Whole of life cycle cost analysis in bridge rehabilitation

Report 2002-005-C-03

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Executive Summary

The report presents a methodology for whole of life cycle cost analysis of alternative treatment options for bridge structures, which require rehabilitation. The methodology has been developed after a review of current methods and establishing that a life cycle analysis based on a probabilistic risk approach has many advantages including the essential ability to consider variability of input parameters.

The input parameters for the analysis are identified as initial cost, maintenance, monitoring and repair cost, user cost and failure cost. The methodology utilizes the advanced simulation technique of Monte Carlo simulation to combine a number of probability distributions to establish the distribution of whole of life cycle cost.

In performing the simulation, the need for a powerful software package, which would work with spreadsheet program, has been identified. After exploring several products on the market, @RISK software has been selected for the simulation. In conclusion, the report presents a typical decision making scenario considering two alternative treatment options.

1 Introduction

In Australia, over 60% of bridges for local roads are over 50 years old and approximately 55% of highway bridges are over 20 years old (Stewart 2001). Structural deterioration increases with the age of the bridge structure due to corrosion, fatigue, wear and tear and other methods of material deterioration. At the same time loads, vehicles and legal load limits for bridges have been increasing. When the ageing bridge structures are subjected to these kinds of excessive loads, then the structural capability of it reduces. Therefore, a method to satisfy the ever-increasing loads and traffic has to be found for a particular deteriorated bridge.

Brige performance can be expressed in terms of reliability. In the bridge assement procedure, the reliability of the bridge can be compared against an acceptable limit of the reliability. If the current reliability index is greater than the minimum acceptable limit then the bridge needs to be repaired. However, the calculation of the acceptable reliability index is extensive and time consuming. Therefore it has been decided that the most suitable approaches for bridge rehabilitation assessment are, estimating the cost effectiveness of the rehabilitation method and risk ranking. This report aims at selecting the optimal rehabilitation method for a deteriorated bridge using the life cycle cost analysis.

1.1 Economic Analysis

It is now necessary to evaluate each of the options available to an asset manager and select the best or the optimal option. There are several economic tools available for evaluation of the options. Benefit Cost Analysis (BCA) is applied for road projects because of two reasons as shown by Austroads (1996).

There is no market for road space where consumers can give their preferences,

It is impossible or very costly to charge users for all the effects of road use.

There are a number of criteria defined for the economic evaluation of road/bridge projects. They are discussed here in brief and finally the best criteria for the particular bridge rehabilitation has been selected and discussed in detail in the next section.

1.1.1 Benefit Cost Ratio (BCR)

Austroads (1996) recommends the following formula for the benefit cost ratio.

$$\frac{\textbf{Discounted community (user + non-user) benefits}}{\textbf{Change in discounted Road Transport and Traffic Authority lifecycle (capital and maintenance) costs}}$$

Special attention should be paid for the situations where changes in lifecycle costs are small (eg. Maintenance only options where the increase in cost due to implementation of the option is smaller). In such a situation net present value will be a more appropriate method.

1.1.2 Net Present Value (NPV)

Net present value is defined as discounted benefits (user + non-user) – discounted Road Transport and Traffic Authority costs of the project over the total life of the structure. NPV is popular among economists because it gives a direct measure of benefits and avoids the possible distortions of the BCR ratio. However, it does not imply the rate of return of the project (i.e. Intensity of benefits per unit agency cost). As shown by an example in Austroads (1996), using NPV is favorable in larger projects where BCR gives the same value for several available options.

1.1.3 Net Present Value per dollar Investment (NPVI)

This is defined in Austroads (1996) as follows:

$$\frac{\textbf{Discounted life cycle benefits – discounted capital and maintenance costs}}{\textbf{Discounted capital costs}}$$

NPVI has the same advantages and disadvantages as BCR. However it is favorable in situations where capitals costs are funded by other sources.

1.1.4 Internal Rate of Return (IRR)

Internal rate of return is the interest rate received for an investment consisting of payments (negative values) and income (positive values) that occur at regular periods. It is expressed as a percentage per annum. IRR is closely related to the NPV. IRR is the rate used in discounting total benefits and costs in such a way that both are the same. Therefore IRR is the interest rate corresponding to a 0 (zero) net present value. However IRR always does not give a mathematical solution and is not a stand alone economic assessment in a whole of life cycle cost analysis.

1.1.5 First Year Rate of Return (FYRR)

This is defined in Austroads (1996) as follows:

$$\frac{\textbf{Discounted benefits in the first operating year}}{\textbf{Discounted capital and first year maintenance costs}}$$

This criterion is used in assessing the optimal project staging. It determines whether the net benefits of a project can be increased if the project implementation is performed earlier or later than the expected day of implementation.

1.1.6 Selecting the best ranking criterion

In this particular project, the optimal rehabilitation method for the bridges has to be ranked using one of the above explained selection criteria. If the deteriorated bridge is to be rehabilitated then the future benefits of that bridge will be the same for all the alternatives. Therefore, the “cost” is the prime deciding factor in making a decision in selecting a particular rehabilitation scheme. Whole Life cycle cost analysis (WLCCA) is an evaluation method, which uses an economic analysis technique that allows comparison of investment alternatives having different cost streams. WLCCA evaluates each alternative by estimating the costs and timing of the cost over a selected analysis period and converting these costs to economically comparable values considering time-value of money over predicted whole of life cycle.

There can be risks arising from the rehabilitation of a deteriorated bridge structure. These risks can be different for different rehabilitation method. Therefore, both optimal life cycle cost analysis and risk ranking analysis offer the basis for the rehabilitation of bridge structures.

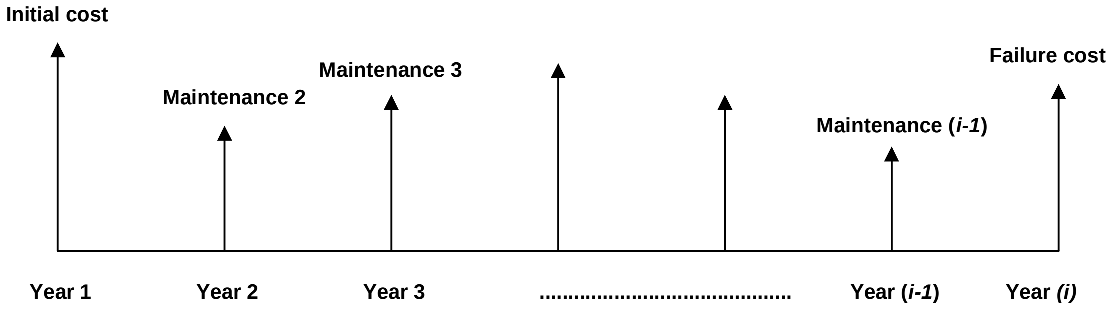
2 Life cycle cost analysis

In a bridge rehabilitation program, there are a number of costs and benefits involved from time to time. In selecting an optimal rehabilitation method, it is necessary to consider not only the initial rehabilitation costs but also the costs associated with essential maintenance and expected failure. Making a decision for the rehabilitation method will be found by minimizing the life cycle costs. Such a decision analysis is referred as a whole of life cycle costing, cost-benefit or cost-benefit-risk analysis. Life cycle costs will assess the cost effectiveness of design decisions, quality of construction or inspection, maintenance and repair strategies (Stewart 2001). The costs associated in a rehabilitation project may initially include:

- Initial cost
- Maintenance, monitoring and repair cost
- Costs associated with traffic delays or reduced travel time (Extra user cost)
- Failure cost

As shown by Austroads (1996), all of these costs are valued in resource cost terms (ie. Market prices + subsidies - taxes). ARRB Transport Research Ltd provides annual updates of resource vehicle operating and time costs. These will be discussed in detail in a subsequent section. For simplicity, if monitoring, repair, extra user cost are considered as the maintenance cost then the cash flow for any rehabilitation method can be sown as in Figure 2-1.

Figure 2-1: Cash flow for the rehabilitation of bridge



In order to be able to add and compare cash flows, these costs should be made time equivalent. It can be presented in several different ways, but the most commonly used indicator in road asset management is the Net Present Value (NPV) of the rehabilitation option. The Life Cycle Cost Analysis (LCCA) method converts all the costs to present values by discounting them to a common time, usually the base date. The present value analysis has to be considered together with Internal Rate of Return (IRR).

There are several parameters to be considered in the present value analysis.

2.1 Study period

The study period begins with the base date, that is the date to which all cash flows are discounted. Because the cost of each alternative rehabilitation strategy can be compared reasonably, only if the benefits gained are the same, the alternatives should be compared over the same operational time period which is known as study period. As a rule of thumb, the analysis period should be long enough to incorporate all or significant component of each alternative's life cycle including one rehabilitation in each alternative. Generally, study period or the evaluation period is based on the economic life of major assets in the project. For bridges, the study period is normally longer than the pavements (more than 40 years). Assets with economic life longer than the evaluation period should be given a residual value (resale value).

2.2 Residual value

This is the net worth of a bridge structure at the end of the LCCA study period. Unlike other future costs, a particular alternative's residual value can be positive or negative, a cost or a value.

2.3 Discount rate and inflation

The costs are incurred in a project in different times. The interest rate used to discount is a rate that reflects an investor's opportunity cost of money over time. Discount rate is defined as "the rate of interest reflecting the investor's time value of money (Mearig et al. 1999). It is the interest rate that would make an investor feel the same way if he receives a payment now or a large payment at sometime in the future. The LCCA can be performed in constant dollars or current dollars. Constant dollar analyses exclude the rate of general inflation. Current dollar analyses include the rate of general inflation in all costs, discount rates and price escalation rates. Both methods give the identical present value.

It is obvious that the discount rates are normally influenced by the economic, social and political factors. Discount rates used by various countries are different. For example Australia 4%, US 2-3%, UK Department of Transport 8%, Sweden 4% and Finland 6% (Val and Stewart 2003). The discount rates normally are updated and published. Therefore a standard discount rate can be obtained from such published data. For AUSTROADS or national work, 7% is the recommended discount rate (Austroads, 1996).

2.4 Evaluation factors

Table 2-1: Evaluation factors for the analysis

Factor	Common value
Evaluation period	40 years
Price year	Current year
Discount rate	4-7%
Residual value	If the useful life of the asset exceeds the evaluation period an allowance should be made for the residual value. For projects with 30 year evaluation period this is taken as zero (Austroads, 1996)

2.5 Formulation of whole of life cycle cost

Objective function for the optimal bridge rehabilitation can be formulated as the maximization of,

$W = B_{\text{lifecycle}} - C_{\text{lifecycle}}$

Where $B_{lifecycle}$ is the benefit which can be gained from the existence of the bridge after rehabilitation and $C_{lifecycle}$ is the cost associated with the bridge during its whole life. Since the benefit from the bridge will be the same irrespective of the rehabilitation method considered, it is possible to consider only the cost component. Therefore the new objective function will be the minimization of the total cost during its whole life cycle subjected to reliability and other constraints.

Minimize $W = C_{lifecycle}$

From the first part of Section 2, $C_{lifecycle}$ can be estimated as,

$C_{lifecycle} = C_{\text{initial}} + C_{\text{repair}} + C_{\text{user}} + C_{\text{failure}}$

When all these input costs are defined it is straightforward to calculate the present value of them. However all the input costs have a high degree of uncertainty. In order to deal with such uncertainties it is necessary to include the probabilistic behaviour of the input costs. In the following sub sections all these cost components have been discussed in detail.

2.5.1 Modeling of the initial cost

Initial rehabilitation cost will include preliminary design cost, start up costs, material cost and labor cost (supervisors, skilled and unskilled). All these costs will incur in the base time of the project. Therefore the calculation of initial cost component is straight forward.

2.5.2 Modeling of the maintenance (repair) cost

Modeling of the future maintenance cost is complicated. Thoft-Christensen (2000) divided this cost into three categories namely, functional repair cost $C_1(t_{r,i})$, fixed repair cost $C_2(t_{r,i})$, and unit dependent repair cost $C_3(t_{r,i})$, if a repair is to be taken place at the time $t_{r,i}$. r is the discount rate and i is the number of occurrence of repair. Therefore the corresponding maintenance cost is defined by Thoft-Christensen (2000) as,

$$C_{ma\,\mathrm{int}\,enance}(t_{r,i}) = C_1(t_{r,i}) + C_2(t_{r,i}) + C_3(t_{r,i})$$

The expected repair cost discounted to the time $t=0$ is the summation of the single repair cost.

$$C_{repair} = \sum_{i=1}^{n} \left(1 - P_f(t_{r,i})\right) C_{ma\,\mathrm{int}\,enance}(t_{r,i}) \frac{1}{(1+r)^{t_{r,i}}}$$

where n is the number of failures during the life cycle of the bridge and P_f is the updated failure probability at each repair time.

2.5.3 Modeling of user cost

User cost may be of two folds, during initial rehabilitation and during the next periodic inspection, maintenance or repair. User cost may be calculated in terms of costs associated with traffic delay, and in case of using alternate routes wear and tear of user vehicle. The expected user cost may be formulated as,

$$C_{user} = \sum_{i=1}^{n} C_{user}(t_{r,i}) \frac{1}{(1+r)^{t_{r,i}}}$$

2.5.4 Modeling of the failure costs

Expected cost of failure needs to be consider in the life cycle cost of structure in order to make a decision about a cost-effective solution with risk of failure included. Due to uncertainties associated with structural properties, loads and environmental conditions the cost of failure is a random variable. This expected failure cost is included in the life cycle cost criterion based on Neumann-Morgenston (Von Neumann and Morgenston 1944) decision theory under the assumption that utilities are express in monetary values. Failure of different alternatives may occur at different times so in order to obtain consistent results costs of failure are discounted to a present value. (Val and Stewart 2004)

$$C_F(T) = \frac{c_F}{(1+r)^t}$$

where c_F is the cost of failure set at the time of decision making, t, the time of failure and r the discount rate. Structural failure events are random events with time dependant probabilities of occurrence, due to uncertainties associated with structural properties, loads and environmental conditions. It is common to consider failure at discrete points in time so that their probabilities are equal to the cumulative probability of failure over a corresponding time interval. Thus, $C_F(T)$ is a discrete random variable which at failure time t_i assumes different values, c_i ,

$$c_i = \frac{c_F}{(1+r)^{t_i}}$$

with probabilities of occurrence p_i, for a single structure, which can fail only once during T years of service, and when c_F is assumed the same for all possible failure modes, expected cost of failure is defined by Stewart et al. (2004) as,

$$E[C_F(T)] = \sum_{i=1}^{M} p_i c_i$$

where M is number of points in time at which the possibility of failure occurrence is considered. An alternative with the minimum expected life cycle cost may then be selected as the optimal alternative, which is included the risk of each alternative in monetary value.

The first step of including failure cost to the decision analysis based on probabilistic life cycle cost is to evaluate failure probabilities of a structure over its service life, which is obtained by a probabilistic time-dependant analysis of the structure taking to into account uncertainties associated with the structural properties and environmental conditions. The probability distribution of the cost of failure is then necessary to combine with the probability distribution of other variables.

For a single structure with only one possible failure during its service life the probability distribution of the cost of failure with taking into account the discount rate is

$$f(C_F) = \begin{cases} P_f(t_i) - P_f(t_{i-1}) & C_F = \dfrac{c_F}{(1+r)^{t_i}} \\ 1 - P_f(t_M) & C_F = 0 \end{cases}$$

where $P_f(t_i)$ is cumulative probability of failure at time t_i *(i=1,2,3,…,M)*, M the number of point in time at which failure may occur, $t_0 = 0$ and t_M denotes the latest possible time of failure . It is assumed that repair/replacement of a failed structure will occur immediately after the structure is inspected. The time between inspections, Δt , is define as $\Delta t = t_i - t_{i-1}$.

2.5.5 Life cycle cost

The formulation of the life cycle cost can be preformed in a spreadsheet as shown in

Figure 3-1. All the possible cost components need to be added to this spreadsheet for each and every rehabilitation option considered. Cash flows can be given as input variables for the respective year and finally the calculation of present value is performed using the built in financial function for NPV.

Figure 2-2: Spreadsheet for the LCCA calculation

Year **Costs**	**Number**	**Unit cost 1000 $**	**Total 1000 $**	**1**	**2**	**3**
Initial cost						
Preliminary design cost						
Start up cost						
Raw material cost						
FRP sheets						
Labour cost						
Supervisors and technicians						
Other skilled workers						
Unskilled workers						
Maintenance cost						
Inspection						
Annual maintenance						
Material cost						
Labour cost						
Traffic control cost						
Repair cost						
Material cost						
Labour cost						
Traffic control cost						
User cost						
Work zone user cost						
During initial rehabilitation						
During maintenance						
Failure cost						
Probability of failure						
Cost of failure						
Damages						
Loss of life						
Injury						
Total						

Sensitivity analysis

Discount rate

Discount rate (%)	**NPV ($)**	**IRR (%)**
4		

Initial cost

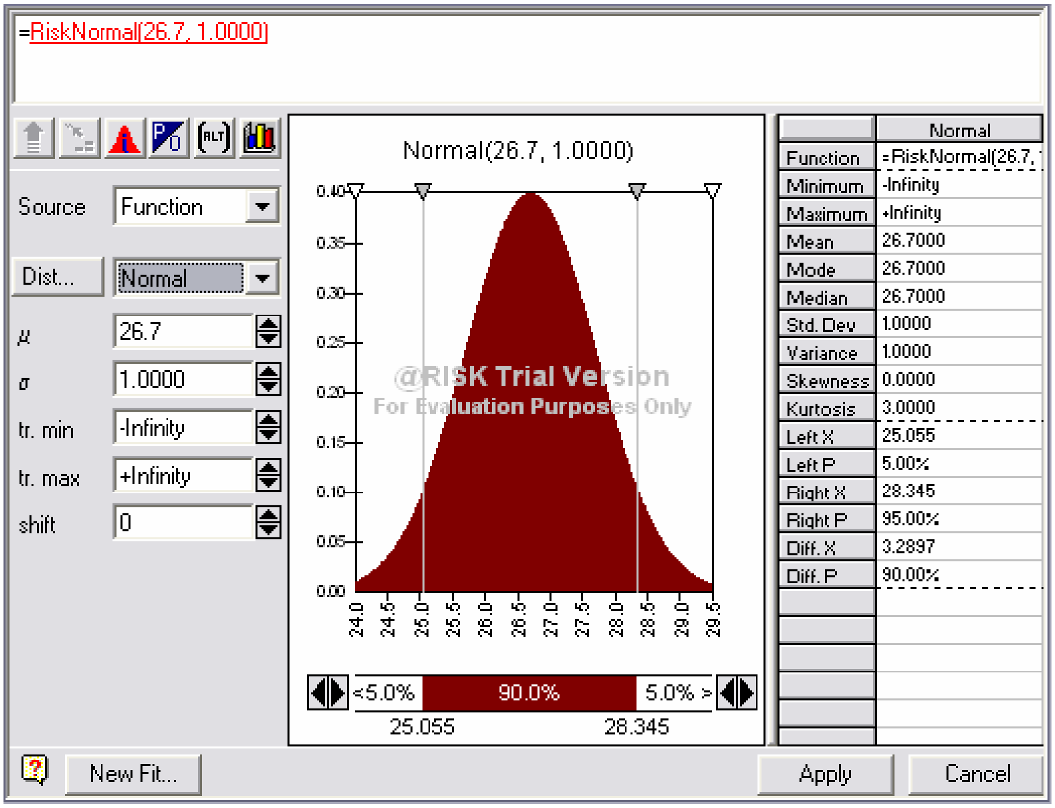
Initial cost (%)	**NPV ($)**
75	
100	
125	

Road usage

Road usage	**NPV ($)**
High	
Medium	
Low	

The probabilistic behavior (mean and standard deviations) of any of the input cost should be entered to the respective cells of the spreadsheet in terms of the distribution function considered as shown in Figure 2-3. In this given example the most likelihood value for the cost component is given as 26.7 (× 1000) dollars and its distribution is given as normal with 26.7 as mean, 1.0 as standard deviation and 90% confidence interval.

Figure 2-3: Distribution function for cost components



=RiskNormal(26.7, 1.0000)

Source: Function
Dist...: Normal
μ: 26.7
σ: 1.0000
tr. min: -Infinity
tr. max: +Infinity
shift: 0

	Normal
Function	=RiskNormal(26.7,
Minimum	-Infinity
Maximum	+Infinity
Mean	26.7000
Mode	26.7000
Median	26.7000
Std. Dev	1.0000
Variance	1.0000
Skewness	0.0000
Kurtosis	3.0000
Left X	25.055
Left P	5.00%
Right X	28.345
Right P	95.00%
Diff. X	3.2897
Diff. P	90.00%

In a similar way each cost component can be given as input parameters and include the probabilistic behavior as shown in Figure 2-3.

Eventually the decision analysis should be subjected to a sensitivity analysis to make sure that the decision is not unreasonably affected due to the uncertainties of the costs associated.

3 Evaluating the options

3.1 Identifying the options

Once the deficiency of the bridge is decided, the treatment options need to be considered. The range of options vary depending on the nature of the problem. Options available for treating deficient bridge structures have been expanded over the years with new developments in materials and structural technology. A range of options which can be considered in such a situation is given below:

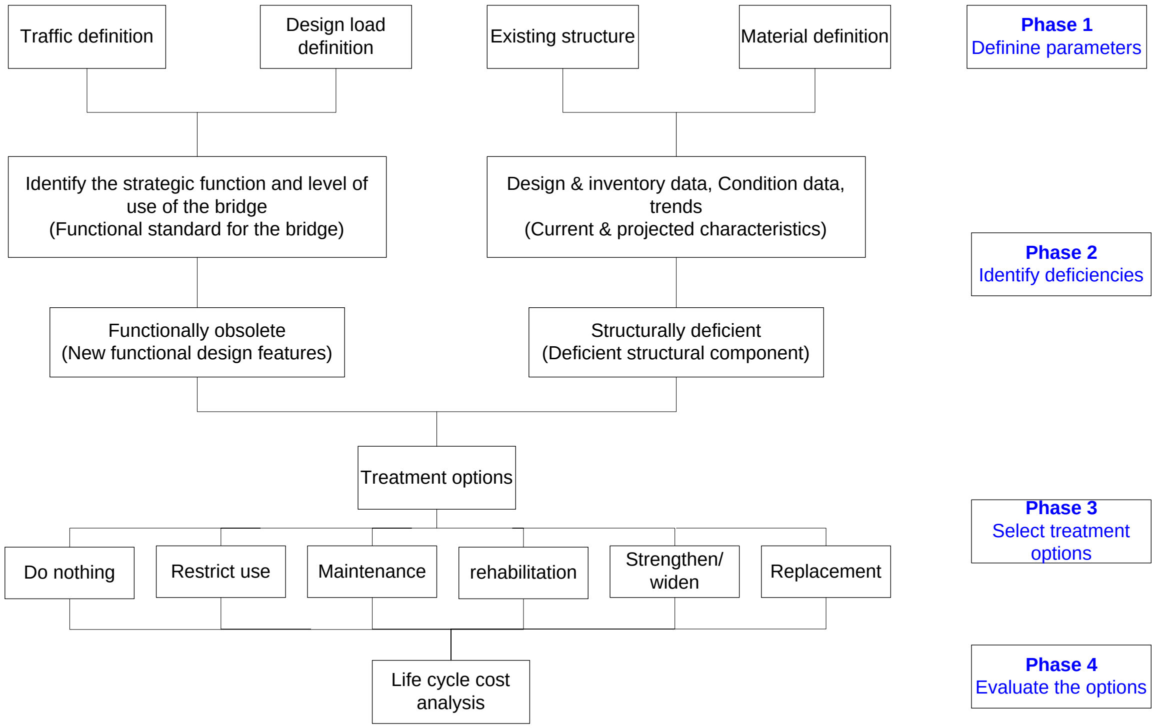
- No action
- Restrict use
- Maintain and monitor

- Rehabilitate
- Strengthen/widen
- Replace super-structure
- Replace entire bridge

These options need to be investigated using the cost effectiveness and the risk involved in the service life of the bridge. The overall structure of selecting a rehabilitation method for a particular bridge is summarized in

Figure 3-1.

Figure 3-1: Flow-chart for the rehabilitation of bridge structures



4 Data needed to establish the input parameters for the LCCA

All the costs and parameters considered here are highly uncertain. Therefore each and every term is discussed here in detail as to how the probabilistic nature of each parameter can be included in the analysis.

4.1 Capital cost

Capital cost for each alternative should be assessed. In a bridge rehabilitation project, capital cost will be the initial maintenance cost. It will include the material cost, labor cost, user delay costs etc.

Material costs cannot be the same for one particular time to the other. Therefore it is necessary to determine means and standard deviations of all bid items and compare them with current Queensland Department of Main Roads and contractor estimated costs.

4.2 Maintenance, monitoring and repair cost

In estimating the maintenance cost the updated failure probability in each maintenance stage needs to be known. If there are data available for the failure of each repair strategy, it is possible to evaluate the probability related to that effect.

4.3 Extra user cost

User costs vary significantly from one alternative to the other due to the different work zone requirements for the rehabilitation activities related to each alternative. User cost estimation should allow for any underlying traffic growth, and generated or diverted traffic. There are user cost models available in literature. It is necessary to review these available models and determine which one will predict the user cost with a reasonable accuracy. The suitability of the models can be explored using the data for user costs available in the road network of Queensland (if there are any).

However, the user cost has been a controversial issue. In the best practice, LCCA should include work zone user costs along with the other costs associated with the rehabilitation. In the budget of the institution which performs the rehabilitation, the normal costs will appear but not the user cost.

Costs associated with traffic delays or reduced travel time can be modeled using the duration of repair, the number of lanes closed, the total number of lanes, the marginal functional repair cost for one vehicle and roadblock costs per number of hours and lanes.

4.4 Failure cost

In estimating the failure cost, the probability of failure of a bridge structure needs to be known as shown in the previous section.

5 Sensitivity analysis

LCCA estimations should be investigated to establish sensitivity to the uncertain parameters of the analysis such as analysis period, discount rate, traffic growth rates, traffic speeds, capital costs and accident predictions.

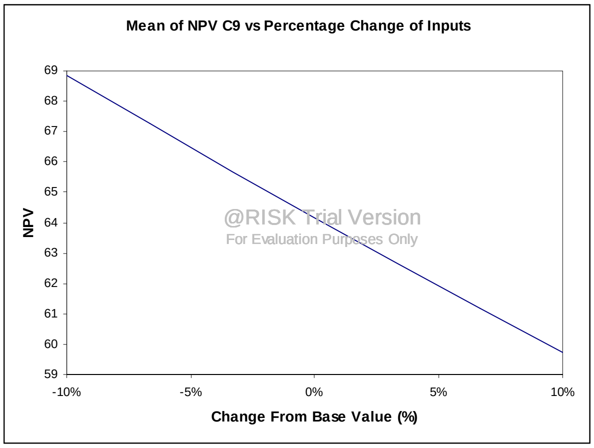
Austroads (1996) has suggested the variables and ranges for a road project as shown in Table 5-1.

Table 5-1: Sensitivity tests – variables and ranges (Austroads, 1996)

Variable	Suggested minimum value	Suggested maximum value
Capital cost (final costing)	-10% of estimate	+10 to 20% of estimate
Operating and maintenance cost	-10% of estimate	+10% of estimate
Total traffic volume	-10 to 20% of estimate	+10 to 20% of estimate
Normal traffic growth rate	-2% pa (absolute) of the forecast rate	+2% pa (absolute) of the forecast rate
Traffic generated or diverted by project	-50% of estimate	50% of estimate
Traffic speed changes	-25% of estimated change in speed	+25% of estimated change in speed
Accident changes	-50% of estimated change	+50% of estimated change

A probabilistic LCCA performed using an appropriate simulation software should have the capability of presenting the impact of uncertain model parameters on the final result. Figure 5-1 gives a typical result.

Figure 5-1: Sensitivity analysis of NPV for a % change of input cost



6 Risk analysis

Most of the analytical models use input variables as discrete fixed values. They are considered to be certain in such situations. However, normally the majority of the input variables are uncertain. Therefore many of the input variables in the LCCA are uncertain for a particular project. Uncertainty may be the result of the assumptions, estimates and projections made in the analysis. For example time to first rehabilitation may occur in a range of years, the bid cost of the materials is not fixed and discount rate can be varying (Darter and Smith). Therefore the resulting mean LCCA value is always probability based. As a result there is a risk involved in calculating LCCA value for any of the rehabilitation method. As shown by Darter and Smith it is necessary to include a risk analysis or risk ranking in any LCCA calculation. Table 6-1 shows the LCCA input variables and the general method of initializing them (FHWA, 1998).

Table 6-1: LCCA input variables

LCCA component	Input variable	Source
Initial and future costs	Preliminary engineering	Estimate
	Construction	Estimate
	Maintenance	Assumption
Timing of costs	Bridge performance	Projection
User costs	Current traffic	Estimate
	Future traffic	Projection
	Hourly demand	Estimate
	Vehicle distributions	Estimate
	Dollar value of delay time	Assumption
	Work zone configuration	Assumption
	Work zone hours of operation	Assumption
	Work zone duration	Assumption
	Work zone activity years	Projection
	Crash rates	Estimate
	Crash cost rates	Assumptions
NPV	Discount rate	Assumption

Risk ranking can be used to compare the relative risks of various alternatives. This can be done using the deterioration rates, relative frequency of over load, costs of failure, cost and efficiency of repair strategies etc (Stewart et al. 2000). The traffic delays or the reduced travel time depends on the traffic volume. Therefore expected cost of failure is a more meaningful measure for the risk ranking. Thoft-Christensen (2000) defined the risk for a failure mode as the product of the failure cost and the probability associated with that. Damage cost and costs associated with loss of life and injury can be considered as the cost of failure. Cost of failure must be discounted to a present value. The probability associated with the failure is related to structural reliability. In this approach, the reliabilities for each option of rehabilitation can be ranked from higher risk to lower risk and a decision of selecting the optimal rehabilitation method can be based on both life cycle cost analysis and risk ranking.

It has been proposed by Thoft-Christensen (2000) that for a bridge rehabilitation program, a risk based structural optimization is more suitable than reliability based optimization.

6.1 Software used in this analysis

Risk analysis approach is calculation intensive. However this approach can be incorporated into deterministic approach using user-friendly software. There are a number of software available for the risk analysis in a LCCA estimation project. Risk analysis software can be stand alone programs (Microsoft Visual Basic, C++ etc.) or simple add-ins to spreadsheets such as Microsoft Excel or Lotus. Darter and Smith used Crystal Ball risk analysis software together with a LCCA spreadsheet in the probabilistic-based LCCA estimation. The mean and standard deviations of the inputs can be entered into the spreadsheet and a simulation can be performed. Frequency distribution of the predicted LCCs of each alternative and some LCC statistics (mean, standard deviation, coefficient of variability, range) are illustrated as the outputs (Darter and Smith).

It was decided to explore the risk analysis in a spreadsheet environment because of the flexibility of having a wide variety of problems and spreadsheets are easily understood. @RISK, Crystal Ball, Evolver and Anthil softwares have been investigated as the possible options for selecting software for this analysis. In this project it was decided to use @RISK 4.5 software Professional version in Microsoft Excel spreadsheets. In @RISk software it is possible to continue the calculations in a spreadsheet and a sensitivity analysis can be performed using a Monte Carlo Simulation.

6.2 Structural reliability

The reliabilities of bridge structures cannot be directly decided based on the observations of failures or other experimental studies. In such situations reliability calculations are based on predictive models and probabilistic models. As shown by Stewart (2001), when the load effect (S) exceeds the resistance (R), the failure of structural element occurs. Therefore reliability can be expressed as the probability of failure (pf) as follows,

$$p_f = \Pr(R \leq S) = \Pr(R - S \leq 0) = \Pr(G(R,S) \leq 0) = \int_0^{\infty} F_R(r)\, f_s(r)\, dr$$

where G(R,S) is the “limit state function” and FR(r) is the cumulative probability density function of the resistance. Limit states normally selected for reliability analysis are:

Ultimate limit state – flexural failure, shear failure, collapse

Serviceability limit state – cracking, durability, deflection, vibration

6.2.1 Reliability distributions

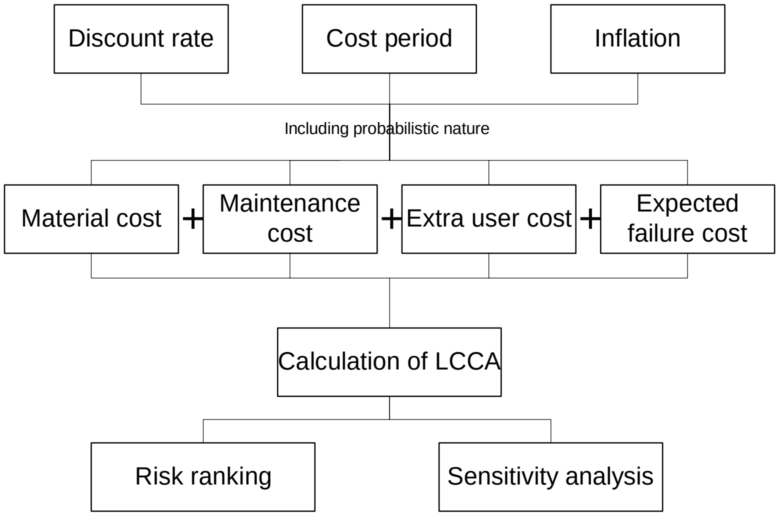
A group of bridges has to be considered from the Department of Main Roads in order to find a number of distributions for reliability based optimal design for bridge rehabilitation. Thoft-Christensen (2000) reported a lognormal distribution for the initial reliability, weibull distribution for the corrosion initiation time and a uniform distribution for the deterioration rate. Similar kind of distributions may need to be established for this particular project using the existing data. Finally optimal rehabilitation strategy can be selected based on such distributions.

Probabilistic life cycle costing together with the risk ranking offers prominent improvements in selecting the most suitable rehabilitation strategy. This approach is superior to the deterministic approach used in traditional bridge management systems.

7 Decision support tool for selecting the optimal rehabilitation strategy

The basic steps involved in the LCCA estimation are shown in Figure 7-1.

Figure 7-1: Flow-chart for the LCCA estimation

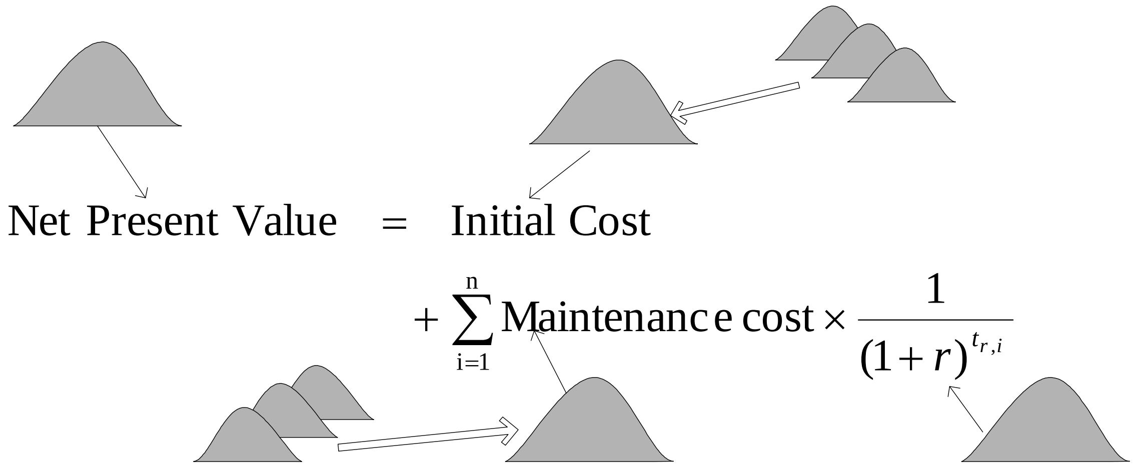


8 Procedure in WLCCA

Two treatment options have been selected to study the probabilistic-based risk analysis approach to LCCA in the rehabilitation of the deteriorated Tenthill Creek Bridge in Queensland. These prospective options are strengthening the bridge using FRP composites and using post tensioning.

Figure 8-1 shows the NPV formula as an economic indicator in analyzing the rehabilitations options for the selected bridge. Risk analysis approach uses random samples from the probability based uncertain input variables (initial cost, future cost, discount rate and year of rehabilitation) to generate probabilistic description of the output result, NPV. Using Monte Carlo Simulation it is possible to select thousands of samples from each input distribution and generate the output result (NPV) for a separate *what-if* scenario. The results calculated from each what-if scenario can be saved and further statistical analysis can be performed. As a result, risk analysis results can be illustrated in the form of probability distributions. It shows a range of possible outcomes and the weight of its occurrence as well. This is necessary in making a consensus decision.

Figure 8-1: Probability distributions in Net Present Value calculations



$$\text{Net Present Value} = \text{Initial Cost} + \sum_{i=1}^{n} \text{Maintenance cost} \times \frac{1}{(1+r)^{t_{r,i}}}$$

r = discount rate
$t_{r,i}$ = year of maintenance
n = number of maintenance

General procedure in conducting a risk analysis can be summarized as follows (FHWA, 1998):

- Identify structure and logic of problem
- Include uncertainty using probability
- Perform simulation
- Analyze and interpret results
- Make an informed decision

In the next section the procedure has been illustrated by using a bridge rehabilitation in Queensland.

8.1 Problem description

Queensland Department of Main Roads is considering two alternatives for the bridge rehabilitation. Using FRP composites and post tensioning as the method of strengthening is considered as "alternative A" and "alternative B" respectively. An example shown in FHWA (1998) has been used as a guideline for the analysis in this report. The study period is 40 years. The routine maintenance cost difference between the two alternatives is assumed to be negligible. User costs are ignored to make this analysis simple. Discount rate may range from 5 to 9 percent. Average and Standard deviations for the initial and rehabilitation costs are shown in

Table 8-1. They can be obtained from an analysis of recent bid records.

Table 8-1: Average and standard deviations for department costs

Cost item	Alternative A		Alternative B
	Average	Std. Dev	Deterministic
Initial cost ($ Millions)	26.5	0.75	25
Future rehabilitation cost ($ Millions)	7.0	0.5	5.0

Parameter	Alternative A			Alternative A		
	Min	Most likely	Max	Min	Most likely	Max
Initial bridge design (years)	20	25	30	17	20	23
Future rehabilitation (years)	13	15	17	8	10	12

Discount rate (%)	Min	Most likely	Max
	5	7	9

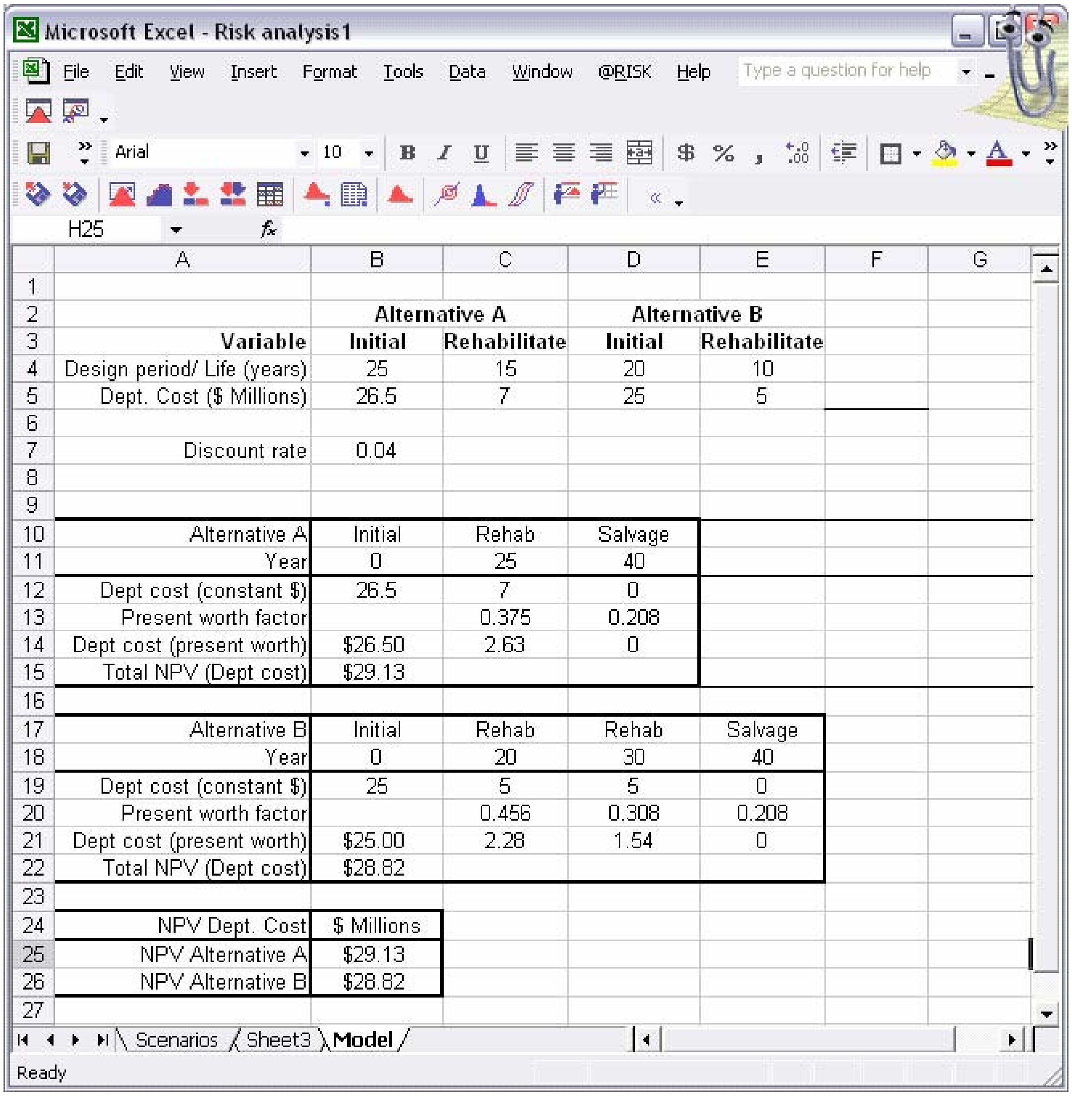
8.1.1 Identify structure and logic of problem

This involves identifying the basic elements and organizing them in an analytical model. In this example model is expressed as the formula for NPV.

$$NPV = \text{Initial Cost} + \sum \text{Future Costs} \left[\frac{1}{1+i} \right]^n$$

where *i* is the discount rate and *n* is the number of years from the base year where the future cost occurs. This model can be programmed in a spreadsheet as shown in Figure 8-2.

Figure 8-2: Model in a spreadsheet



	A	B	C	D	E	F	G
1							
2		Alternative A		Alternative B			
3	**Variable**	**Initial**	**Rehabilitate**	**Initial**	**Rehabilitate**		
4	Design period/ Life (years)	25	15	20	10		
5	Dept. Cost ($ Millions)	26.5	7	25	5		
6							
7	Discount rate	0.04					
8							
9							
10	Alternative A	Initial	Rehab	Salvage			
11	Year	0	25	40			
12	Dept cost (constant $)	26.5	7	0			
13	Present worth factor		0.375	0.208			
14	Dept cost (present worth)	$26.50	2.63	0			
15	Total NPV (Dept cost)	$29.13					
16							
17	Alternative B	Initial	Rehab	Rehab	Salvage		
18	Year	0	20	30	40		
19	Dept cost (constant $)	25	5	5	0		
20	Present worth factor		0.456	0.308	0.208		
21	Dept cost (present worth)	$25.00	2.28	1.54	0		
22	Total NPV (Dept cost)	$28.82					
23							
24	NPV Dept. Cost	$ Millions					
25	NPV Alternative A	$29.13					
26	NPV Alternative B	$28.82					
27							

8.1.2 Include uncertainty using probability

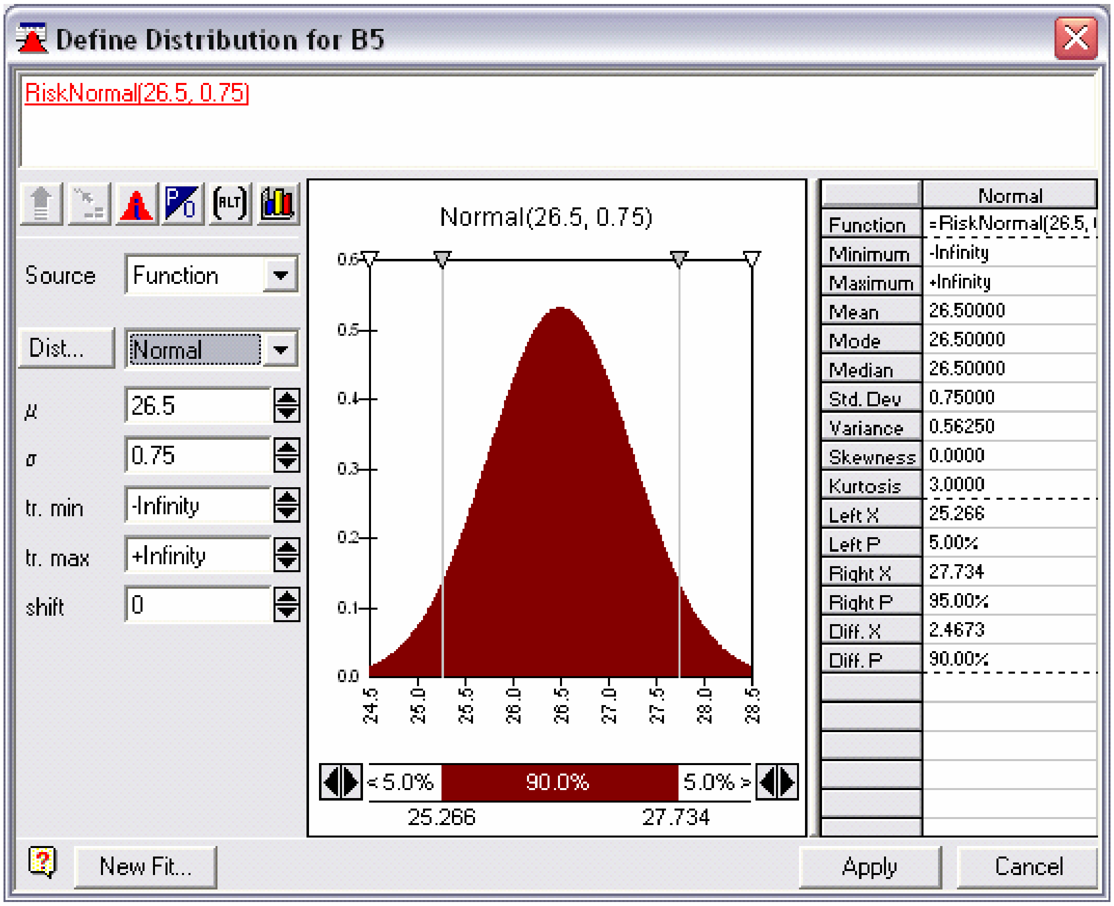
In this step probability distributions should be defined for the uncertain input variables identified in the previous step (Section 8.1.1). In probability distributions it is possible to give most likelihood value for a particular input variable and the range of values it can be given. The commonly used probability distributions for this kind of an analysis are triangular, normal, general, uniform and discrete. FHWA (1998) has used the distributions shown in Table 8-2.

Table 8-2: Summary of input distributions (FHWA 1998)

Variable	Distribution type
Initial cost	Normal
Future rehabilitation cost	Normal
Service life – initial construction	Triangular
Service life – rehabilitation	Triangular
Discount rate	triangular

Figure 8-3 shows an example of an input variable defined using a normal distribution with a mean of 26.5 and standard deviation 0.75.

Figure 8-3: Defining input variables using probability distributions



Define Distribution for B5

RiskNormal(26.5, 0.75)

Source: Function

Dist...: Normal

μ: 26.5

σ: 0.75

tr. min: -Infinity

tr. max: +Infinity

shift: 0

	Normal
Function	=RiskNormal(26.5,
Minimum	-Infinity
Maximum	+Infinity
Mean	26.50000
Mode	26.50000
Median	26.50000
Std. Dev	0.75000
Variance	0.56250
Skewness	0.0000
Kurtosis	3.0000
Left X	25.266
Left P	5.00%
Right X	27.734
Right P	95.00%
Diff. X	2.4673
Diff. P	90.00%

8.1.3 Perform simulation

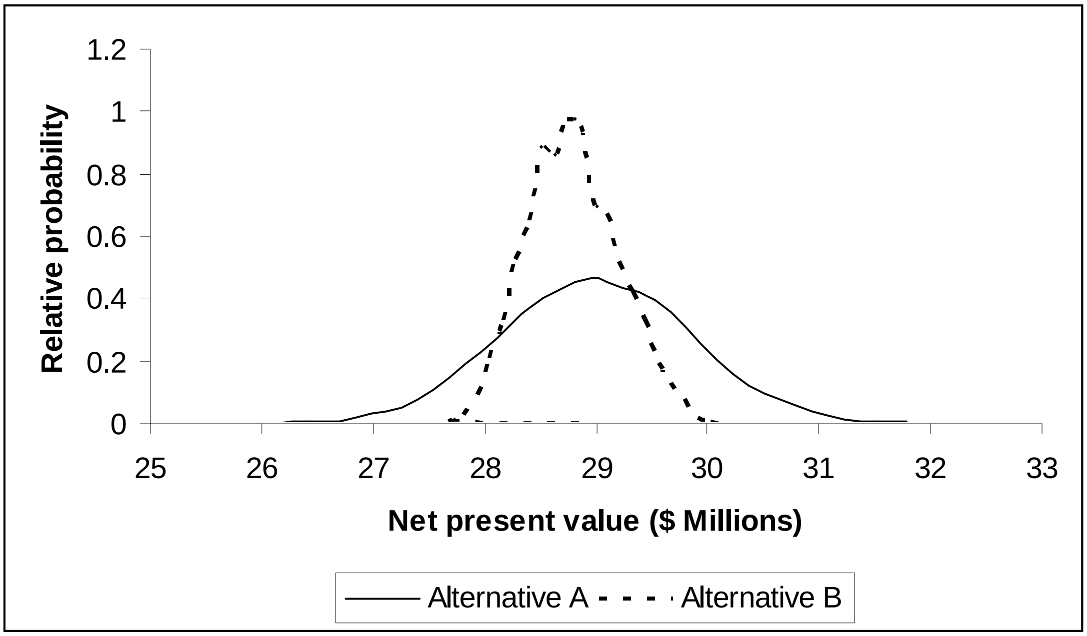
A simulation is a rigorous extension of sensitivity analysis. It selects different random sets of values from the input probability distributions and calculates discrete result for each set. It makes an array of results in form of distribution covering all possible outcomes. In @RISK software there are two simulation methods and the most commonly used method is the Monte Carlo simulation where the number of iterations can be given as an input variable by the user. Each iteration gives a possible scenario of outcome and each iteration result is captured, compiled and subjected to statistical analysis. This sampling process continues until simulation process converges. A large number of iterations may be required for the convergence.

8.1.4 Analyze and interpret results

If the analysis was performed using deterministic approach, the decision in selecting the best option would be based only on the value of the NPV of the alternatives. Alternative A – $29.15 million and Alternative B - $28.85 million. Therefore it is obvious that Alternative B will be the most economical. Since the analysis is based on probabilistic approach, interpretation of risk analysis is not just comparing NPV. It needs to compare alternatives using risk profiles.

Figure 8-4 shows the risk profile for alternatives A and B in the form of histogram. Area under each curve is the probability of occurrence and the curve shows the variability about the mean.

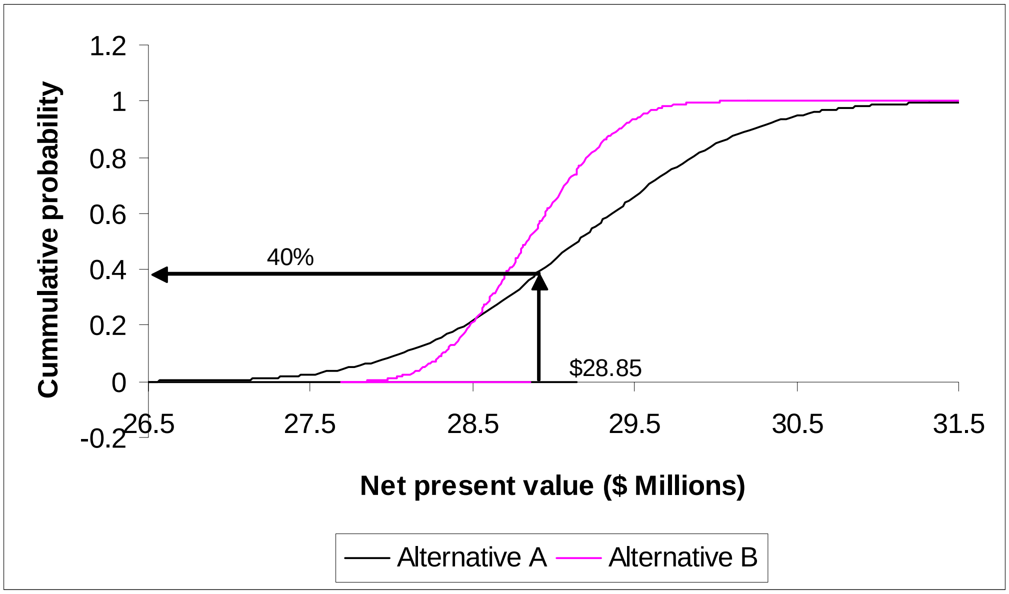
Figure 8-4: Comparing alternative in histogram form



The wider the distribution is the greater the variability. Therefore Alternative A is more uncertain than alternative B.

Figure 8-5 shows the risk profile for alternative A and B in cumulative form. There is about 40% probability that cost for alternative A is less than $28.85 (cost for alternative B). The flatter the slope is the greater the variability. Therefore Alternative A is more uncertain than alternative B

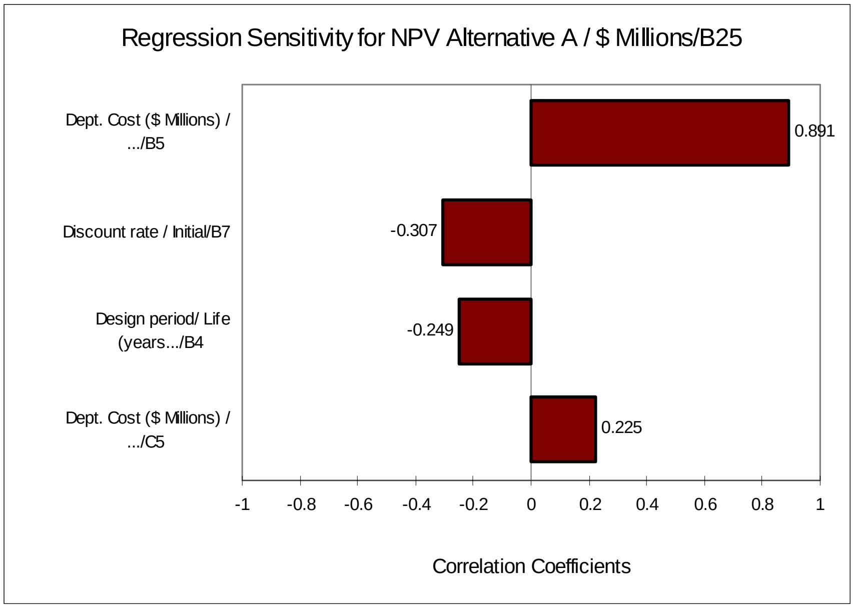
Figure 8-5: Comparing alternative in cumulative form



8.1.4.1 ***Sensitivity analysis***

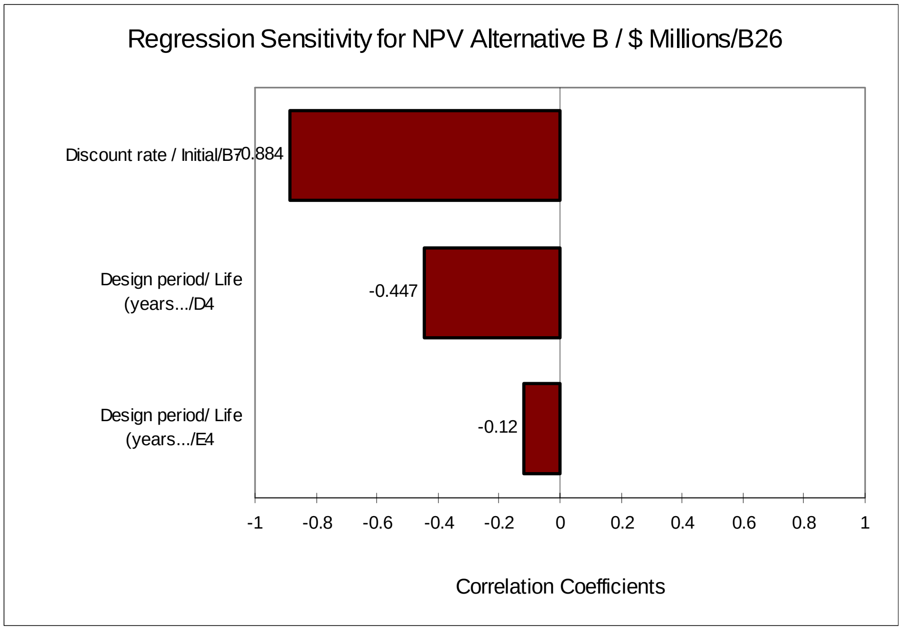
Sensitivity analysis is performed as part of risk analysis. Sensitivity analysis identifies the important input parameters when determining the output distributions. The results of this analysis are normally shown as Tornado graphs (Figure 8-6 and Figure 8-7). Initial cost for Alternative A has a correlation coefficient of 0.89 indicating: If initial cost moves one std. dev. (either direction) then NPV will move 0.89 of a std. dev in same direction

Figure 8-6: Sensitivity analysis in Tornado graph form (Alternative



A)

Figure 8-7: Sensitivity analysis in Tornado graph form (Alternative B)



The higher the correlation coefficient is the more important the input variable in determining the output result. As shown by FHWA (1998), the input variables having correlation coefficients less than 0.6 are insignificant. Therefore for alternative A, Dept cost is important while for alternative B, discount rate is the most important in the analysis.

8.1.5 Make an informed decision

In this example alternative B is better than alternative A considering the risk profiles. However it depends on the definition of the level of risk the organization can tolerate, whether small spread in possible results or greater amount of spread acceptable.

9 Summary

The LCCA of each rehabilitation alternative should include the following.

- Brief description of the rehabilitation alternative
- Brief explanation reasoning why each alternative is selected
- Description of the assumptions made during the LCCA
- Conceptual or schematic documentation indicating the design intent of the alternative
- Detailed LCCA of project alternative
- A number for the risk ranking
- A summary table that compares the total life cycle costs of all the alternatives

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