	675000	5.05	1500	1046400	15	1618150	9.45
Road Surfacing	698	670000	5.01	1000	697600	15	1298800	7.59
Expansion Joints	26	475000	3.55	27500	715000	15	1119450	6.54
Parapets	121	556250	4.16	1750	211750	15	747100	4.36
TOTAL CAPITAL COST Rs.		13375000			NET PRESENT VALUE Rs.		17121250	

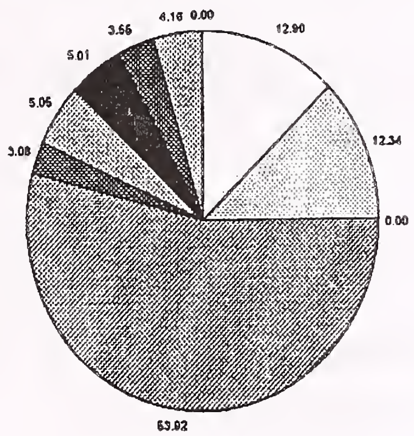
TABLE 2. THREE SPAN ALL CONCRETE DECK BRIDGE OVER RIVER XYZ

SPANS 14, 26.5 & 14 Mtrs.

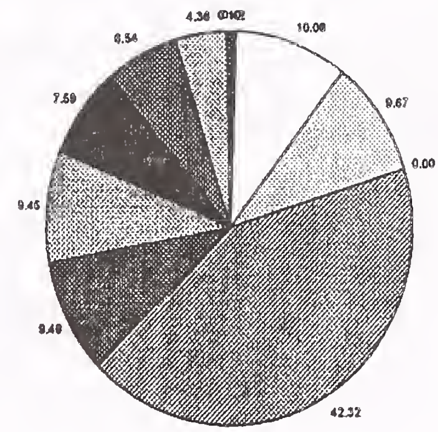
7.3 m C'Way Width, 1.5+2.0 FOOTPATHS, 2 X 0.5 PARAPETS
8.00 = EXPECTED LONG-TERM INFLATION PER CENT
13.50 = LONG-TERM MARKET COST OF CAPITAL PER CENT
5.09 = DISCOUNT RATE PER CENT

Bridge Element	Area or Length OR No.	Capital Cost (Rs.)	Per cent	Repair/ Replace Rate (Rs.)	Repair/ Replace Rate (Rs.)	Life Years	Total Life Cost (Rs.)	Per cent
Minor Inspection	1	0	0.00	5000	5000	6	16650	0.08
Principle Inspection	1	0	0.00	25000	25000	6	71800	0.36
Abutments	–	1725000	10.96	–	–	120	1725000	8.75
Piers	193	2460000	15.63	75	14500	20	2468500	12.52
Steel Beams	1165	6382500	40.54	160	186400	15	6608850	33.53
Concrete Deck	752	2387500	15.16	55	41350	20	2411750	12.24
Bearing	24	412500	2.64	125000	3000000	25	1622650	8.23
Waterproofing Membrane	698	675000	4.29	1500	1046400	15	1618150	8.21
Road Surfacing	698	670000	4.26	1000	697600	15	1298800	6.59
Expansion Joints	26	475000	3.02	27500	715000	15	1119900	5.68
Parapets	121	556250	3.53	1750	211750	15	747100	3.79
TOTAL CAPITAL COST Rs.		15743750			NET PRESENT VALUE Rs.		19708750	100 Per cent

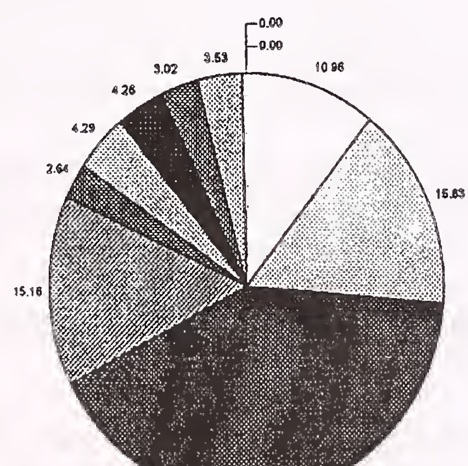
Pie Charts for examples on Pages 31 & 32



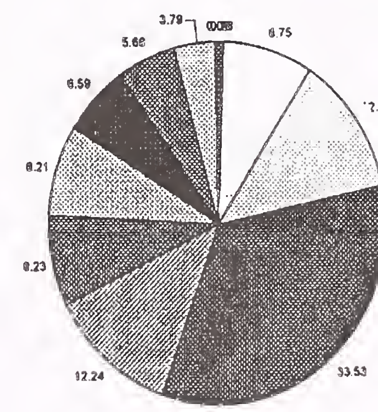
Pie Chart for Capital Cost
All Concrete



Pie Chart for NPV
All Concrete



Pie Chart for Capital Cost
Composite



Pie Chart for NPV
Composite

Pie Chart for NPV
Composite

Sr. No.	BRIDGE ELEMENT	All Concrete		Composite	
		Capital Cost	NPV	Capital Cost	NPV
1	Minor Inspection	0.00	0.10	0.00	0.08
2	Principle Inspection	0.00	0.42	0.00	0.36
3	Abutments	12.90	10.08	10.96	8.75
4	Piers	12.34	9.67	15.63	12.52
5	Steel Beams	0.00	0.00	40.54	33.53
6	Concrete Deck	53.92	42.32	15.16	12.24
7	Bearing	3.08	9.48	2.64	8.23
8	Water Proofing Membrrane	5.05	9.45	4.29	8.21
9	Road Surfacing	5.01	7.59	4.26	6.59
10	Expansion Joints	3.55	6.54	3.02	5.68
11	Parapets	4.16	4.36	3.53	3.79

- Minor Inspection
- Principle Inspection
- Abutments
- Piers
- Steel Beams
- Concrete Deck
- Bearing
- Water Proofing Membrrane
- Road Surfacing
- Expansion Joints
- Parapets

Example 2: Whole Life Costing to choose between 3 options for the Repairs and Rehabilitation for an Existing Bridge

The example is for the selection of the most economical option for a deck rehabilitation project.

The time frame to be considered is 50 years from the date of inspection. The project engineer has inspected the bridge. He has gathered further from historical records the following life cycles for various repair treatments.

(1)	Deck replacement	50 Years
(2)	Rehabilitation – patch, waterproof and pave	15 Years
(3)	Milling and replacing top coat of asphalt	15 Years
(4)	Replace waterproofing and asphalt	30 Years
(5)	Physical residual life without rehabilitation (Do Nothing)	5 Years

- He has, therefore, concluded that he has 3 options available to him as under:

Option (1) : Immediate rehabilitation: patch, waterproof and pave and thereby extend the useful life of the deck by 15 years, after which replace the deck. In year 30 clean and replace the top asphalt and in year 45 replace waterproofing and asphalt; replace deck a second time in year 65 from date of inspection.

Option (2) : Do nothing now and replace the deck, waterproof and pave in 5 years, at the end of the useful life of the bridge. In year 20 clean and replace the top asphalt surfaces. In year 35 replace waterproofing and asphalt; replace the deck in year 55 from date of inspection.

Option (3) : Replace the deck now, waterproof and pave. In year 15 clean and replace the top asphalt. In the year 45 clean and replace top asphalt surface; replace deck in year 50.

The result of financial analysis performed for the above examples are shown in Tables 3 and 4.

While the example cannot be said to be an accurate comparison, it is sufficient to demonstrate what can be achieved in terms of Whole Life Costing.

TABLE 3. COST DATA (INDIAN RUPEE)

Year	Option 1	Option 2	Option 3
0	600000	–	1000000
5	–	1000000	–
15	1000000	–	100000
20	–	100000	–
30	100000	–	200000
35	–	200000	200000
45	100000	–	200000

Number of Options	:	3
Discount Rate (r)	:	0.06
Life Cycle	:	50 years

Table 4. Net Present Value (Indian Rupee)

YEARS	OPTION 1		OPTION 2		OPTION 3	
	COST	NPV	COST	NPV	COST	NPV
0	600000	600000	0	0	1000000	1000000
5	0	0	1000000	747258	0	0
15	1000000	417265	0	0	100000	41727
20	0	0	100000	31180	0	0
30	100000	17411	0	0	200000	34822
35	0	0	200000	26021	0	0
45	100000	7265	0	0	200000	14530
Total NPV	–	1041941	–	804460	–	1091079

- In each of three Repair –Rehab Options, the PV of the estimated expenditure in the projected year is calculated based on

$$PV = \frac{C}{(1+r)^n}$$

For example, in option 2, the deck is replaced and water proofed and paved 5 years from the current year.

n = 5 years
C = Rs.1,000,000

$$PV = \frac{1000000}{(1+0.06)^5} = 747258$$

- Total NPV in each option is the sum of various PV's for each stage of maintenance action in the overall strategy of the available options.

- Residual Life and Value

The various alternatives considered may have useful lives at the end of the time frame. This is termed as the 'Residual Life'. There is no precise method of assessing this. A thorough knowledge of the performance of past rehabilitation inputs and experienced engineering judgement, is probably the best way of assessing the useful residual life. From the residual life of elements the 'Residual Value' of the structure is calculated.

There are several methods available for calculating the residual value. The method used here is the 2nd cycle replacement method.

Let us consider two options say options (1) and (3).
Let the 2nd replacement of option (1) be n1, years
and 2nd replacement of option (3) be n3 years n1 > n3
Option (3) will be the base case.

The calculations for residual values based on Year of Replacement (2nd cycle) are shown below:

Option	Year of replacement	Replacemnet Cost	Residual year	Value at year N	Differential value	Residual value
1 3	n_1 n_3	C C	n1-n3 0	C_1 C_3	C_{d1} C_{d3}	C_{R1} C_{R3}

Where,

r = Discount rate per cent

C = Replacement Cost

$C_3 = C$ $\quad C_{d3} = C_3\text{-}C = 0$ (Option 3 is taken as base option)

$$C_1 = \frac{C_3}{(1+r)^{n_1-n_3}} \qquad C_{R3} = 0$$

$$C_{d1} = C1\text{-}C \qquad C_{R1} = \frac{C_{d1}}{(1+r)^{n_3}}$$

In the example

- The time to deck replacement is considered as 50 years. The base option is taken as option 3 in which the deck is replaced in year 0, and the deck replacement costs Rs.1,000,000 at today's price.

A sample calculation of residual value for option 1 is given below:

C = 1,000,000 (todays cost of deck replacement)

$$C_1 = \frac{C_3}{(1+r)^{n_1-n_3}} = \frac{1000000}{(1+0.06)^{65-50}} = 417{,}265$$

Where,

r = 6 per cent

N1 = 65 years (in Option 1)

N3 = 50 years (in option 3 which is taken as base option)

$C_{d3} = C_3\text{-}C = 0$

$C_{d1} = C_1\text{-}C = 417265 - 1{,}000{,}000 = 582735$

$$C_{R1} = \frac{C_{d1}}{(1+r)^{n_3}} = \frac{582735}{(1+0.06)^{50}} = 31636 \quad C_{R3} = 0$$

Similarly, for option 2 the residual life can be worked out.

- The Net Present Value for each option taking residual value into account is evaluated as under:

e.g., in option 1, NPV [adjusted for residual value] = total NPV – Residual value

= 1,041,941 – 31,636 = 1,010,305

	Option 1	Option 2	Option 3
Total NPV	1041941	804460	1091079
Residual value =	(31636)	(13721)	0
Adjusted Residual value at 50 years	1010305	790739	

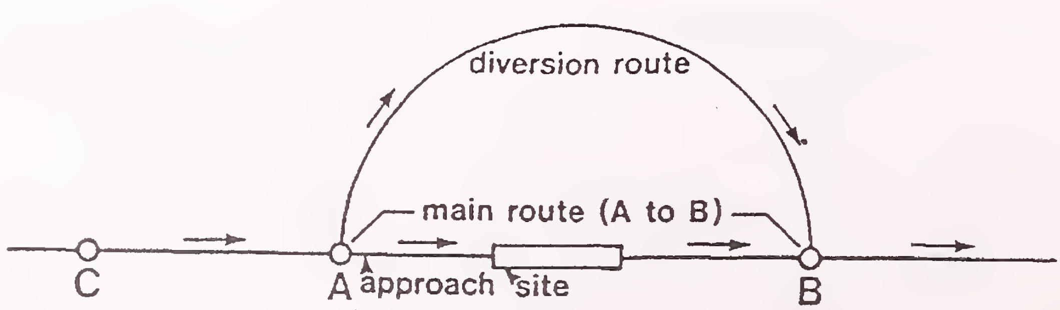
- **Preferred option on the basis of WLC: Option 2 which has the least NPV**

Appendix-B

TRAFFIC DELAY COST MODEL WITH SPECIFIC REFERENCE TO QUADRO

For a model for undiscounted traffic delay costs or road user delay costs (for example along the lines of QUADRO software used in the UK[11]), the following census needs to be undertaken :

- Traffic type, capacity and flow rate
- Sequence, number, timing and methodology of lane closures; working out and posting of vehicle speed and weight restrictions
- Length and quality of diversion
- Structure of model: rural and/or urban areas or otherwise
- Structure of model: all categories of highways or otherwise
- Structure of model: major and/or minor bridges or otherwise
- Hybrid maintenance schemes in which the bridge and the associated length of highway are both simultaneously closed during periods of future maintenance will lead to savings in traffic delay costs. In such cases, depending on the circumstances, a major portion of the future traffic delay costs could be allocated to the highway/road as compared to the bridge.
- A single-lane closure or restriction of the carriageway might have the impact of demanding the simultaneous maintenance of a series of bridges/flyovers in close proximity, thus causing traffic delay costs to be apportioned equally to all the bridges in the series. For heavily used routes, maintenance, including painting of steel bridges/elements, are carried out at night time. However, in assessing the traffic delay costs, it may be necessary to ascertain whether it is required to maintain some carriageway restrictions during day time as well.
- Vehicle delay costs must recognise:
  - Increase in journey time
  - Vehicle operating costs (labour, fuel, vehicle maintenance, etc.)
  - Queing
- **THE QUADRO SYSTEM**
  - In order to operate, the QUADRO requires a network. This comprises of the main route on which the works are to take place and a representative diversion route, together with the traffic flows for both routes. It also requires details regarding the length of works site, its location on the main route in relation to the diversion route and the duration, timing, and traffic management and other arrangements at each site. Works sites can be specified either individually or as a series of sites.



- For each job, QUADRO calculates the extra user costs due to the presence of works, allowing for traffic transfer to the diversion route. The programme then discounts the cost from the year the site is closed to a chosen present value year. The discounted costs of each job are summed to a total discounted cost for the profile. This is carried out for both 'low ' and 'high' traffic and economic growth scenarios. For economic decision making, the preferred option is that with the lowest present value of costs.

Appendix-C

FUTURE TRENDS IN THE DEVELOPMENT OF WLC, RISK AND DECISION MAKING FOR BRIDGE PROJECTS

The scope of WLC can be extended as per the following:

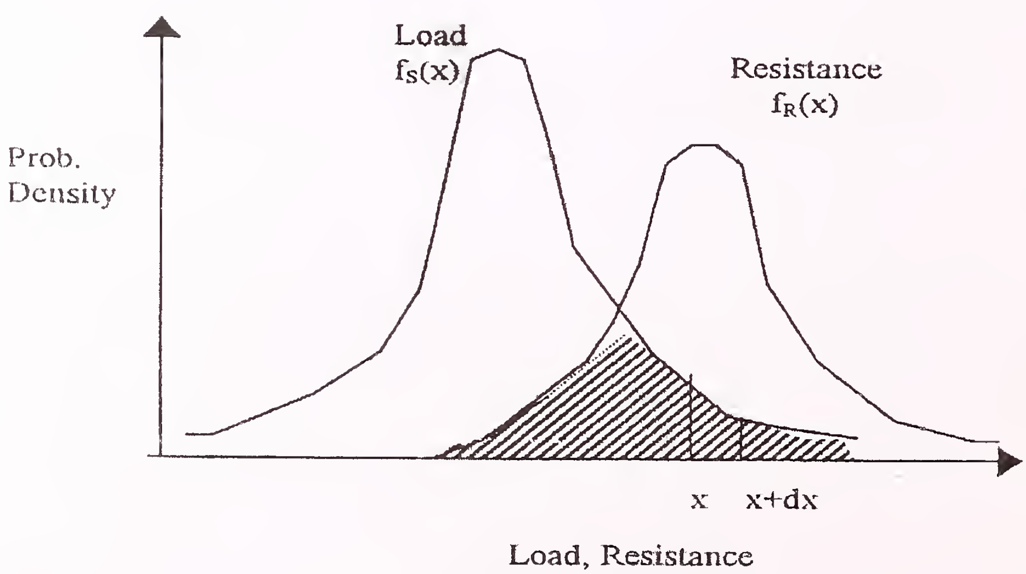
- Introduce the concept of Reliability and Risk, Develop Risk-Based Framework for screening, evaluation, ranking, prioritization of bridges needing repairs/remedial action.
- Develop Multi-Criteria Decision making tools.
- Include, when appropriate, the above within the framework of an overall Bridge Management System (BMS)

The following sections which are topics of extensive worldwide research are intended to provide background information on the possible lines of development for the suggestions in these sections. Refer [2], [13], [16], [17] and [18] for greater detail.

C.1. Uncertainty and Risk

Risk is evaluated from the relation[13],
Risk= Probability of Failure x Consequence

Structural reliability techniques[19] are used for evaluating the probability of failure, Pf, of a bridge/bridge component. As shown in **Fig. 12**, probability density functions for loads S (demand requirement) and resistance R (supply capacity) are required which are arrived at on the basis of statistical analysis of existing data.



$$P_f = P[S \geq R] = \int_{-\infty}^{+\infty} P[x \leq S < x + dx] P[R \leq x] dx = \int_{-\infty}^{+\infty} f_s(x) f_r(x) dx$$

P = Probability of event

Fig. 12. Evaluation of probability of failure (P_f) from the probability density functions of load (S) and resistance (R)[19]

General guidelines concerning the modelling and management of risk issues are to be found[20]:

The consequences of failure should be evaluated with regard to the following:

- **Human**: health and safety, exposure to hazard, and the potential loss of life and injury
- **Environmental:** damage to the environment
- **Traffic**: disruption to traffic, as road user costs
- **Economic:** disruption to the economy, loss of assets, and economic losses
- **Business**: with respect to funding, rebuilding/repair costs, private investment, etc.

The systematic application of risk techniques involves the probabilistic evaluation of exposure to various perceived 'Hazard' scenarios with full or partial failure consequences, and also a value for the cost of loss of human life or injury.

A risk based approach in which the probability of a bridge/network closure forms the central issue can be used to provide the framework for the three main activities related to bridge management, namely, economic appraisal, load assessment, inspection/maintenance.

C.2. WLC Including Risk

Risk can be incorporated into WLC by the formula given below[13]:

$$NPV = \sum_{t=0}^{t=N} \left[\frac{B_t - C_t}{(1+r)^t} + \frac{CftPft}{(1+r)^t} \right]$$

Where,

Pft = Probability of failure in year 't'

Cft = Cost of failure in year 't'

B_t = Estimated benefits in year 't'

C_t = Estimated costs in year 't'

C.3. Risk Based Assessment and Prioritisation of Bridges for Remedial Work

The methodology involves[2]

- Screening of bridges based on condition surveys.
- Standard load assessment using an assessment version of a national bridge standard (IRC and ISI). Load testing may also be used to rate the bridges.
- Risk assessment of sub-standard bridges, which do not meet assessment criteria.
- Ranking of bridges in terms of risk.
- Design of remedial actions for each bridge.
- Prioritization of bridges for the optimal allocation of resources for remedial work on different bridges.

For greater detail refer [18], [16], [21] and [17].

C.4. **Risk-Based Maintenance Planning**

The concepts of structural reliability developed[19] can be extended to maintenance issues.

For a bridge/network of bridges the maintenance strategy would be based on the optimum set of repairs for which the total bridge/network risk is a minimum.

A risk based method can form the overall framework of an effective inspection/maintenance strategy with a view to reducing the operational costs and improving the structural integrity of bridges. This can be achieved by optimizing the inspection frequency and maintenance strategy, by using techniques in which the structural reliability of deteriorating structures is kept above a minimum acceptable level.

A reliability - based maintenance plan involves assuming (preferably deriving) a target probability of failure, which should not be exceeded. With reference to **Fig. 13** when the target value is likely to be exceeded, maintenance/repair is called for to keep the P_f below the target value. Such interventions effectively increase the service life of the bridge/bridge component. The maintenance interval between interventions which affect the frequency of inspections also be observed.

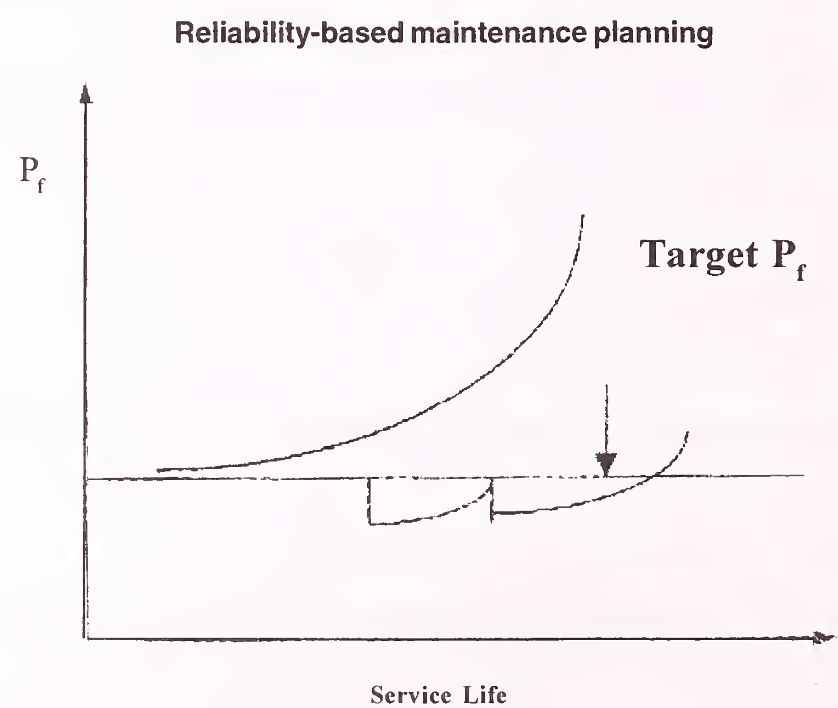


Fig. 13. Extension of service life using a reliability-based planning methodology, in which the P_f is not exceeded in the projected useful service life

C.5 Multi-criteria Decision Making

Invariably, if the goal is to select the best remedial action from a range of repair alternatives, the decision is based on various criteria as shown in **Fig. 14**[2]. The references [13] and [22] are relevant.

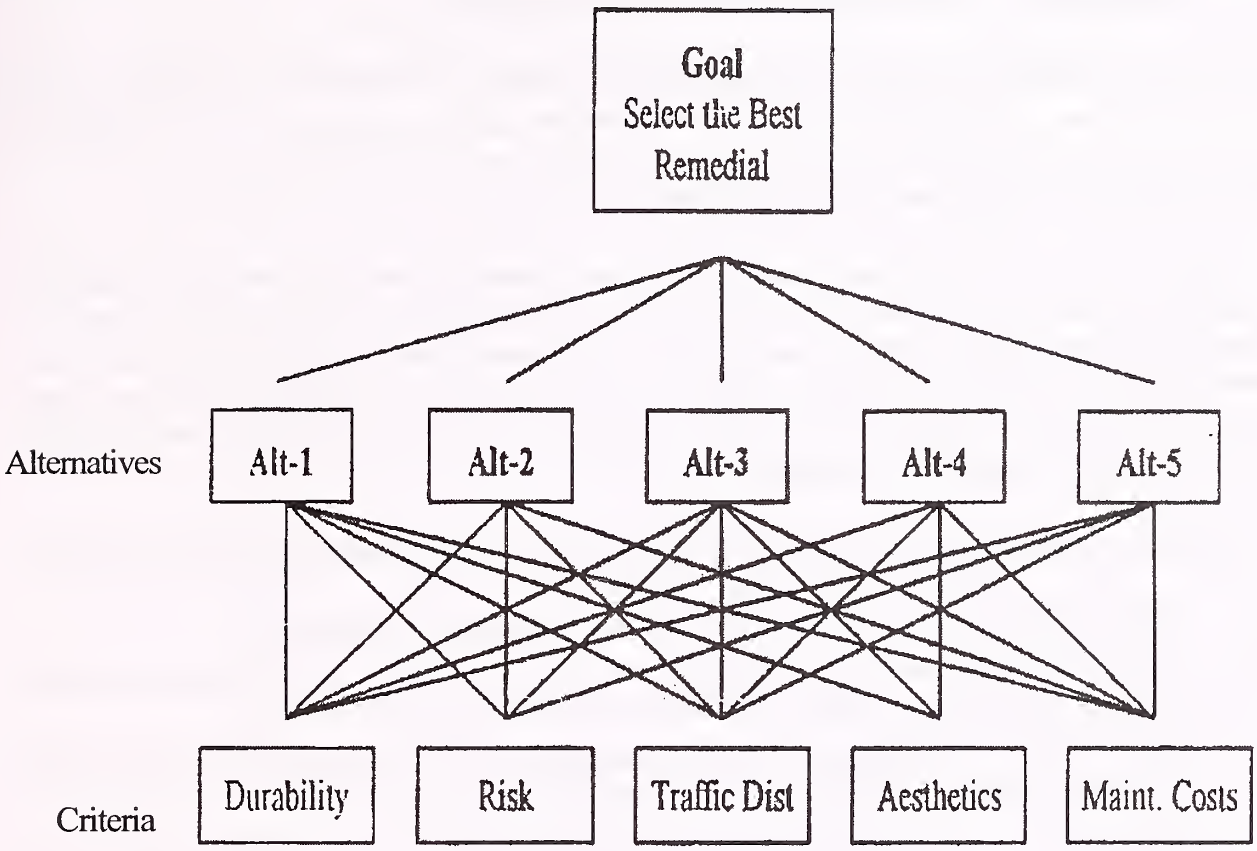


Fig. 14. Relationship between alternatives and criteria in a multi-criteria based decision-making framework[2]

Appendix–D

MODELLING BRIDGE DETERIORATION ON THE BASIS OF MARKOV PROCESS

D.1. Background Introduction to Bridge Deterioration

In order to plan and prioritize future maintenance works, it is required to postulate a model that can predict the state of deterioration-type of deterioration, and the rate that is likely to develop in bridge structures. An optimal long-term bridge maintenance policy can be developed if the rate of deterioration of various components can be predicted.

Bridges deteriorate due to various mechanisms, like, Alkali Silicate-Reaction fatigue, corrosion of steel reinforcement and steel members, carbonation, weld failures, delamination of concrete, etc. These mechanisms rarely occur in isolation and different mechanisms may be active at the same time or at different stages in the life of a bridge. Although, deterioration is a continuous process in time, the nature of deterioration is such that it becomes 'visible' or first noticed in the structure after a passage of ten to fifteen years from the time it was built.

The amount and type of deterioration evidenced depends on a number of factors, such as,

- Design quality and craftsmanship standards of original construction.
- Type of construction-steel, composite, concrete, prestressed concrete, etc. and various permutations of these types in different kinds of bridges.
- Type of traffic – Designed and Current. Increased traffic intensity and volume, vehicle speeds and axle loads accelerate the declamation process.
- Environment in which the bridge exists, hot marine environments being the most aggressive.
- Past maintenance actions.

Since there are various materials used for bridge construction and various components of a bridge are also made of different materials, deterioration modelling is based on the deterioration of individual components rather than of the entire bridge.

It becomes immediately apparent that there are considerable uncertainties involved in modelling deterioration, not least of which are a lack of historical data and even where such data exists, it may be of debatable quality or be inadequate requiring some form of extrapolation. Despite on-going research worldwide, a rigorous analytical model for estimating deterioration in bridge components due to the various deterioration mechanisms, is yet to be developed for direct use in assessing the long-term durability of a bridge.

In view of the above, **a time-dependant probabilistic model is envisaged for bridge deterioration.** The model must follow from a relatively simple concept and be capable of being fine tuned and up-dated with time on the basis of assessed deterioration and information inferred from inspection records as they become available.

D.2. **Probabilistic Markov Model for Bridge Deterioration**

The parameters required for the Markov Model are developed directly from observations on the deterioration of a number of nominally identical bridge components. The deterioration model will provide a probabilistic estimate of the rate of deterioration for a particular component of the bridge. Maintenance actions modify the deterioration of the component and this is reckoned. **The model will help to evaluate the probability that a component will be in a particular state at a future point in time given that the present condition of the component and the future maintenance policy are known.**

After estimating the level of deterioration at some future time 't', a WLC analysis can be used to cost the likely future maintenance for a given type of bridge element. Deterioration modelling is attracting research and development interests around the world[21,23].

The following assumptions are made when adopting the Markov approach.

- *Bridge components are grouped according to type* (e.g., bearings, expansion joints, prestressed concrete, T-Beams predominantly in flexure, etc.)
- *Suitable 'condition states' are defined for each component.* Although, deterioration is a continuous process, the condition of a particular bridge component is expressed relatively according to a numerical scale. Whereas, the scale may vary from country to country, a typical scale in which the *Condition Points or Condition Ratings* varies from 1 (insiginifcant) to 5 (serious) can be adopted. The annual probability of the component remaining in the same state or deteriorating to other states also require definition. **Fig. 15** shows the evolution of the conditional probabilities (sum of probabilities = 1 at any discrete time) for a particular bridge element category as the component

Markov Process Model for Deterioration

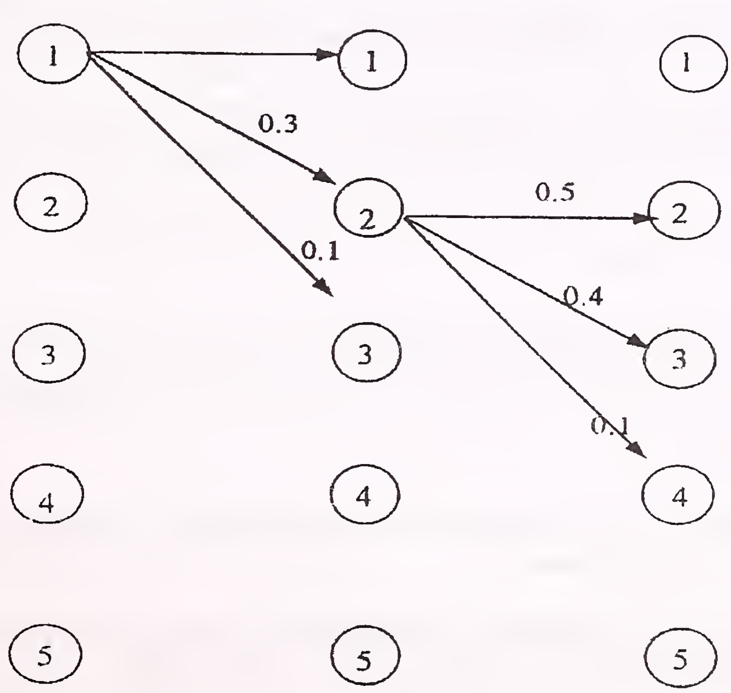


Fig. 15. Markov deterioration process showing condition states and conditional probabilities[2]

decays with time. Each condition state is discrete and given by the aggregated value of the inspection points shown in circles. The probabilities associated with the component deteriorating to different condition states in the future is identified between yearly intervals.

- Whilst the states and probabilities adopted by the model are to be initially chosen based on 'expert' opinion (i.e., subjective judgement of experienced inspectors), they can be updated using Bayesian inference techniques from the results of periodic inspection records as they become available.
- Whilst the Markov approach is amenable for implementing in the short-term, it is also possible to include Markov deterioration modelling in the long-term within the context of an overall risk based management system (currently, risk issues require further research and development)[18].

D.3. **Basic Probabilistic Equations and Scope**

Let X (t) denote the 'condition state' of a component at time.

Suppose the entire history of the *'condition states'* of the component has been monitored, finding that,

$$X(1) = x_1,\ X(2) = x_2 \ldots\ldots\ X(t) = x_t$$

Then the probability that the next value of the condition process, X(t+1) will equal any particular value xt +1, given its entire history, is

$$P\,[X\,(t+1)=x_{t+1} \mid (X\,(1)=x_1)\ I(X\,(2)=x_2)\ I \ldots I(X(t) = x_t)]$$

The above equation represents a stochastic process, intact the Markov process. The deterioration of a number of bridge components can be reasonably assumed to be 'path independent' and the future behaviour depends only on its present state and not its past history, i.e., the deterioration process is memoryless. The deterioration of the component in the next time step will depend only on its present condition and not on the entire history of deterioration, and the Markovian equation can be re-written as,

$$P[X(t+1) = x_{t+1} \mid X(t) = x_t]$$

Let the condition states be discretely defined on the basis of condition points as K=1,2,3...I. Then the probability that the process is in state I at time step t is expressed as,

$$qi\ (t) = P\ [X(t)=i]$$

A discrete Markov process is referred to as a Markov Chain (Benjamin and Cornell, 1970) and can be described by two parameters.

(1) the distribution of the condition states q1, for a particular bridge component at time (t), i.e., the state in which the system was at time zero.

$$qi\ (O) = P\ [X\ (o) = i]\quad \text{for all } i$$

(2) the transition probabilities pij (t), expressed in the form of a matrix, giving the conditional probabilities that the process will be in state *j* at time *t* given that it was in state *i* at the previous step.

P_{ij} (t) =P[X (t)=j |X(t-1)=j] for all i, j pairs

In general the transition probabilities will be functions of time. For most types of bridge components an older component and a newer component, which are in the same condition at present, are equally likely to transit to a next inferior state if no maintenance action is taken. Therefore, for a given type of bridge component, it is reasonable to assume that the transition probabilities are independent of the age of the component and this renders the Markov process homogenous with time and the transition probabilities are simply written as P_{ij}.

The two model parameters have to be derived for each type of bridge component from a statistical analysis of the available data on the condition of each type of component. Where such data are not readily available (inferred from historical trends) they can be taken based on the subjective judgement of experienced inspectors. The model can then be updated based on future inspection results.

From the /x/ matrix of transition probabilities for a homogeneous Markov chain the k-step matrix$^{(k)}$ of transition probabilities $P_{ij}{}^{(k)}$ can be derived as

$$P_{ij}^{(k)} = \sum_{r=1}^{t} P_{ir}^{(k-1)} P_{rj}$$

$$\text{or } \Pi^{(k)} = \Pi^{(k-1)} \Pi = \Pi^{n}$$

Thus, for any time step t, the $P_{ij}^{(k)}$ gives the conditional probability that the process will be in state *j*, k steps later, given that it is in state *i* at step *t*.

If the present condition of a bridge component is known from inspection, the probability of the component deteriorating to any other condition after k time steps can be determined from the above relationship. If the initial state probabilities q_i (0) are known then the unconditional probability that the component will be in any particular state j at any particular time t can be conveniently be obtained as-

$$q_j(t) = \sum_{r=1}^{t} q_i^{(0)} P_{ij}^{(t)}$$

$$q(t) = q(0)\, \Pi^{(t)}\, \Pi = q(0)\, \Pi^{t}$$

In general, the transition probabilities will be a function of future maintenance actions on the component. For a set of feasible maintenance actions on the component, the Markov model will need transition probabilities Pij (m) on all i, j pairs and all m belonging to M.

D.4. Problems Associated with the Use of the Markov Process for a Bridge Deterioration Model

The general problems associated with this approach as used currently in USA and Europe are discussed below:

- A number of classes of components (e.g. neoprene bearing or post-tensioned T-girders, full penetration butt-welds in the tensile zones) are to be predetermined (UK has only 20+, whilst USA has 100 +), and as a consequence the common grouping for a particular bridge component for a stock of bridges implies that the condition states and probabilities are updated for all the bridges in the group at one time, based on the data from a single sample inspection.
- There are also uncertainties arising from the 'imprecise' nature of the condition points in describing the deteriorated condition of a component and the subjective judgement of the inspector which are not taken into consideration. Care is called for in employing the Bayesian updating technique based on the inspection records for a type of component in the bridge stock. The distributions used in the updating of the transition probabilities need careful development and thought[25].
- The Markov approach having the problems as described above is at best a crude model and it would be more appropriate in the long-term to refine it by defining the condition states and transition probabilities associated, in an explicit manner-bridge-wise, for each element of the bridge.
- As such, the definition of the *'condition states'* need to be changed from the present subjective scale of 1 to 5 to one associated with a scale of reading from NDT tests appropriate to the predominating deterioration mechanism present in the component. Although, no allowance is made for the possible correlation between different deterioration mechanisms, this correlation is difficult to incorporate rationally even in the condition ratings. Furthermore, it is likely that for a given component, a particular type of deterioration will tend to predominate.
- For very important causeways/bridges, the last two issues are important as any element in the bridge is likely to be built to a better quality with better craftsmanship and quality control than in a minor bridge in which the same element type can also exist. It is obvious that to update the state and probabilities from an inspection on a minor bridge would be very inappropriate for a strategically important bridge even though both bridges may belong to the same stock of bridges.

D.5. Recommendations for Implementing a Deterioration Model for Indian Bridges

Adopt a Markov approach to predict the rate of future deterioration in bridges. This model will be able to predict the condition of a component at some future time and identify the need for maintenance repairs. The model will form the basis of the durability module in the multi-criteria decision support system of a BMS (refer Section 10.5). This is in keeping with a whole life approach in which WLC will form the basis of the financial module in such a BMS support system.

Set-up a Working Commission charged with the formulation of a guideline. Their scope of work to be:

- To identify the class of individual bridge components. The more the components, the greater will be the accuracy in the approach. Components can be further classified into sub-components identified as belonging to a particular type of construction, particular material type, etc. Reference may be made to the existing classification used in current practices in USA and Europe.

- Derivation of transition probabilities associated with each component type as evinced in the national stock of bridges. The transition probabilities associated with each component type are updated annually for all such components in a given stock of bridges on the basis of inspections. Whereas, the conditional probabilities that form the elements of the transition matrix are fixed in time at t=0, they may in future be allowed to vary in time. Furthermore, the use of Bayesian inference techniques to update the transition probabilities associated with each component type based on sample inspections, need well judged development, as pointed out in Section A.4.

- To formulate a scale to rate the condition states of a given component and to provide a rational basis to deal with the future refinements as pointed out under Section B.4. It is thought better to relate the scale of condition states directly to ranges of readings given by Non-Destructive Tests and/or partially destructive test results. Such inspections involving testing can be done in accordance with the time scale as set down in[3] and the transition probabilities updated at that time. However, the relative importance of the same component type could vary between a major and a minor bridge and there is bound to be variation in the state of deterioration due to differing standards of workmanship and quality evidenced from bridge-to-bridge. In the long-term, the transition probabilities and the condition state scale should be updated for each component of each bridge in the national bridge stock. With increasing computer and communication sophistication these actions can be effectively logged and easily accessed for reference.

Appendix-E

GLOSSARY OF TERMS

The following define the various terms used in Whole Life Costing of projects. Not all of them have a reference in the text. However, the vocabulary is universal, and therefore is listed.

Annual equivalent cost	:	The discounted life cycle costs converted to the uniform amount which would pay-off these costs over the study period.
Annuity	:	A series of equal payments of receipts to be paid or received annually.
Asset life cycle	:	The life cycle of an asset from conception to major rehabilitation, disposal or replacement.
Cost to benefit ratio (CBR)	:	The ratio of a project's discounted net benefits to initial costs.
Capital expenditure	:	Expenditure for the acquiring of fixed assets.
Cost of capital	:	The annual cost to a company of raising long-term finance.
Debt finance	:	A company's long-term borrowings (defined as those borrowings which do not have to be repaid in less than one year).
Depreciation	:	An accounting device that distributes the monetary value (less residual value) of a fixed asset over the estimated years of productive or useful life it is a process of allocation, not valuation.
Direct costs	:	Those costs related directly to the acquisition, ownership, operation, maintenance and disposal of the asset itself.
Discount factor	:	The factor for any specific rate that translates expected cost or benefit in any specific future year into its present value. The discount factor is equal to 1/(1+r) where r is the discount.
Discount rate	:	The minimum acceptable rate of return for the company. The discount rate normally equals the Company's Weighted Average Cost of Capital (WACC) adjusted to specific project risk.
Discounted cash flow	:	A technique to reduce all cash flows to their present value by multiplying them by an approximate discount factor. This technique is used to calculate NPV and present cost.
Economic life	:	The period until economic obsolescence of an asset dictates replacement with a lower cost alternative.

Equity : The shareholders' funds in a company (share capital plus retained profits).

Financial gearing : The ratio of a company's long-term debt to capital employed.

Fixed asset : A resource with a relatively long service life acquired for use in producing other goods and services.

Functional life : The period over which the need for an asset is anticipated.

Indirect costs : The consequential costs of acquiring, owning, operating or disposing of an asset (such as, the cost of hiring standby equipment when an installation fails)

Internal rate of return(IRR) : That discount rate which gives an NPV which is exactly zero, so that the project's discounted net benefit equals the initial cost.

Legal life : The period until legal requirement dictates replacement of an asset.

Life cycle costing : A technique which takes into account all the lifetime costs of acquiring, owning, operating, maintaining, and disposing of an asset, with these costs reduced to a common base called the present cost.

Monetary costs : Costs which involve the owner or operator of an asset in making cash payments.

Net present value (NPV) : The sum of the discounted life cycle monetary benefits less costs monetary of an asset. It is the sum of money which would need to be set aside today to meet all the eventual costs both present and future.

Nominal terms : All future costs and prices are estimated at their future (nominal) values, i..e. including inflation.

Non-monetary costs : Economic costs to society in general arising from the ownership of operation of an asset by a company, such as, the cost of traffic delays when widening a road.

Payback period : The time it takes the revenue resulting from an investment pays back the cost involved. A simple payback period does not consider the time value of money. A discounted payback period does.

Physical life : The period over which the asset may be expected to last physically.

Probability analysis : An analysis to see how the outcome of a forecast is affected by risk.

Real terms	:	All future costs and prices are estimated at their present day (real) values, i.e. excluding inflation.
Reducing balance depreciation	:	A technique of depreciating an asset at a fixed percentage of its depreciated value each year.
Residual value	:	The value of an asset at the end of the study period.
Revenue expenditure	:	All expenditure concerned with the day-to-day running and operations of a Company, other than capital expenditure.
Risk	:	The name given to an outcome whose probability of occurrence is known.
Saving to investment ratio (SIR)	:	The ratio of the discounted net savings generated by a project to the initial costs.
Sensitivity analysis	:	An analysis which attempts to discern the sensitivity of a forecast to variations in the critical underpinning assumptions.
Service life	:	The life of a asset until its functional, physical, technological, economic, social and legal life (whichever is sooner) dictates replacement.
Social life	:	The period until human desire dictates replacement of an asset.
Straight line depreciation	:	A technique for depreciating an asset at a fixed percentage of its capital cost each year.
Study period	:	The period over which the cycle costs are under consideration from year 0 to year N.
Sunk cost	:	A cost which has already been incurred and which should not be considered in future decision making.
Technological life	:	The period untill technological obsolescence dictates replacement of an asset due to the development of a technologically superior alternative.
Time horizon	:	The number of years until the end of the study period (year N).
Uncertainty	:	The name given to an outcome whose probability of occurrence is unknown.
Weighted average cost of capital (WACC)	:	A company's cost of capital weighted in proportion to the respective market values of its debt and equity.
Weighted evaluation technique	:	A technique to assist in making complex decisions by subjectively weighting the decision making criteria.

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