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Life-Cycle Assessment of Nebraska Bridges

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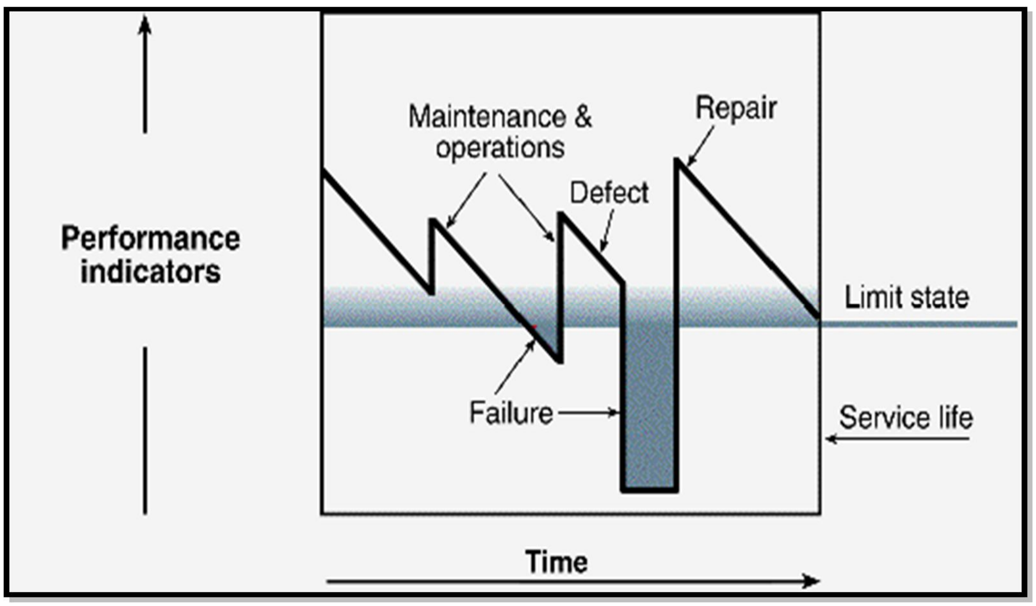
Nebraska Department of Roads (NDOR)

Project Number: SPR-P1(12) M312



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George Morcous

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12. Abstract

Life-cycle cost analysis (LCCA) is a necessary component in bridge management systems (BMSs) for assessing investment decisions and identifying the most cost-effective improvement alternatives. The LCCA helps to identify the lowest cost alternative that accomplishes project objectives by providing critical information for the overall decision-making process.

The main objective of this project is to perform LCCA for different maintenance strategies using the developed deterioration models and updated cost data for Nebraska bridges. Deterministic and probabilistic LCCA using RealCost software for deck overlay decisions, expansion joint replacement decisions, and deck widening versus deck replacement decisions are presented. For deck overlay decision, silica fume overlay, epoxy polymer overlay, and polyester overlay are compared against bare deck with respect to life cycle cost for variable structural life. In expansion joint replacement decisions, two alternatives are compared: relocating abutment expansion joints at the grade beam; and replacing abutment expansion joints at the same place. Deck widening is compared with deck replacement in five different bridges.

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ABSTRACT

Life-cycle cost analysis (LCCA) is a necessary component in bridge management systems (BMSs) for assessing investment decisions and identifying the most cost-effective improvement alternatives. The LCCA helps to identify the lowest cost alternative that accomplishes project objectives by providing critical information for the overall decision-making process.

The main objective of this project is to perform LCCA for different maintenance strategies using the developed deterioration models and updated cost data for Nebraska bridges. Deterministic and probabilistic LCCA using RealCost software for deck overlay decisions, expansion joint replacement decisions, and deck widening versus deck replacement decisions are presented. For deck overlay decision, silica fume overlay, epoxy polymer overlay, and polyester overlay are compared against bare deck with respect to life cycle cost for variable structural life. In expansion joint replacement decisions, two alternatives are compared: relocating abutment expansion joints at the grade beam; and replacing abutment expansion joints at the same place. Deck widening is compared with deck replacement in five different bridges.

ACRONYMS

AASHTO	American Association of State and Highway Transportation Officials
ADT	Average Daily Traffic
ADTT	Average Daily Truck Traffic
BCA	Benefit/Cost Analysis
BLCCA	Bridge Life-Cycle Cost Analysis
BMS	Bridge Management System
EPO	Epoxy Polymer Overlay
FHWA	Federal Highway Administration
IMS	Infrastructure Management System
LCC	Life-Cycle Cost
LCCA	Life-Cycle Cost Analysis
MR&R	Maintenance, Rehabilitation, and Replacement
NBI	National Bridge Inventory
NBIS	National Bridge Inspection Standards
NBMS	Nebraska Bridge Management System
NCHRP	National Cooperative Highway Research Program
NDOR	Nebraska Department of Roads
NPV	Net Present Value
PMS	Pavement Management System
PO	Polyester Overlay
PV	Present Value
SFO	Silica Fume Overlay
TAC	Technical Advisors Committee
TPO	Thin Polymer Overlay
USDOT	United States Department of Transportation

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1 INTRODUCTION

1.1 PROBLEM STATEMENT

According to the U.S. Department of Transportation (USDOT), life-cycle cost analysis (LCCA) is a scientific approach that provides comprehensive means to select among two or more project alternatives (USDOT 2002). LCCA is a necessary component in bridge management systems (BMSs) for assessing investment decisions and identifying the most cost-effective improvement alternatives. NCHRP project 12-43 “Life-Cycle Cost Analysis for Bridges” has resulted in standardized procedures for conducting life-cycle costing of bridges and guidelines for applying LCCA to the repair of existing bridges or the evaluation of new bridge alternatives (NCHRP 483, 2003). The steps of this process are summarized as follows:

- ✓ Establish alternatives
- ✓ Determine timing
- ✓ Estimate cost
- ✓ Compute life-cycle cost
- ✓ Analyze results

The analysis enables cost effectiveness comparison of competing design alternatives that provide benefits of differing duration and cost. LCCA accounts for relevant costs to the sponsoring agency, owner, operator of the facility, and the roadway user that will occur throughout the life of an alternative. Relevant costs include initial construction (including project support), future maintenance and rehabilitation, and user costs (time and vehicle costs). The LCCA analytical process helps to identify the relative cost effective alternatives that accomplishes the project objectives and can provide critical information for the overall decision-making process. However, in some instances the most cost effective option may not ultimately be selected after considering available budget, risk, political, and environmental concerns. Initial cost of the most cost effective alternatives is often much higher. Also, if alternatives are found to have similar life-cycle cost effectiveness, the alternative with the lower initial cost is usually preferred.

1.2 OBJECTIVE

The main objective of this project is to perform life-cycle cost analysis (LCCA) for different maintenance strategies using the developed deterioration models and updated cost data for

Nebraska bridges. The results of the LCCA will be presented in a set of examples that assist decision makers in selecting the most cost-effective improvement actions.

1.3 REPORT ORGANIZATION

The report is organized as follows: Chapter 2 presents the literature review about LCCA approaches and tools. Chapter 3 presents the cost data used in LCCA for Nebraska bridges. Chapter 4 presents the deterministic analysis for deck overlay decisions, expansion joint replacement decisions, and deck widening versus replacement decisions. Chapter 5 presents the probabilistic analysis for the same decisions presented in chapter 4. Chapter 6 summarizes the research work and its main conclusions.

2 LITERATURE REVIEW

2.1 Life-Cycle Cost (LCC)

There are two main cost groups for a complete LCCA: agency cost and user cost. Agency costs consist of maintenance, rehabilitation, and replacement (MR&R) costs. Most routine maintenance activities are performed by the agency's own workforce. Rehabilitation work consists of minor and major repair activities that may require the assistance of design engineers and are given to contractors for construction. Most rehabilitation work is deck related. Major rehabilitation activities involve work on superstructure and may involve deck replacement. The term "bridge replacement" is, on the other hand, reserved for a complete replacement of the entire bridge structure (including substructure). User costs are primarily attributable to the functional deficiency of a bridge such as a load posting, clearance restriction, and closure. These functional deficiencies may cause higher vehicle-operating costs because of such factors as detours, lost travel time, and higher accident rates (NCHRP 483, 2003).

Deciding on the priorities for carrying out the activities for MR&R of bridges is the most challenging task in bridge management. The cost of MR&R consumes most of the available funding for bridge improvements. Therefore, the budget for these activities should be carefully allocated, particularly when LCCA is considered. Setting priorities for MR&R activities is a multi-attribute decision-making problem which requires simultaneous evaluation at both the network level (i.e., which bridge to repair), and the project level (i.e., which repair strategy for a given bridge).

2.2 Review of Available LCCA Tools

A number of tools have been developed for supporting LCCA at the project level and/or network level. Most of these tools are developed in a spreadsheet environment for project level analysis, while few are database multi-module systems developed for both project and network level analysis.

2.2.1 Pontis

In 1992, the first version of Pontis (Latin for bridge) was completed under the auspices of the Federal Highway Administration (FHWA) (Thompson, 1993). The Pontis BMS is used throughout the U.S. for tracking bridge data and predicting future bridge conditions and investment needs. Pontis models bridges at an element level (e.g., the bridge deck, girders, bearings, columns, etc.) and includes deterioration and cost models for each bridge element. The system estimates initial agency costs for bridge work using a set of unit costs specified at the bridge and element level for different operating environments. The latest system predicts future agency costs using a 4^{th} degree equation to model deterioration and to determine the optimal least-cost policy for maintaining each bridge element over time.

In Pontis, the prioritization of bridges is carried out sequentially for two types of repair strategies; the first is maintenance, repair, and rehabilitation (MR&R), which improves the condition of the bridge. The second is improvement actions, which improve the level-of-service (LOS) of the bridge. All bridge projects are ranked by their incremental benefit/cost ratios, and those bridges above the budget limit are carried out. The rest of the list will be analyzed again and prioritized for future years. This procedure is repeated throughout the required analysis period. Pontis has the advantage of being the first complete software application developed for bridge management systems. However, most states use Pontis for data collection and analysis of bridge inspection and inventory data. Only few states have been able to make the currently available versions of Pontis work for bridge management purposes (AASHTO, 2002).

2.2.2 Bridge Life-Cycle Cost Analysis (BLCCA)

NCHRP Project 12-43 produced a BLCCA tool as part of a study to develop a comprehensive bridge life-cycle costing methodology (NCHRP 483, 2003). The tool can be used to compute the present value of lifecycle costs for alternative sets of bridge construction activities, including consideration of agency costs for construction and maintenance; user costs (e.g., accidents, detour costs, and travel time); and vulnerability costs (e.g., risks of damage due to earthquakes, floods, collisions, overloads, and scour). For each project alternative, users must define a sequence of events (e.g., profile of repairs and rehabilitation projects throughout the analysis period), including an indication of costs and uncertainty in their timing.

2.2.3 RealCost

In 1998, the FWHA published a guide on analyzing the life-cycle costs of pavement designs.

Subsequently, it developed RealCost as a software tool that supports its recommended approach. RealCost relies on user estimates of agency costs and predicts user costs due to work zones. It combines these costs into a life-cycle cost analysis and calculates net present value. RealCost provides a deterministic calculation and a probabilistic calculation of a project's net present value (NPV). It performs a Monte Carlo simulation to generate probability distributions for model inputs and outputs, so that users can assess levels of uncertainty (NCHRP 8-36, 2008).

2.2.4 Caltrans BCA Tool

Caltrans developed a spreadsheet tool for conducting Benefit/Cost Analysis (BCA) of its projects. The tool enables the analysis of highway and transit projects. The tool considers agency costs and a number of user cost components. However, the focus of the analytics is on modeling user costs. Users are required to manually enter agency costs by year for each project (Booz Allen et. al, 1999).

2.2.6 Priority Economic Analysis Tool (PEAT)

The Ministry of Transportation of Ontario (MTO) developed PEAT to analyze the costs and benefits of highway, bridge, and intersection projects. The tool helps answer two questions: is the project a good investment, and if so, when should it be implemented? PEAT is designed to support three levels of cost estimates, paralleling the different levels of information available at various stages of the project development process. In estimating future agency costs, the tool uses a simplified pavement deterioration model to trigger preservation work, and estimates annual minor maintenance costs based on pavement condition. For bridge projects, the tool uses estimates of future agency costs that have been developed by the MTO's bridge management system (Cambridge Systematics, 2004).

2.2.7 Washington DOT BCA Tool

The Washington State DOT has developed a BCA tool to analyze lane additions, climbing lanes, high-occupancy vehicle lanes, intersection improvements, interchange improvements, and park-and-ride facilities. The tool considers agency costs and a number of user cost components. Users are provided with default unit costs for estimating initial costs. To estimate future agency costs, users specify a single annual maintenance and operations cost (Hatem, 2007).

2.2.8 Washington Transit Life-Cycle Cost (LCC) Model

The Washington State DOT has developed an LCC tool to assist in analyzing alternative maintenance strategies for public transit vehicles and facilities. The tool helps structure estimates of initial agency costs and future agency costs for two maintenance strategies. Users enter unit costs for a number of common activities, such as tire replacement, engine repair, and brake service. They then specify the number of times these activities are required each year to estimate future agency costs (Hatem, 2007).

2.2.9 Bridgit

Bridgit is a bridge management system developed jointly in 1985 by NCHRP and by the National Engineering Technology Corporation (Hawk, 1999). It is very similar to Pontis in terms of modeling and capabilities. The advantage of Bridgit is its ability to define and distinguish between specific protections systems for components when determining feasible options. However, the disadvantage of Bridgit is the same as for Pontis since they use almost the same prioritization approach.

2.3. Discount Rate

Selecting an appropriate discount rate for public funds is not clear. The discount rate serves two purposes: to reflect the opportunity cost of money, similar to the private sector; and a method by which to quantify the benefits or dis-benefits of delaying actions. Some analysts argue that this comparison of private spending and public spending warrants public-agency use of discount rates at least as high as those used in the private sector. Others suggest that public-sector spending is a special situation that justifies low discount rates, certainly no more than the interest rate at which government can borrow funds in the open market. Government agencies must apply the guidelines issued by the Office of Management and Budget, which are updated by occasional revisions of Appendix C (NCHRP 483, 2003). As of 2011, agencies were instructed to use a current discount rate of 2.7% per annum, based on the nominal interest rate on 30-year Treasury Notes and Bonds. The office of budget and management guidelines (Circular A-94), discount rate equal to 3.0% is recommended to compute life-cycle costs. In this research project discount rate equal to 3.0% is used in LCCA.

2.4. Analysis Period

In general, the analysis period should be long enough to include at least one major rehabilitation activity for each alternative being considered (NCHRP 483, 2003). Generally, the study period or evaluation period is based on the economic life of major assets in the projects. For bridges, the study period is normally longer than pavements (more than 40 years) (Setunge et al., 2002). Chandler (2004) reported 60-year analysis period for evaluating sustainability of bridge decks. There is no specific analysis period value for bridge projects, and agencies reported that this period varied on case-by-case basis (Ozbay et al. 2004).

3 COST DATA

The main source for obtaining maintenance costs is recent bridge contracts. Nebraska Department of Roads (NDOR) has developed spreadsheets for recording the different types of maintenance work performed on bridges. The unit cost of each maintenance action can be estimated by analyzing the maintenance costs and quantities available in contract files. NDOR performed an analysis of maintenance costs and obtained a unit cost for each activity, which has been used in this study. Table 3-1 summarizes the cost of earthwork, piling, substructure, superstructure, deck, W/RRR (widen/rehab, replacement, re-deck), rails, and miscellaneous.

Table 3-1: Summary of unit cost for different bridge activities

Type	Item Code	Name	Work Description	Unit Price	Units
Earthwork	1010.00	Bank Shaping	Repair Channel	$20	CY
Earthwork	1020.00	Rock Riprap	Place Rip Rap	$44	TON
Earthwork	1030.00	Scour Mitigation	Scour Mitigation	$1	LS
Earthwork	1040.00	Erosion Repairs	Erosion Repairs	$1	LS
Piling	2010.00	Piling Repair (unspecified)	Repair Piling	$155	LF
Piling	2020.00	Timber Pile Retrofit/Splice	Timber Pile Repair	$3,000	each
Piling	2030.00	Timber Pile Jackets w/ Epoxy Grout	Timber Pile Repair	$150	LF
Piling	2040.00	Steel Sheet Piles	Place Sheet Piling	$26	SF
Sub	3010.00	Sleeper Beam in Compacted Trench		Incidental	LF
Sub	3020.00	Grade Beam on Micro-Pile		NEED TO FIGURE UNIT COST	
Sub	3030.00	Pier Repair	Repair Pier	$85	SF
Sub	3040.00	Add Concrete Diaphragm	Add Concrete Diaphragm	$15	CF
Sub	3050.00	Add Crash Walls	Add Crash Walls	$157	LF
Sub	3060.00	Abutment Repairs	Abutment Repairs	$49	SF
Sub	3065.00	Abutment Repairs ("pick relevant terms" high abutment, forming possible, excavation possible, man-lift possible, difficult access,	Abutment Repairs ("pick relevant terms" high abutment, forming possible, excavation possible, man-lift possible, difficult access,	$49	SF

		near water)	near water)		
Sub	3070.00	Remodel Abutment for Partial Turndowns	Remodel Abutment for Partial Turndowns	$200	LF along turndown (w/ skew)
Sub	3080.00	Remodel Abutment for Turndowns	Remodel Abutment for Turndowns	$400	LF along turndown (w/ skew)
Sub	3090.00	Replace Existing Abutment Turndowns	Replace Existing Abutment Turndowns	$400	LF along turndown (w/ skew)
Sub	3100.00	Remodel Wing Walls	Break back wing walls to clear bottom of approach slab	$2,000	EA
Sub	3110.00	Concrete Cap Reconstruction	Concrete Cap Reconstruction		LS
Sub	3120.00	Girder Seat Repairs	Girder Seat Repairs	$1,800	EA
Sub	3121.00	Painting Piles and Miscellaneous Steel	Painting Piles and Miscellaneous Steel	$7	SF
Super	4010.00	Girder Repairs (Major Steel)	Repair Steel Girders	$23,766	EA
Super	4020.00	Bearing Device Replacement	Replace Bearing Devices	$2,858	EA
Super	4030.00	Expansion Bearing, TFE	Replace Bearing Devices	$923	EA
Super	4040.00	Bearing Bracket (Welded Steel)	Extend and Repair Girder Seat	$2,500	EA
Super	4050.00	Repair Bearing	Repair Bearing		LS
Super	4060.00	Clean Bearings	Clean Bearings	$200	EA
Super	4070.00	Clean and Paint Bearings	Clean and Paint Bearings	$300	EA
Super	4080.00	Clean and Reset Bearings	Clean and Reset Bearings	$2,000	EA
Super	4090.00	Repair End of Conc. Girders	Repair End of Conc. Girders	$2,500	EA
Super	4100.00	Crack Epoxy Injection	Crack Epoxy Injection	$55	LF
Super	4110.00	Paint Structure (Girders only)	Paint Girders	$25	SF
Super	4120.00	Paint Structure	Paint Structure	$20	SF
Deck	5010.00	Add Approaches	Add Approaches and GB on pile	$38	SF
Deck	5020.00	Replace Approaches	Replace Approaches and GB on pile	$43	SF

Deck	5030.00	Add 20' Approaches (No Paving Sections)	Add 20' Approaches (No Paving Sections)	$38	SF
Deck	5040.00	Finger Joint (Repair or Replace)	Finger Joint (Repair or Replace)	$600	LF
Deck	5050.00	Replace Expansion Joint	Replace Expansion Joint	$300	LF
Deck	5060.00	Re-seal Expansion Joints	Re-seal Expansion Joints	$88	LF
Deck	5070.00	Replace Modular/Finger Expansion Joint	Replace Modular/Finger Expansion Joint	$1,300	LF
Deck	5080.00	Seal Deck Cracks	Seal Deck Cracks	$10	LF
Deck	5090.00	Polymer Overlay	Polymer Overlay	$6	SF
Deck	5100.00	Remove Concrete Overlay	Remove Concrete Overlay	$3	SF
Deck	5110.00	Class l deck repairs	Class l deck repairs	$2	SF
Deck	5120.00	Class ll deck repairs	Class ll deck repairs	$12	SF
Deck	5130.00	Class lll deck repairs	Class lll deck repairs	$60	SF
Deck	5140.00	Class l, ll and lll Deck Repairs	Class l, ll and lll Deck Repairs	$7	SF
Deck	5150.00	2 in. Silica Fume Overlay	Class l, ll and lll Deck Repairs, 2 in. Silica Fume Overlay	$30	SF
Deck	5160.00	Class 5 Mill to Remove Asphalt Overlay	Class 5 Mill to Remove Asphalt Overlay	$1	SF
Deck	5170.00	Bridge Deck Repair (Partial and Full Depth)	Bridge Deck Repair (Partial and Full Depth)	$27	SF
Deck	5180.00	Partial Depth Deck Repair	Partial Depth Deck Repair	$13	SF
Deck	5190.00	Full Depth Deck Repair	Full Depth Deck Repair	$60	SF
Deck	5200.00	2 in. Asphalt Overlay w/ Membrane	2 in. Asphalt Overlay w/ Membrane	$3	SF
Deck	5210.00	Mill 1 1/2" and Fill 2" Asphalt	Mill 1 1/2" and Fill 2" Asphalt taking care to avoid existing membrane	$20	SF
Deck	5230.00	Asphalt Plug at Joint	Asphalt Plug at Joint	$80	LF along turndown (w/ skew)
Deck	5235.00	Install Anti-Icing System		$20	SF
Deck	5240.00	Concrete Repairs	Concrete Repairs	$82	SF
Deck	5250.00	Retrofit Drain Outlets	Retrofit Drain Outlets	$500	EA
W/RRR	6010.00	Widen	Widen to --ft clear width	$180	SF
W/RRR	6020.00	Widen and 2 in. Silica Fume Overlay	Widen to --ft clear width and 2 in. Silica Fume Overlay	$70	SF

W/RRR	6030.00	Widen and Re-deck	Widen to --ft clear and Re-deck	$65	SF
W/RRR	6040.00	Re-deck	Re-deck	$50	SF
W/RRR	6050.00	Rehab Bridge	Rehab Bridge	$70	SF
W/RRR	6060.00	Widen and Rehab	Widen to --ft clear width and Rehab	$70	SF
W/RRR	6070.00	Replace Bridge	Replace with -- ' x --' clear Bridge	$105	SF
W/RRR	6071.00	Replace Bridge with Culvert	Replace with #-#'x#' CBC	$1	LS
W/RRR	6080.00	Remove and Replace Sidewalks	Remove and Replace Sidewalks	$150	SF
Rails	7010.00	Pedestrian Railing (Chain-link Type)	Pedestrian Railing (Chain-link Type)	$50	LF
Rails	7020.00	Repair Bridge Rails	Repair Bridge Rails	$82	SF
Rails	7030.00	Update Bridge Rails	Update Bridge Rails	$305	LF
Rails	7040.00	Update Buttresses for Thrie Beam	Update Buttresses for Thrie Beam	$5,000	EA
Rails	7050.00	Median Barrier	Median Barrier	$120	LF
Misc.	8010.00	Seal Concrete	Seal Concrete	$1	SF
Misc.	8020.00	Anodes	place anodes	$22	EA
Misc.	8030.00	Access Bridge	Access Bridge	$1,500	LF
Misc.	8040.00	Remove Bridge	Remove Existing Bridge	$10	SF
Misc.	8050.00	Miscellaneous	Miscellaneous		LS
Misc.	8060.00	Lump Sum Repairs	Lump Sum Repairs		LS
Misc.	8070.00	Access Crossing (Pipes)	Access Crossing (Pipes)	$15,000	LS

4 DETERMINISTIC ANALYSIS

4.1 INTRODUCTION

Deterministic life-cycle cost analysis is the traditional methodology in which the user assigns each input variable a fixed value usually based on historical data and user judgment. The three examples presented in the following subsections were chosen by the TAC members of the project to demonstrate the application of deterministic LCCA. These examples are: 1) deck overlay decision; 2) expansion joint replacement decision; and 3) deck widening versus deck replacement decision. All examples were analyzed using RealCost software that was developed by FHWA to support the application of LCCA to highway projects. The elements required to perform a LCCA are:

1) Design alternatives;
2) Service life;
3) Analysis period;
4) Discount rate;
5) Maintenance and rehabilitation sequences;
6) Costs.

4.2. Deck Overlay Decision

Selecting the most cost-effective deck overlay system is a good example for applying LCCA. The TAC members of the projects have chosen three types of deck overlay for this investigation: a) Silica Fume Overlay (SFO); b) Epoxy Polymer Overlay (EPO); and c) Polyester Overlay (PO) These three alternatives will be compared with the bare deck option. Table 4-1 lists the basic information of the bridge project considered in this example. The following subsections present the LCCA conducted for each alternative, then, all the alternatives will be compared to determine the one with lowest LCC. Analysis period equal to 60 years is considered to include the major activities for all alternatives. Also, a discount rate of 3% is used based on the Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs (Circular A094) and the recommendations of the TAC members.

Table 4-1: Project information

Project number	77-2(1060)
Control number	12893
Bridge ID	S077 06205L
Location	Lincoln west bypass
Year built	1989
Year reconstruction	-
Inspection date	22-FEB-2011
Design type	Steel continuous
Construction type	Stringer/Multi beam or girder
Structure length	257 ft.
Roadway width	47 ft.
Number of spans	3
Functional classification	Urban
Deck structure type	Concrete
Type of wearing surface	Concrete
Average daily traffic (ADT)	14910
Average daily truck traffic (ADTT)	1491
Deck condition rating	8
Superstructure condition rating	8
Substructure condition rating	8
Area of bridge deck	12,079 SF

4.2.1. Silica Fume Overlay (SFO)

In this example, the following alternatives are investigated: 1) bare deck; 2) silica fume overlay (SFO) on bare deck at condition 5; and 3) SFO on bare deck at condition 6. To conduct this investigation, deterioration models are used to predict the future conditions. Figure 4-1 shows the deterioration curves of bare decks in state bridges with average daily traffic (ADT) less than 1000, between 1000 and 5000, and more than 5000 in state bridges (Hatami and Morcous, 2012). The bridge considered in this example has ADT of 14,910, which is presented by the green curve (ADT > 5000). Because bridge decks are usually replaced at condition 4, the service life of bare concrete deck is considered to be about 40 years. Age of deck at condition 5 and 6 is about 38 and 30 years, respectively. It should be noted that this curves include both deck and slab bridges. Figure 4-2 shows that 57% of state bridges are deck bridges and about 30% are slab bridges.

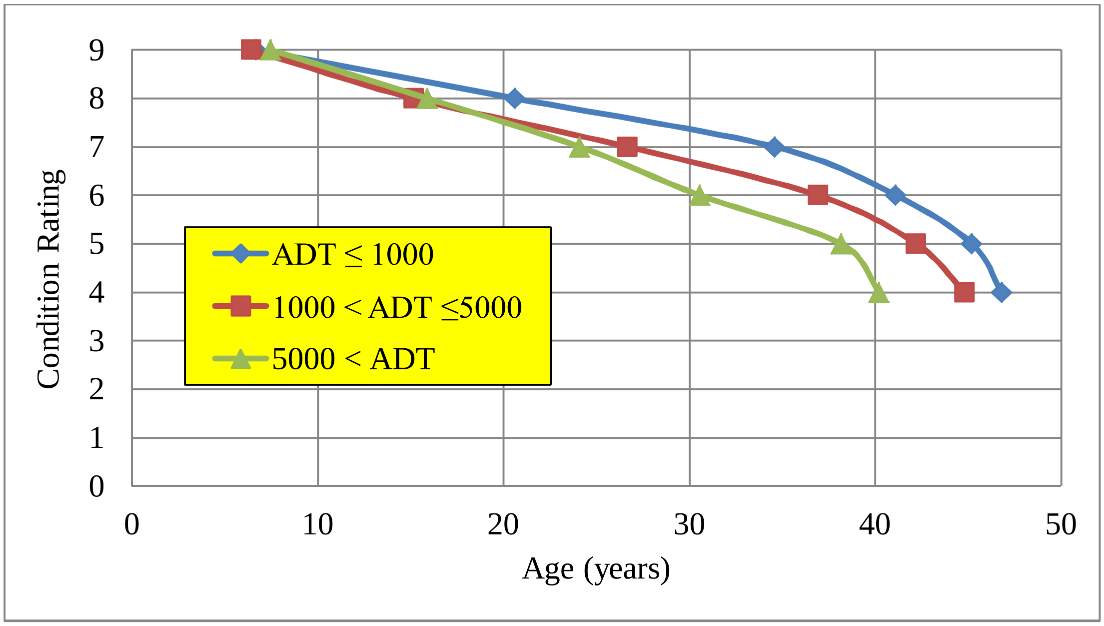

Figure 4-1: Original deck deterioration curve in state bridges

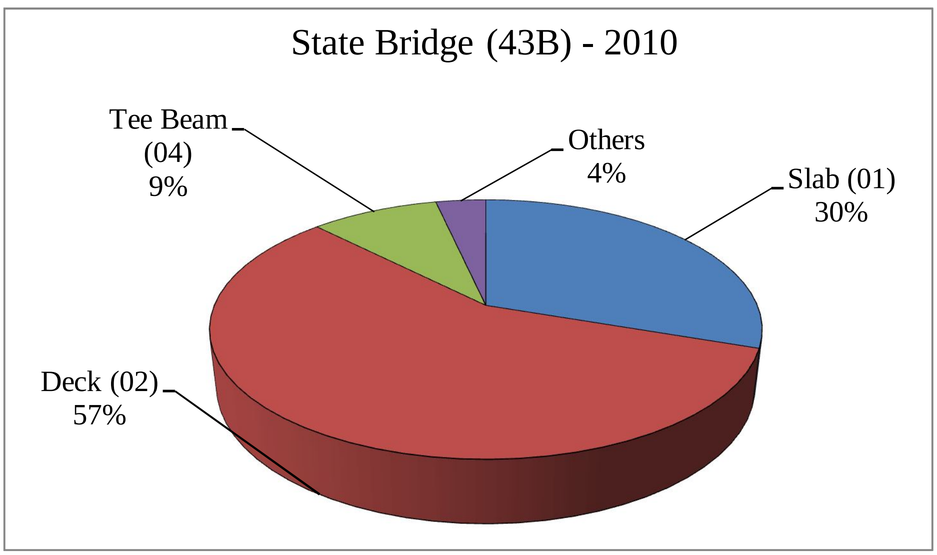

Figure 4-2: Distribution of structures type in state highway structures (without culverts)

Figure 4-3 shows the deterioration curves of slab and deck state bridges. This figure indicates that there is no significant difference between the deterioration of slab and deck bridges.

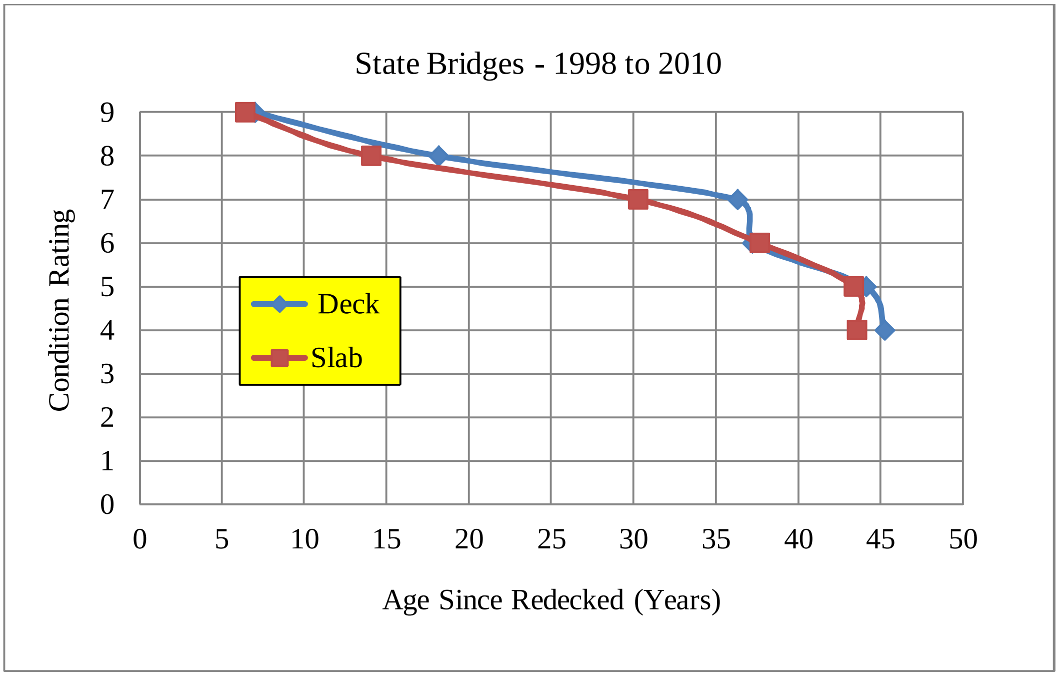

Figure 4-3: Deterioration curves for decks and slabs in state bridges

Figures 4-4 and 4-5 show the distribution of duration to re-deck and replace the slabs in state bridges at year 2010, respectively. This figure indicates that most of the state bridges have re-decking or slab replacement after 25 to 40 years. The average ages to re-deck and slab replacement in state bridges are 35.4 and 33.1 years, respectively.

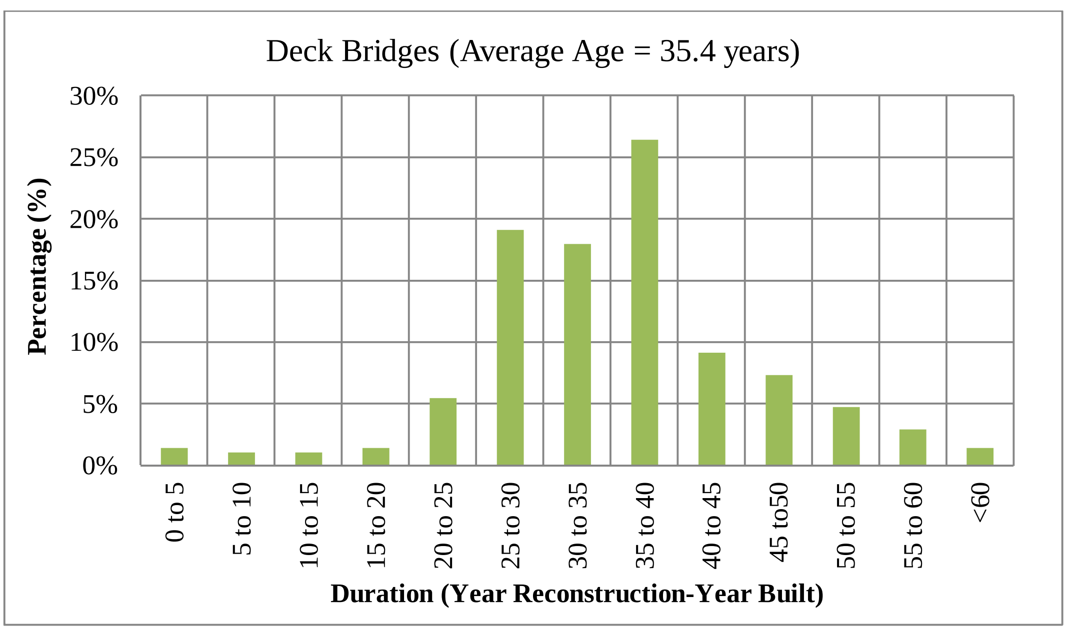

Figure 4-4: Histogram of state bridges for different durations to re-deck – year 2010

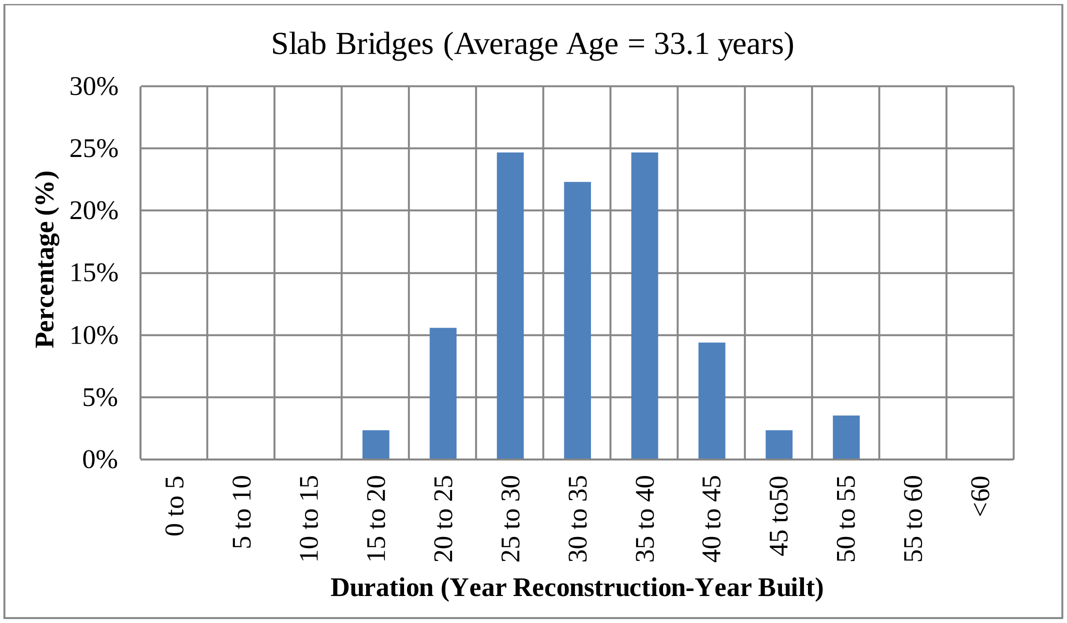

Figure 4-5: Histogram of state bridges for different durations to slab replacement – year 2010

Figure 4-6 presents the deterioration curve developed for replacement decks in state bridges using condition data from 1998 to 2010 (Hatami and Morcous, 2012). This figure shows that the service life of replacement decks is approximately 37 years. The shorter service life of the replacement deck then original deck might be due to the increased traffic volume and deterioration of superstructure, which usually leads to replacing the whole bridge after 75 to 80 years.

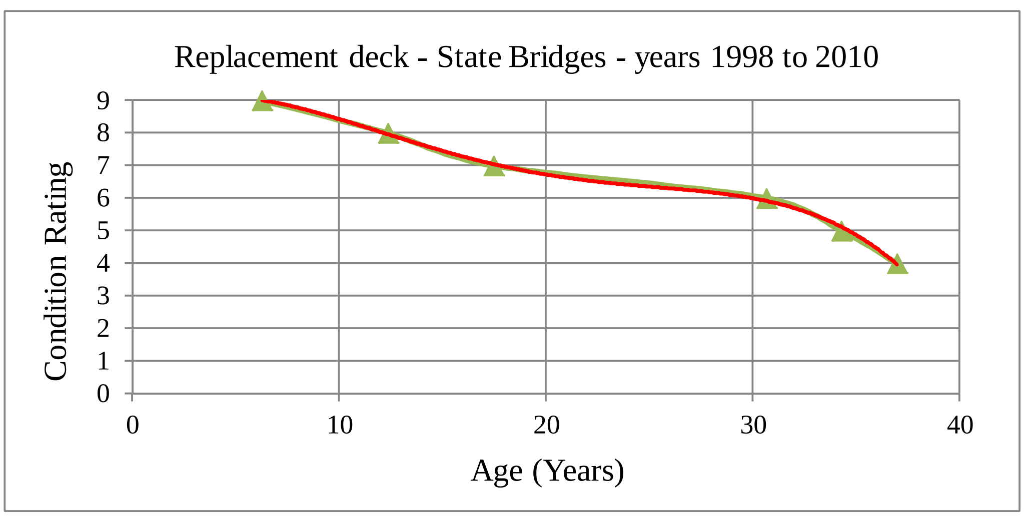

Figure 4-6: Replacement deck deterioration curve in state bridges

Silica fume overlay have been used as a wearing surface on bridge decks in Nebraska since the early 1980s. This overlay is used on bridge deck which has condition rating 5 or 6. According to 2010 data, there are 70 state bridges with silica fume overlay on their decks (Hatami and Morcous, 2011). Figure 4-7 presents the histogram of bridge decks which have been overlaid by silica fume. This figure clearly shows that most of the state bridges overlaid by silica fume have duration to overlay between 25 to 30 years. There is not enough data for developing deterioration model for this type of overlay. However, service life of 25 years for silica fume overlay has been recommended by TAC members. It is assumed that the structural life of the deck will extend for 25 years by applying the SFO at conditions 5 or 6.

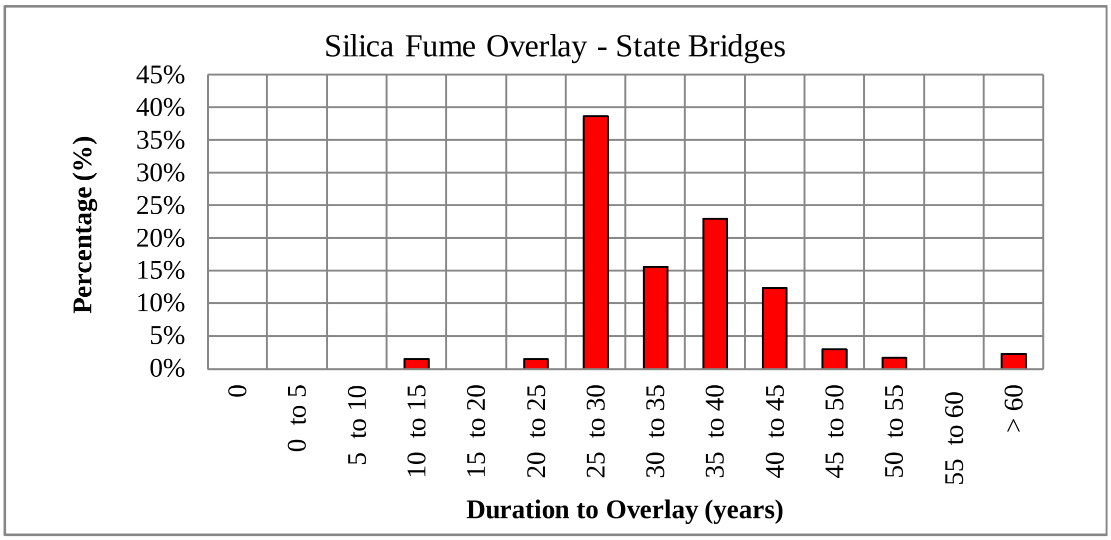

Figure 4-7: Duration to overlay histogram of silica fume overlay – year 2009

To compare the LCC of SFO versus bare deck, the following sequence of activities is considered. No action in alternative 1 (bare deck) until the deck is at condition rating 4, then, deck is replaced. For alternative 2, no action until the deck is at condition rating 5, then, SFO is applied. For alternative 3, no action until the deck is at condition rating 6, then, SFO is applied. It is assumed that deck condition will remain the same after each application of SFO.

Based on collected cost data in chapter 3, cost of alternative 1 (deck replacement) is 50$/SF and area of bridge deck is 12,079. Therefore, the cost of deck replacement will be: 50×12,079 = $603,950. Cost of deck repair and applying silica fume overlay on deck at condition 5 and 6 are

30$/SF and 25.3$/SF, respectively. Therefore total cost of applying silica fume overlay on bridge deck at condition 5 will be: 30×12,079 = $362,370 and at condition 6 will be: 25.3×12,079 = $305,599. User costs are eliminated from the analysis of all alternatives due to the difficulty of getting reliable estimate for user cost in each alternative.

In order to compare the LCCA for different alternatives, RealCost program has been used. Table 4-2 listed the results of net present value (NPV) and equivalent uniform annual cost (EUAC) for alternatives 1, 2 and 3. Figure 4-8 shows the net present value for alternatives 1 to 3. The results show that alternative 2 (SFO at condition 6) has a lowest net present value and is the best alternative.

Table 4-2: LCCA results for example 1

Total Cost	Alternative 1: Bare Deck	Alternative 2: SFO at Condition 5	Alternative 3: SFO at Condition 6
	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)
Undiscounted Sum	*$326.46*	*$333.38*	*$277.82*
Present Value	$138.05	$116.47	$111.12
EUAC	$4.99	$4.21	$4.02

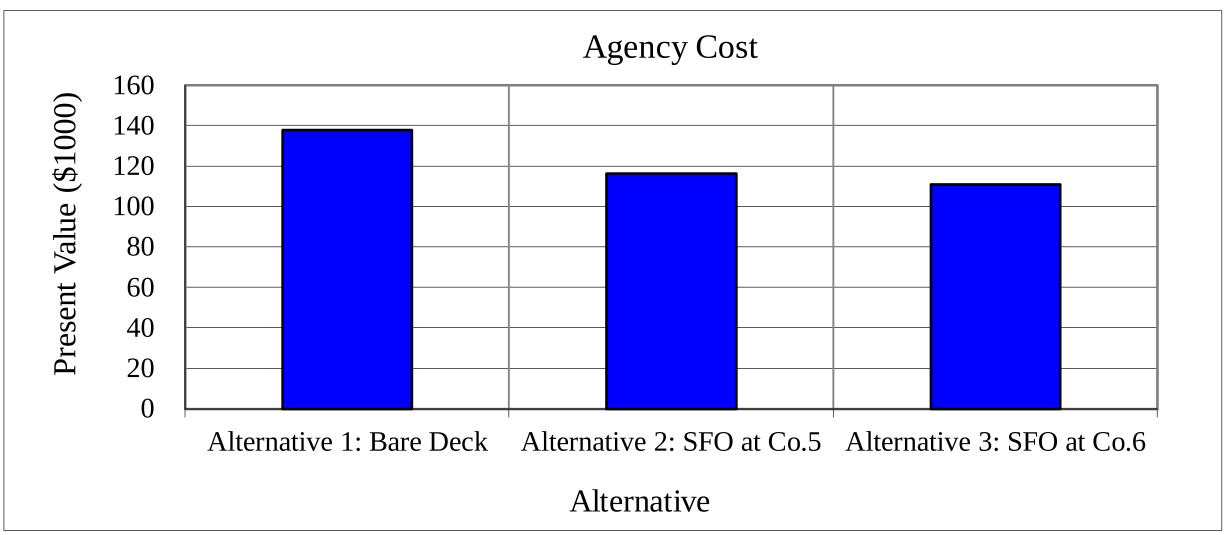

Figure 4-8: Net present value for SFO alternatives 1, 2 and 3

4.2.2. Epoxy Polymer Overlay (EPO)

Epoxy Polymer Overlays (EPOs) have been used to seal bridge decks in the United States for over 40 years. Thin Polymer Overlays (TPOs) consist of an epoxy polymer binder and aggregates with a thickness not exceeding 10 mm (3/8 in.). An EPO overlay is more expensive than a traditional overlay; however it has several advantages:

- Adds very little dead load
- Very fast cure times
- Shallow depths which eliminates the need for raising the approach slabs
- Transition from overlaid lane to non-overlaid lane during construction
- A waterproof, long-lasting wearing surface
- Excellent skid resistance
- Allows better appraisal of deck condition under the overlay than thicker concrete or asphalt overlays

EPO is one of the materials used recently as an overlay on bridge decks in Nebraska. Since there isn't enough data about how EPO will affect deck deterioration, TAC members suggested studying the service life of EPO needed to extend the life of a bridge deck and delay a more expensive action to become cost effective. The following alternatives were suggested to consider:

1. Do nothing (bare deck)
2. SFO only, applied at condition 6
3. SFO only, applied at condition 5
4. EPO on bare deck at condition 7 (or year 15, whichever is first).
5. EPO on concrete overlay at condition 7 (or year 15, whichever is first)

Alternatives 1, 2 and 3 have been investigated in previous section. Deterioration curve for bare deck and replacement deck (figures 4-1 and 4-2) show that age of deck at condition 7 is 24 and 18 years, respectively. It means that in both alternative 4 and 5, 15 years governs. Therefore, in this section LCCA for EPO on bare deck after 15 years is considered and the results are compared with alternatives 1 to 3.

EPO overlay could provide a service life of 20 to 25 years when properly installed on sound decks (NCHRP report 423). Engineering expertise at NDOR recommended an average service life about 10 years for EPO as there are evidences of failure in early ages. Therefore, design alternatives considered are:

Alternative 1: EPO with service life of 5 years;

Alternative 2: EPO with service life of 10 years;

Alternative 3: EPO with service life of 15 years;

Alternative 4: EPO with service life of 20 years;

Alternative 5: EPO with service life of 25 years.

For the first 15 years of bridge decks, there is no action taken, after this, the first EPO is applied. Because alternatives have different service life for EPO, multiple applications are considered until the end of the analysis period. For example, there are 9 applications for alternative 1 (15 + 9×5 = 60 years) and 3 applications for alternative 3 (15 + 3×15 = 60 years). It's assumed that deck condition remains the same after each application of EPO. TAC members suggested to use 6$/SF for each application of EPO. After 2 applications they recommended to add cost of 3$/SF for removal at time of next application.

Table 4-3 listed the results of net present value (NPV) and equivalent uniform annual cost (EUAC) for alternatives 1 to 5. The results for net present value in Table 4-3 are presented in Figure 4-9. This figure clearly shows that the longer the service life of EPO, the lower the net present value.

Table 4-3: LCCA results for EPO example

Total Cost	Alternative 1: EOP @ 5 YRS	Alternative 2: EPO @ 10 YRS	Alternative 3: EPO @ 15 YRS	Alternative 4: EPO @ 20 YRS	Alternative 5: EPO @ 25 YRS
	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)
Undiscounted Sum	$796.47	$380.49	$253.66	$172.13	$144.95
Present Value	$295.74	$151.10	$105.12	$79.83	$66.28
EUAC	$10.69	$5.46	$3.80	$2.88	$2.39

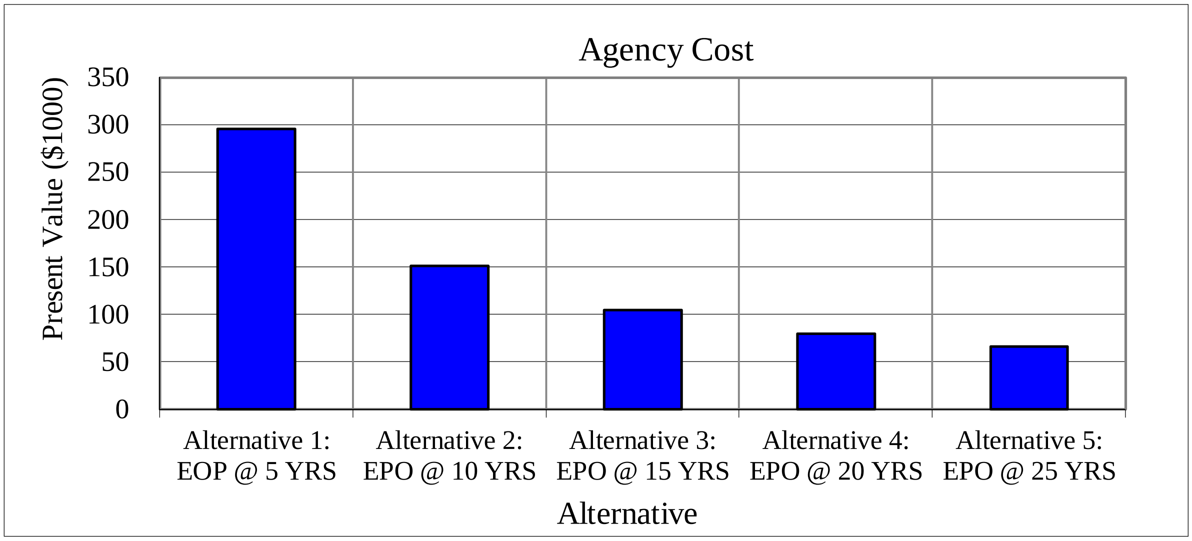

Figure 4-9: Net present value for EPO alternatives 1 to 5

In order to find the minimum service life of an EPO required to delay a more expensive action, results of net present value for bare deck, SFO applied on deck at conditions 5, SFO applied on deck at condition 6, and different service life for EPO on bare deck at condition 7 are plotted in Figure 4-10. This figure vividly shows that the minimum required service life of EPO to delay a more expensive action to be cost effective is between 11 to 14 years.

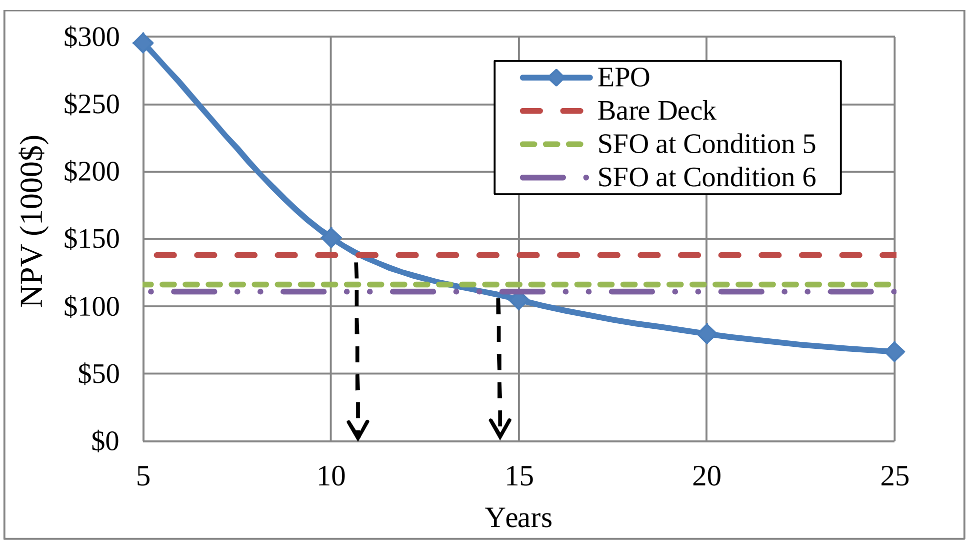

Figure 4-10: Minimum required service life of EPO

In order to compare the results of bare deck, SFO, and EPO, the following alternatives have been considered:

- Alternative 1: Bare deck;
- Alternative 2: SFO applied on deck after 25 years;
- Alternative 3: EPO applied on deck after 15 years and repeat every 10 years.

There is no action in alternative 1 (bare deck) until 40 years, then, deck is replaced, which extends its service life for additional 37 years. For alternative 2 (SFO), there is no action until 25 years, then, SFO is applied to extend the service life of the deck for 25 years and after that the deck is replaced. For alternative 3 (EPO), there is no action until 15 years, then, the EPO is applied. Because EPO has service life of 10 years, multiple applications are considered until the end of the analysis period.

Initial cost of 30$/SF is used for all alternatives, which results in 30×12,079 = $362,370 that represents the construction cost of a new bare deck. This initial cost extends structural service life of alternatives 2 and 3 for 70 years. However, because of deck replacement in alternative 1, structural service life extends for 40 years. The cost of deck replacement in alternative 1 is: 50×12,079 = $603,950. Cost of deck repair and applying SFO in alternative 2 is: 30×12,079 = $362,370. Cost of EOP is equal to 6$/SF for each application and after 2 applications cost increases by 3$/SF for removal at time of next application.

Table 4-4 listed the results of net present value (NPV) and equivalent uniform annual cost (EUAC) for alternatives 1 to 3. The results for net present value in Table 4-4 are presented in Figure 4-11. This figure clearly shows that the net present value for bare deck and EPO are almost same and are lower than SFO alternative.

Table 4-4: LCCA results for bare deck, SFO, and EPO

Total Cost	Alternative 1: Bare Deck Agency Cost ($1000)	Alternative 2: SFO Agency Cost ($1000)	Alternative 3: EPO @ 10 Years Agency Cost ($1000)
Undiscounted Sum	*$707.48*	*$760.98*	*$691.09*
Present Value	$503.58	$550.82	$504.68
EUAC	$18.20	$19.90	$18.24

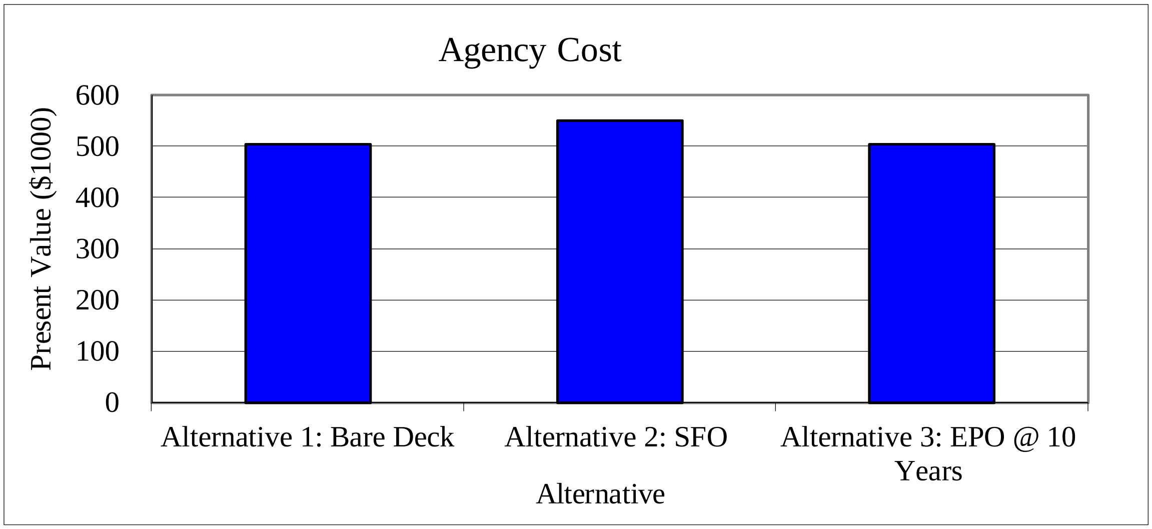

Figure 4-11: Net present value for bare deck, SFO, and EPO

To determine the service life of the EPO need to have to be cost effective when different structural life of the deck is used, sensitivity analyses have been done for different EPO and deck structural life. EPO with structural life of 10, 15, and 20 years and deck structural life of 60, 65, 70, 75, 80, and 85 years have been considered. The results of net present value for bare deck, SFO, and different service life for EPO on bare deck with different structural life for deck are plotted in Figure 4-12. This figure vividly shows that the minimum required service life of deck to delay a more expensive action to be cost effective is about 73 years for EPO with service life of 10 years.

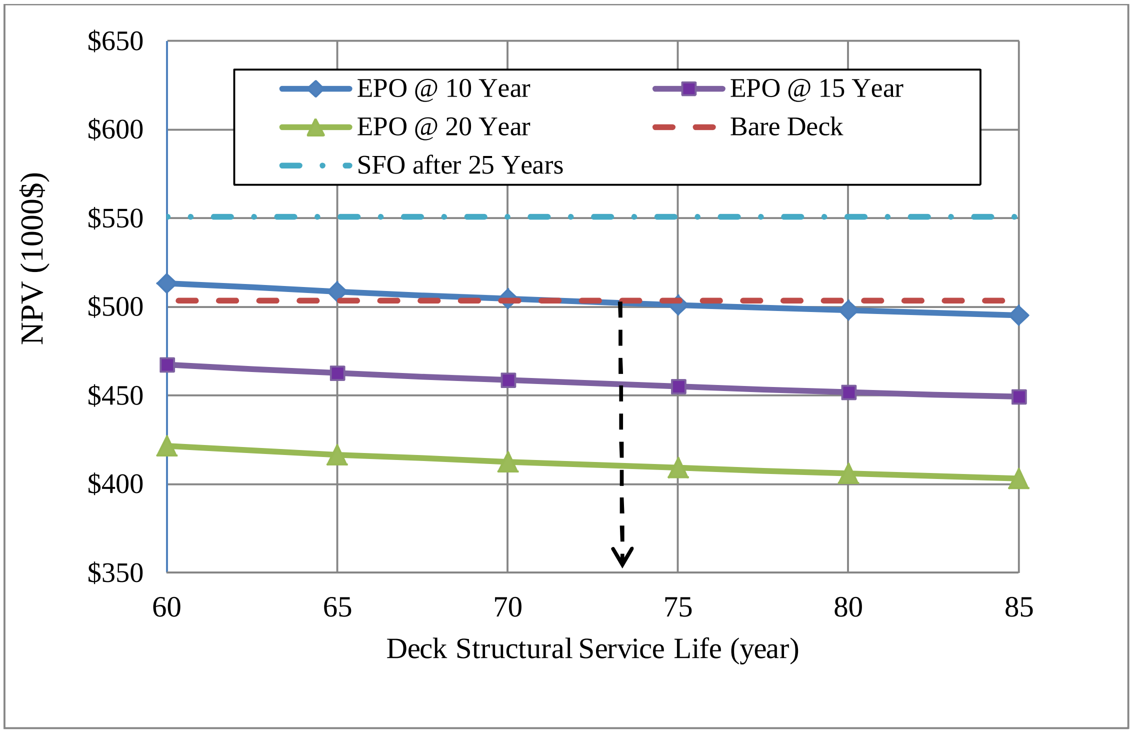

Figure 4-12: Minimum required service life of Deck for EPO with variable service life

4.2.3. Polyester Overlay

Polyester concrete is a composite material consisting of a polyester binder and aggregate. In other words, polyester concrete is similar to Portland cement concrete, with the cement binder being replaced by polyester resin. Polyester concrete is rapid setting, and bridge decks receiving a polyester concrete overlay (typically ½ to 2 inches in depth) can typically be opened to traffic two to four hours after placement. Polyester concrete has higher compressive and flexural strengths (8,000 psi and 2,200 psi, respectively), abrasion resistance, chemical resistance, and lower permeability to chloride ions than Portland cement concrete. This combination of properties has made polyester concrete an attractive choice for the repair/rehabilitation of Portland cement concrete bridge decks.

Polyester Overlays (POs) constructed in accordance with AASHTO Specifications should have a service life of 25 years. Engineering expertise at NDOR conservatively suggested an average service life about 16 years for PO when applied at deck condition 7. The design alternatives for polyester overlay are:

Alternative 1: Polyester overlay with service life of 8 years;

Alternative 2: Polyester overlay with service life of 12 years;

Alternative 3: Polyester overlay with service life of 16 years;

Alternative 4: Polyester overlay with service life of 20 years;

Alternative 5: Polyester overlay with service life of 24 years.

In all these alternatives, no action is applied in first 15 years of bridge decks. Because PO has different service life, alternatives with multiple applications are considered until the end of the analysis period. For example, PO has 6 applications in alternative 1 (15 + 6×8 = 63 years), 4 applications in alternative 2 (15 + 4×12 = 63 years), and 3 applications in alternative 3 (15 + 3×16 = 63 years). TAC members suggested to use 9$/SF for each application of PO. After 2 applications, additional cost of 3$/SF is used for removal before next application.

Table 4-4 listed the results of net present value (NPV) and equivalent uniform annual cost (EUAC) for alternatives 1 to 5. The results for net present value in Table 4-4 are presented in Figure 4-13. This figure clearly shows that the longer the service life of PO, the lower the net present value.

Table 4-4: LCCA results for EPO example

Total Cost	Alternative 1: Polyester Overlay @ 8 YRS	Alternative 2: Polyester Overlay @ 12 YRS	Alternative 3: Polyester Overlay @ 16 YRS	Alternative 4: Polyester Overlay @ 20 YRS	Alternative 5: Polyester Overlay @ 24 YRS
	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)
Undiscounted Sum	*$683.97*	*$443.90*	*$335.19*	*$253.66*	*$203.83*
Present Value	$267.76	$183.95	$144.78	$118.48	$101.80
EUAC	$9.68	$6.65	$5.23	$4.28	$3.68

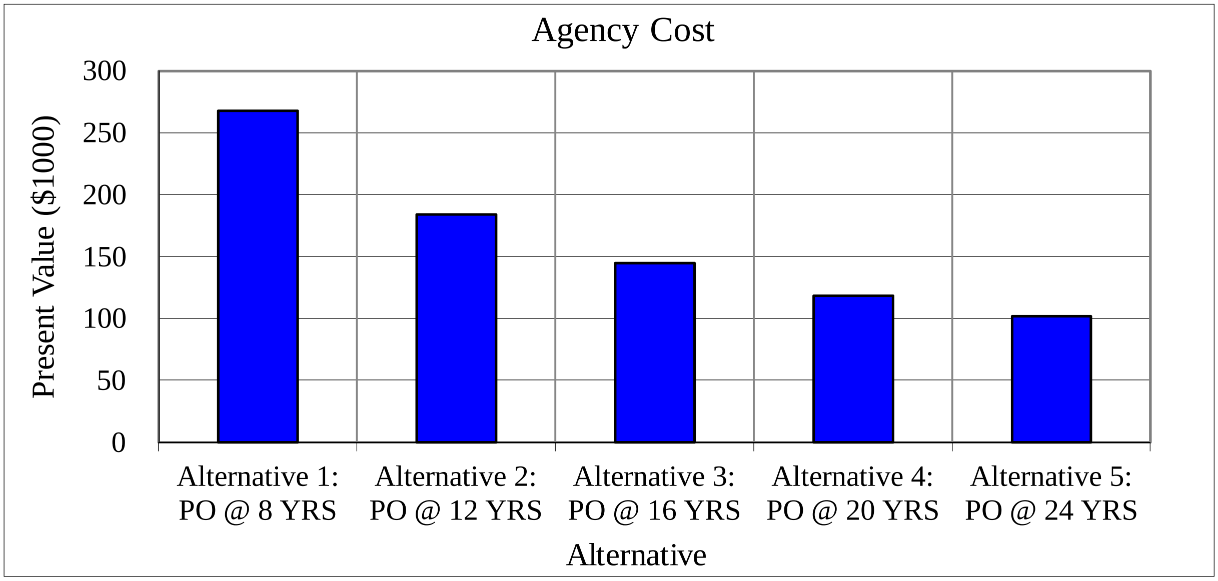

Figure 4-13: Net present value for alternatives 1 to 5 for PO

Figure 4-14 shows the NPV versus service life for EPO and PO. This figure clearly shows that PO has a better performance than EPO. For example, when NPV equals to $150,000, EPO has a service life of 10 years, however, PO has a service life of 15 years.

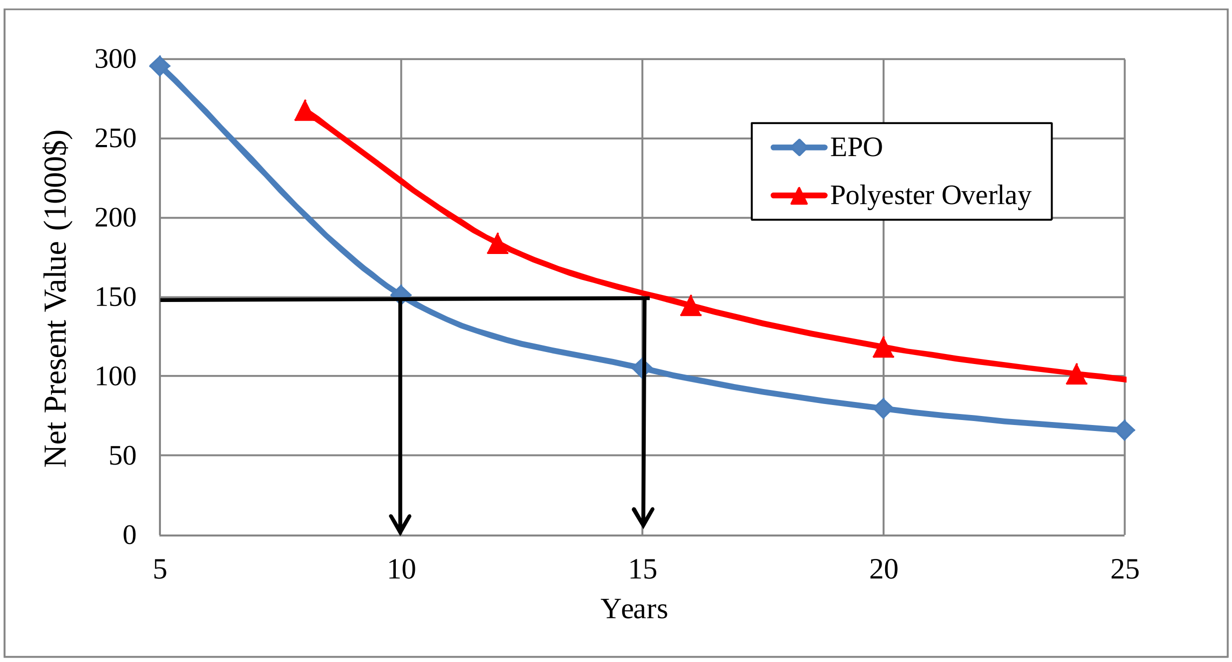

Figure 4-14: Comparison of service life versus net present value for polyester overlay and EPO

In order to find the minimum service life of a PO required to delay a more expensive action, results of net present value for bare deck, SFO applied on deck at conditions 5, SFO applied on deck at condition 6, and different service life for PO are plotted in Figure 4-15. This figure shows that the minimum service life of PO to delay a more expensive action is between 17 to 22 years.

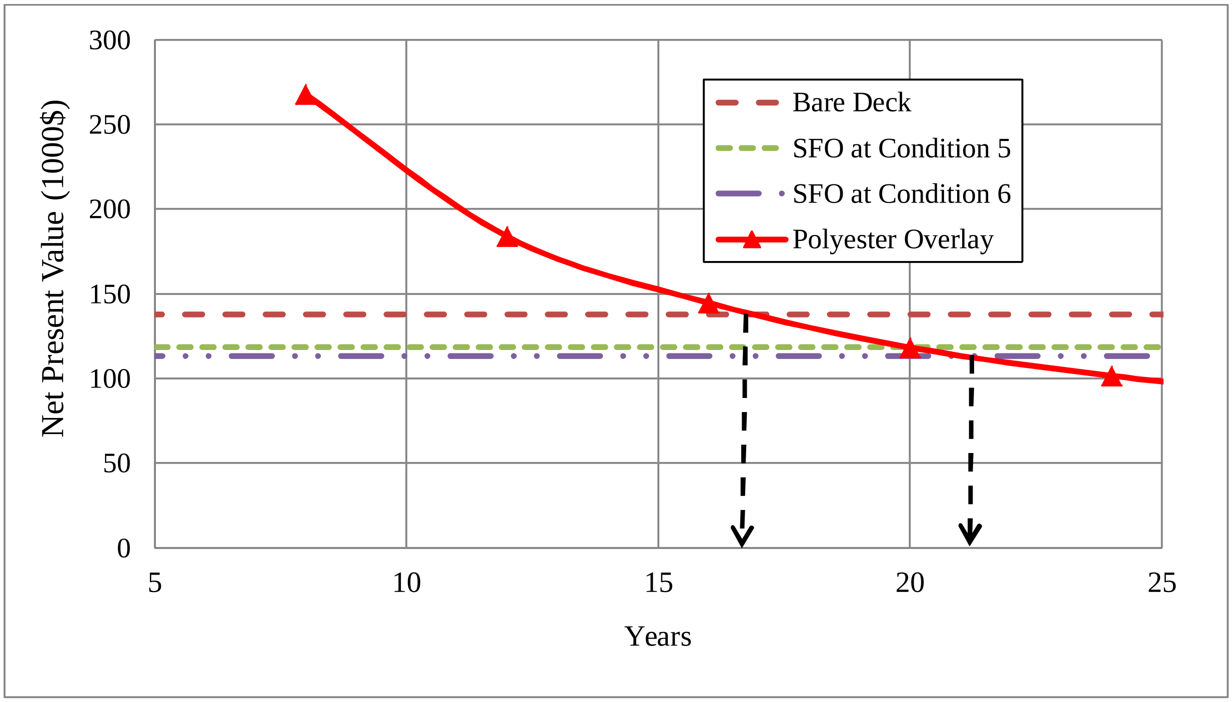

Figure 4-15: Minimum required service life of polyester overlay

4.3. Expansion Joint Replacement Decision

The problem investigated in the case study is the selection of lowest LCC alternatives for replacing deteriorated expansion joints. Two alternatives are defined: alternative 1) Replacing the abutment expansion joint and relocating at the grade beam; and alternative 2) Replacing the abutment expansion joint at the same place. The same project used in example 1 is adopted in this case study. The main parameters considered in this analysis are the deterioration of girder ends (superstructure) and bearings.

To determine activity times, deterioration curves for superstructure and bearings are developed. Figure 4-16 shows the deterioration curves for superstructure at moderate and severe environments. Moderate and severe environments represent those superstructures with bearing condition higher than 5 and superstructures with bearing condition less than 5, respectively. Superstructures in alternative 1 are considered to be in a moderate environment category and superstructures in alternative 2 are considered to be in a severe environment category. Figure 4-16 clearly shows that service life of superstructures in a moderate environment is around 60 years and service life of superstructures in a severe environment is around 47 years. Service life of superstructure is considered the time which it takes the superstructure to deteriorate from excellent condition (condition 9) to poor condition (condition 4).

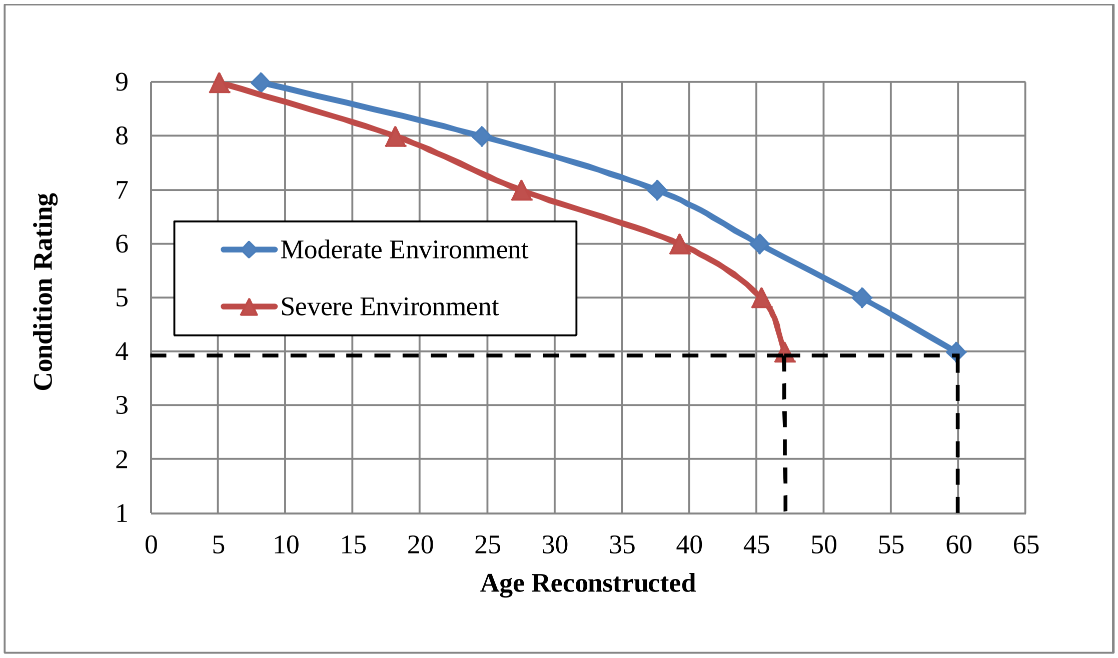

Figure 4-16: Deterioration curves for girders at moderate and severe environment

Figure 4-17 presents the bearing deterioration curves in moderate and severe environments. For alternative 1, bearings are considered to be in a moderate environment category, while for alternative 2, bearings are considered to be in a severe environment category. Service life of bearings in moderate and severe environments is about 50 and 37 years, respectively.

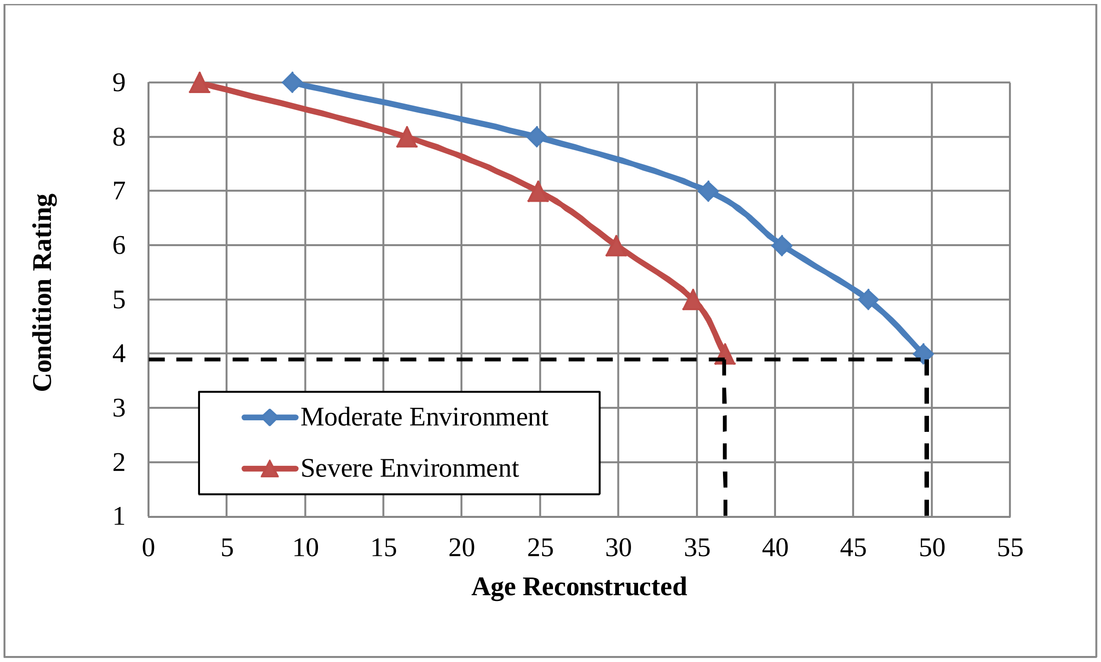

Figure 4-17: Deterioration curves for bearings in moderate and severe environment categories

The analysis period considered in this case study is 70 years to include all major activities for both alternatives and the discount rate equal to 3% is used similar to the first case study. For alternative 1, construction cost is estimated at about $262,000. Table 4-5 shows the construction cost breakdown for alternative 1. For alternative 2, initial construction cost is estimated to be $25,000 total as shown in Table 4-6. Cost of replacing expansion joints, as recommended by TAC members, is $10,000 every 7 years. Because of faster bearing and superstructure deterioration in alternative 2, bearing are replaced after 37 years and superstructure (girders) should be repaired after 47 years. However in real practice, replacing bearing and repairing superstructure is done at same time, therefore, both of these activities are considered after 37 years. There are 36 bearings in a bridge, and each bearing costs about $937 based on standard item number 6616.65. Therefore, construction cost is estimated to be 36 * $937 ≃ $34,000 for replacing bearings in bridge superstructure. The superstructure (girder) repair is assumed to be $23,766/each. Therefore the construction cost for superstructure is estimated to be 12 * $23,766 ≃ $285,192.

Table 4-5: Construction cost for alternative 1

					PAVERS COMPANIES		CONSTRUCTORS, INC.		DOBSON BROTHERS	
		Item	QUANTITY		UNIT PRICE	AMOUNT	UNIT PRICE	AMOUNT	UNIT PRICE	AMOUNT
MOBILIZATION		30.60	1	LUMP	$42,000.00	$ 42,000.00	$ 24,100.00	$ 24,100.00	$ 24,500.00	$ 24,500.00
CONCRETE FOR PAVEMENT APPROACHES CLASS 47BD-4000	25	3050.15	215.4	CY	$ 215.00	$ 46,311.00	$ 210.00	$ 45,234.00	$ 215.00	$ 46,311.00
EPOXY COATED REINFORCING STEEL FOR PAVEMENT APPROACHES	26	3051.10	35735	LB	$ 1.28	$ 45,740.80	$ 1.25	$ 44,668.75	$ 1.30	$ 46,455.50
ABUTMENT NO.1 EXCAVATION	27	6000.10	105	LS	$ 1,750.00	$ 1,750.00	$ 1,710.00	$ 1,710.00	$ 1,800.00	$ 1,800.00
ABUTMENT NO.2 EXCAVATION	28	6000.11	105	LS	$ 1,750.00	$ 1,750.00	$ 1,710.00	$ 1,710.00	$ 1,800.00	$ 1,800.00
PREFORMED EXPANSION JOINT, TYPE A	29	6005.32	110	LF	$ 61.75	$ 6,792.50	$ 60.30	$ 6,633.00	$ 62.00	$ 6,820.00
CLASS 47B-3000 CONCRETE FOR BRIDGE	30	6010.22	29.2	CY	$ 600.00	$ 17,520.00	$ 590.00	$ 17,228.00	$ 605.00	$ 17,666.00
CLASS 47BD-4000 CONCRETE FOR BRIDGE	31	6010.26	52.2	CY	$ 605.00	$ 31,581.00	$ 590.00	$ 30,798.00	$ 610.00	$ 31,842.00
PREPARATION OF BRIDGE AT STATION 588+56	32	6030.00	1	EACH	$20,500.00	$ 20,500.00	$ 20,100.00	$ 20,100.00	$ 21,000.00	$ 21,000.00
EPOXY COATED REINFORCING STEEL	33	6131.50	10680	LB	$ 1.28	$ 13,670.40	$ 1.30	$ 13,884.00	$ 1.30	$ 13,884.00
SUBSURFACE DRAINAGE MATTING	34	6139.50	53	SY	$ 36.00	$ 1,908.00	$ 35.10	$ 1,860.30	$ 36.00	$ 1,908.00
HP 12 X 53 INCH LB STEEL PILING	35	6210.14	1140	LF	$ 36.00	$ 41,040.00	$ 35.10	$ 40,014.00	$ 38.00	$ 43,320.00
BRIDGE SHORING	36	6510.60	3.333	LS	$ 7,200.00	$ 7,200.00	$ 7,030.00	$ 7,030.00	$ 7,500.00	$ 7,500.00
GRANULAR BACKFILL	37	8091.00	210	CY	$ 34.00	$ 7,140.00	$ 33.20	$ 6,972.00	$ 34.00	$ 7,140.00
SECTION TOTALS						$ 284,903.70		$ 261,942.05		$ 271,946.50

Table 4-6: Construction cost for alternative 2

from	CN	12893		SECTION 0003 GROUP 6A BRIDGE AT STA. 588+28.72 RT. 3 SPAN WELDED PLATE STEEL GIRDER BRIDGE						
					PAVERS COMPANIES		CONSTRUCTORS, INC.		DOBSON BROTHERS	
		Item	QUANTITY		UNIT PRICE	AMOUNT	UNIT PRICE	AMOUNT	UNIT PRICE	AMOUNT
MOBILIZATION	38	30.60	1	LUMP	$ 20,000.00	$ 20,000.00	$ 10,000.00	$ 10,000.00	$ 10,250.00	$ 10,250.00
EXPANSION JOINT REPAIR	39	6004.60	115	LF	$ 128.00	$ 14,720.00	$ 126.00	$ 14,490.00	$ 130.00	$ 14,950.00
SECTION TOTALS						34,720.00 $		24,490.00 $		25,200.00

Figure 4-18 shows the frequent maintenance cost input data in RealCost program for activity 1 in alternative 2 (replacing abutment expansion joints at the same place). Figure 4-19 shows the distribution of agency cost for alternatives 1 and 2.

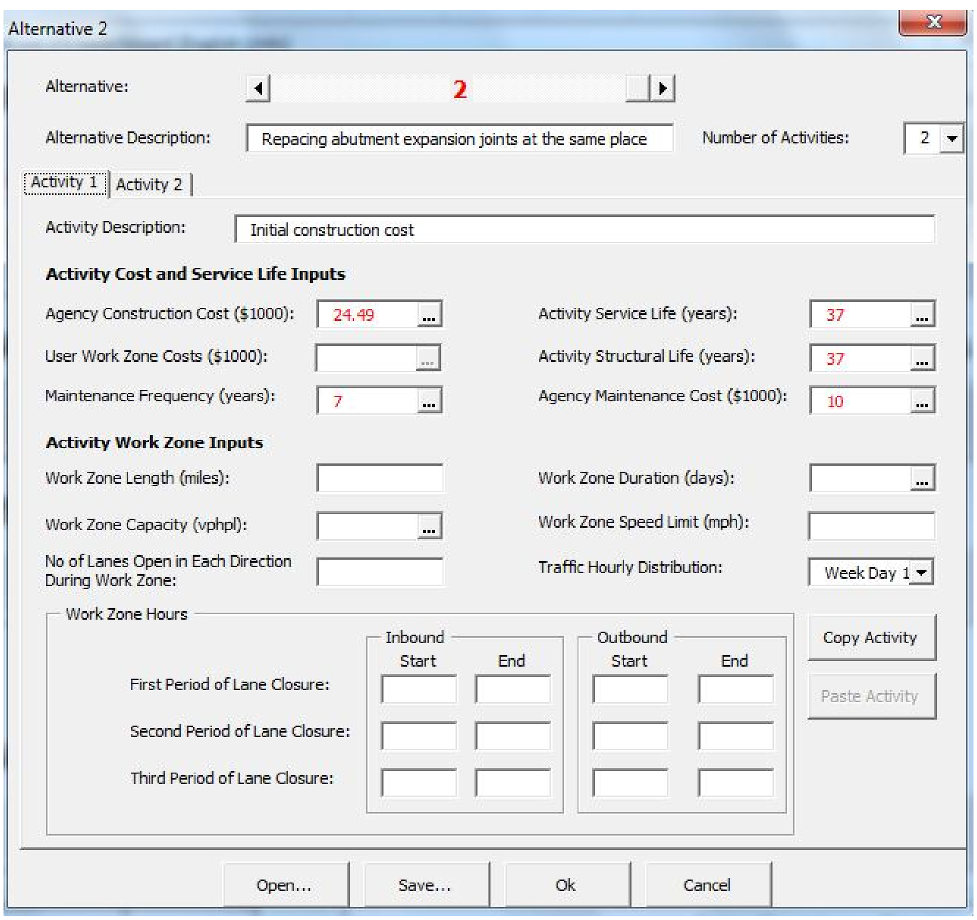

Figure 4-18: Frequency maintenance cost input data in RealCost program

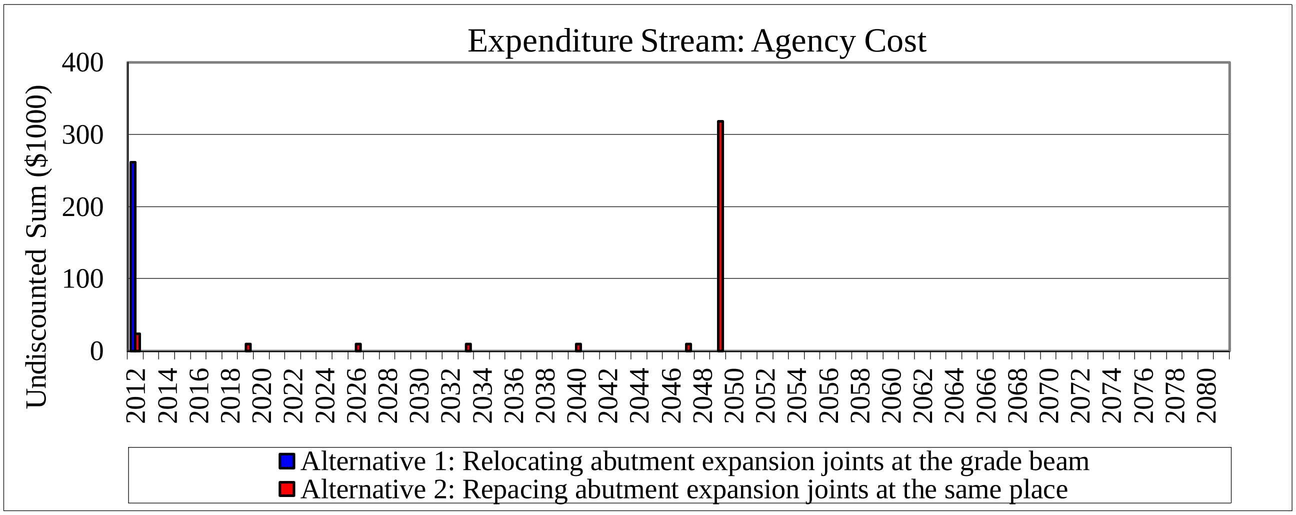

Figure 4-19: Distribution of agency cost for alternatives 1 and 2 in example 2

Table 4-7 lists the results of NPV and EUAC for alternatives 1 and 2. Figure 4-20 shows the net present value for alternatives 1 and 2. The results clearly show that alternative 2 (Replacing abutment expansion joints at the same place) has the lower LCC.

Table 4-7: LCCA results for example 2

Total Cost	Alternative 1: Relocating abutment expansion joints at the grade beam	Alternative 2: Replacing abutment expansion joints at the same place
	Agency Cost ($1000)	Agency Cost ($1000)
Undiscounted Sum	*$261.94*	*$298.06*
Present Value	$261.94	$84.79
EUAC	$14.75	$4.78

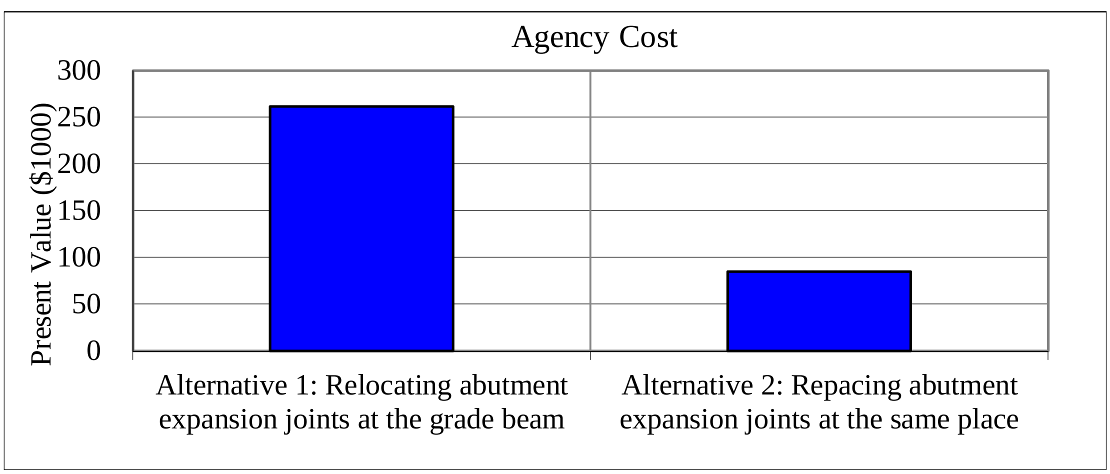

Figure 4-20: Net present value for alternatives 1 and 2 in example 2

4.4. Deck Widening VS Deck Replacement

This example compares deck widening and deck replacement for 5 different bridges in the state of Nebraska. These bridges are located in district 7 and their information is listed in Table 4-8. The two alternatives investigated in this example are: alternative 1) Widen, ACC overlay with membrane, wrap piling, replace approaches; and alternative 2) Replace bridges, add approaches and SFO. Service life and cost of different activities in alternatives 1 and 2 are determined based on engineering expertise of TAC members. Tables 4-9 and 4-10 present the cost, service life and sequence of different activities for alternative 1 and alternative 2 respectively. The analysis period recommended for this example is 40 years, and a discount rate equal to 3% is considered similar to the previous examples.

Table 4-8: Project information for example 3

Structure Number	S089 03274	S089 03382	S089 03529	S089 03586	S089 03805	All Bridges
Length, existing (ft)	73.00	73.00	57.00	65.00	61.00	329.00
width out-to-out, existing (ft)	26.20	26.20	26.20	26.20	26.20	131.00
width curb-to-curb, existing (ft)	24.00	24.00	24.00	24.00	24.00	120.00
length along skew, existing (ft)	26.20	30.25	26.20	26.20	26.20	135.05
replacement lengths from Hydro (ft)	80.00	85.00	70.00	85.00	70.00	390.00
out-to-out replace width for 36ft clear per NMDS (ft)	38.67	38.67	38.67	38.67	38.67	193.33
out-to-out for 28ft clear remain-in-place width per NMDS (ft)	28.00	28.00	28.00	28.00	28.00	140.00

Table 4-9: Cost, service life and sequence of activities in alternative 1- example 3

Activity	Action	Unit cost ($/unit)	Units (SF or ft)	Mobilization and difficulty factor	Year 2014 cost/value	Service life (years)	Year cost/value occurs
1	widen	$180.00	1481	1.37	$365,091	20	2014
2	ACC overlay with membrane	$3.33	46060	1.37	$210,130	20	2014
3	wrap piling	$450.00	40	1.37	$24,660	20	2014
4	replace in 2034	$105.00	75400	1.37	$10,846,290	80	2034
5	add approaches in 2034	$35.00	19333	1.37	$927,033	80	2034

Table 4-10: Cost, service life and sequence of activities in alternative 2 - example 3

Activity	Action	Unit cost ($/unit)	Units (SF or ft)	Mobilization and difficulty factor	Year 2014 cost/value	Service life (years)	Year cost/value occurs
1	replace all with bridges in 2014	$105.00	75400	1.37	$10,846,290	80	2014
2	add approaches in 2014	$35.00	19333	1.37	$927,033	80	2014
3	SFO in 2039	$30.00	70200	1.37	$2,885,220	20	2039

In RealCost program, the activity service life defines when the next activity will start. While, the activity structural life defines the actual life of the act6ivity and is used for calculating residual value of that activity. For example, activity 2 in alternative 2, adding approach slab in year 2014, has a service life of 80 years. The silica fume overlay (SFO) will be applied on bridge deck in year 2039, which means after 25 years from activity 2 (2039-2014 = 25). Therefore, the service life of activity 2 is equal to 25 years and its structural life is 80 years. Figure 4-21 shows the input data for activity 2 in RealCost program. Figure 4-22 shows the distribution of agency cost for alternatives 1 and 2. Table 4-11 lists the results of NPV and EUAC for alternatives 1 and 2. These results are presented in Figure 4-23, which shows that alternative 2 (deck widening) has a lower net present value than deck replacement.

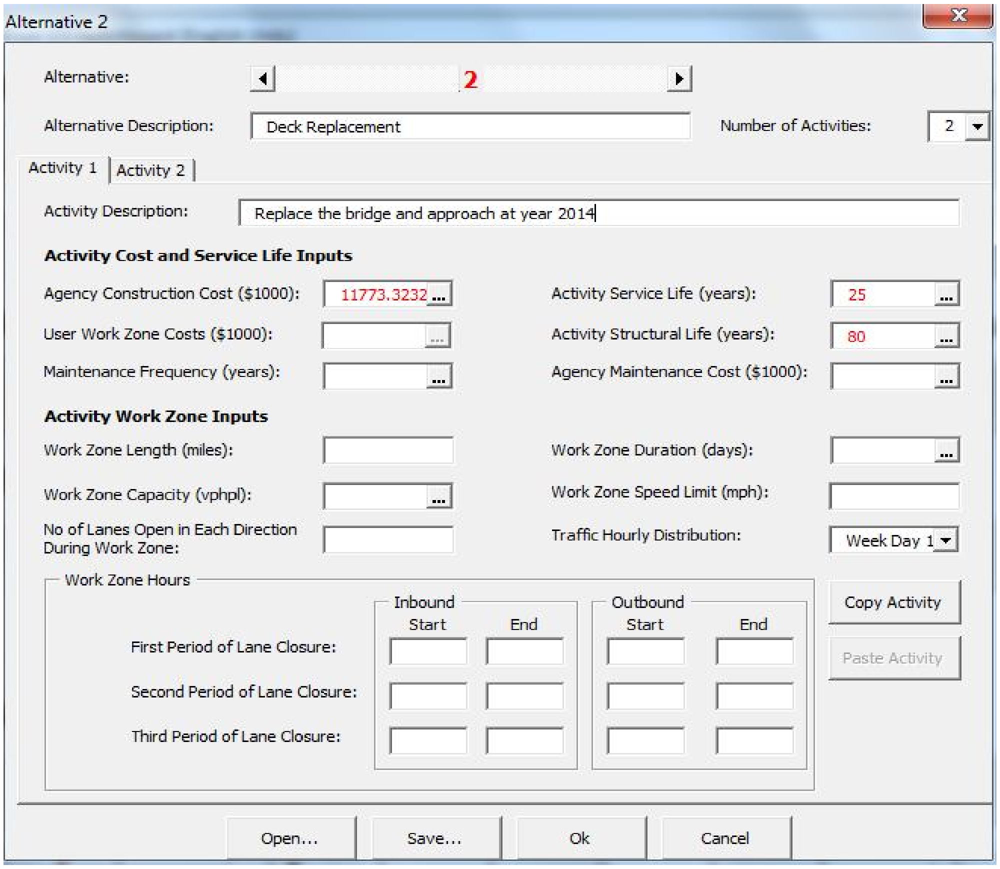

Figure 4-21: Input data for structural and service life for alternative 2 in RealCost program

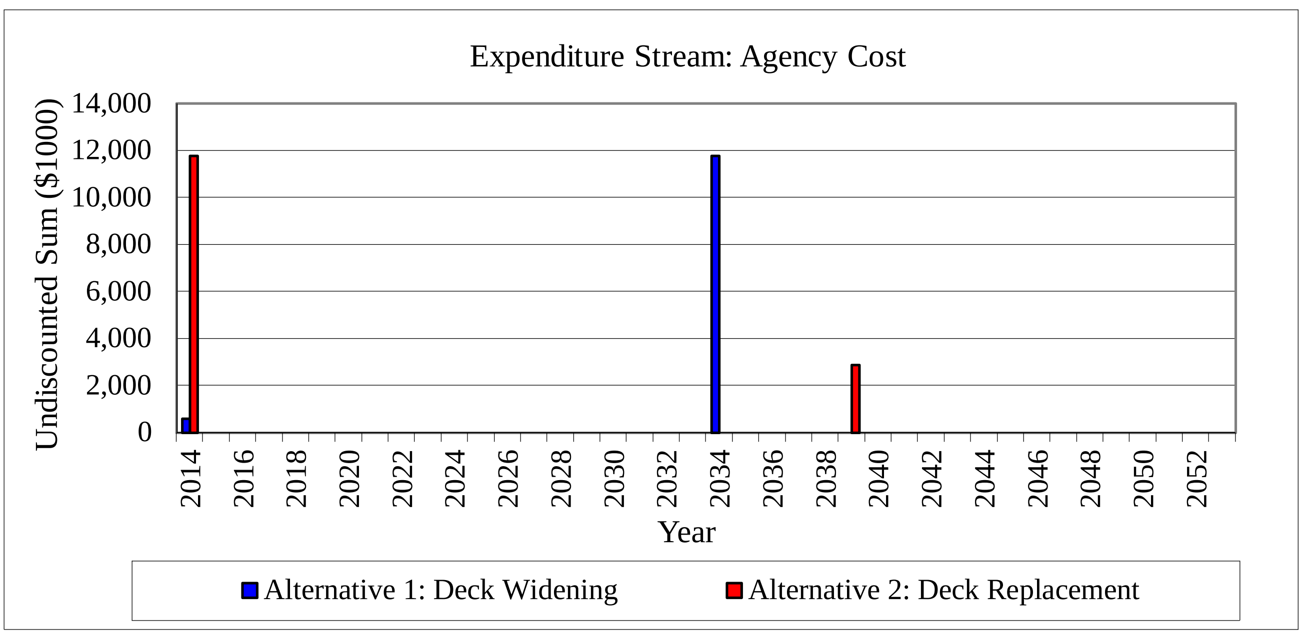

Figure 4-22: Distribution of agency cost for alternatives 1and 2 in example 3

Table 4-11: LCCA results for example 3

Total Cost		
Total Cost	Alternative 1: Deck Widening	Alternative 2: Deck Replacement
	Agency Cost ($1000)	Agency Cost ($1000)
Undiscounted Sum	*$3,543.21*	*$7,617.79*
Present Value	$3,597.74	$11,702.90
EUAC	$224.21	$729.33

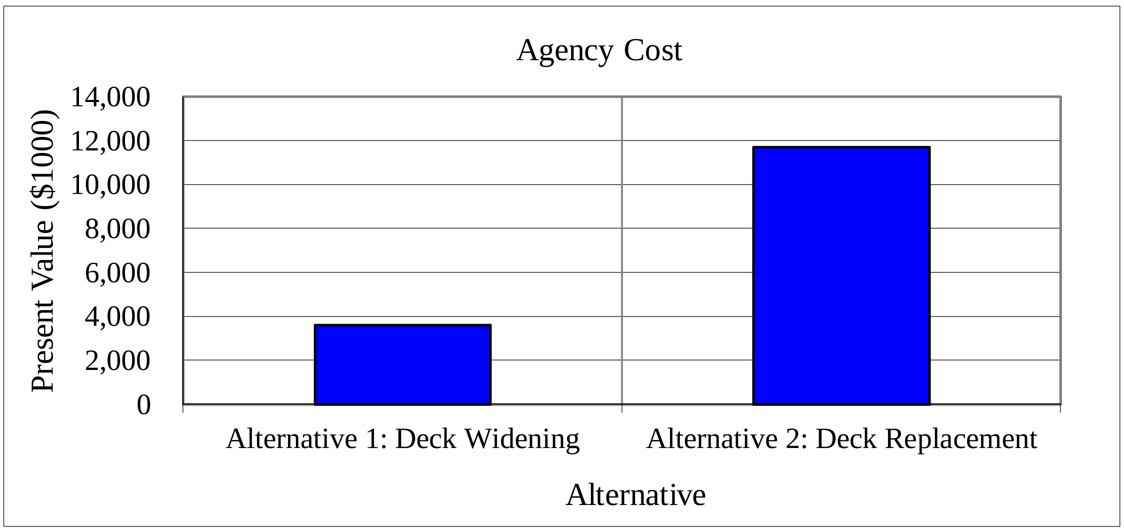

Figure 4-23: Net present value for alternatives 1 and 2 in example 3

4.5. Summary

In this chapter, deterministic LCCA for deck overlay decisions, expansion joint replacement decision, and deck widening versus deck replacement are presented. For deck overlay decision, SFO on bare deck at condition 5 and 6, EPO and PO on bare deck at condition 7 were compared with bare deck. Results have shown that SFO on bare deck at condition 6 had the lowest net present value. Also, the minimum required service life of EPO and PO to delay a more expensive action were between 11 to 14 and 17 to 22 years, respectively. In expansion joint replacement decision, relocating abutment expansion joints at the grade beam; and replacing abutment expansion joints at the same place were compared. Results have demonstrated that replacing abutment expansion joints at the same place has the lower net present value. For deck widening versus deck replacement decision, analysis results of five bridges have shown that deck widening had a lower net present value than deck replacement.

5 PROBABILISTIC ANALYSIS

5.1 Introduction

Probabilistic methods allow decision makers to evaluate the risk of an investment utilizing uncertain input variables, assumptions, or estimates (FHWA 1998). Probabilistic LCCA tools conduct a simulation (typically using Monte Carlo simulation) to sample the input and generate a probability distribution function (PDF) for the different economic indicators considered in the analysis. Walls and Smith (1998) proposed a probabilistic methodology for pavement LCCA, which used Monte Carlo simulation and risk analysis Excel Add-in tools. StratBenCost (NCHRP 2-18, 2001) uses a similar approach and provides default median and ranges for all variables relevant to the user costs. With deterministic LCCA, discrete values are assigned to individual parameters. In contrast, probabilistic LCCA allows the value of individual analysis inputs to be defined by a frequency (probability) distribution. For a given project alternative, the uncertain input parameters are identified. Then, for each uncertain parameter, a sampling distribution of possible values is developed. Simulation programming randomly draws values from the probabilistic description of each input variable and uses these values to compute a single forecasted present value (PV). This sampling process is repeated through thousands of iterations. From this iterative process, an entire probability distribution of PVs is generated for the project alternative along with the mean PV for that alternative. The resulting PV distribution can then be compared with the projected PVs for alternatives, and the most economical option for implementing the project may be determined for any given risk level. Probabilistic LCCA also allows for the simultaneous computation of differing assumptions for many different variables. It conveys the likelihood that a particular LCC forecast will actually occur.

5.2 Probabilistic Parameters

RealCost is FHWA’s Microsoft Excel based LCCA software package that is based on the FHWA Technical Bulletin of 1998. The software can perform LCCA in either a deterministic or a probabilistic form. For the deterministic approach, discrete values are assigned for each input variable. In contrast, probabilistic LCCA allows the value of individual analysis inputs to be defined by a probability distribution (FHWA, 2004). For a given project alternative, the uncertain input parameters are identified. Then, for each uncertain parameter, a probability distribution needs to be determined. Seven types of probability distributions are available in RealCost. For each probability distribution chosen, the values that define the type of distribution, as shown in Table 5-1, must be entered.

Table 5-1: Probability distributions and the values to be provided

Probability Distribution Type	Values to be Provided
Uniform	Minimum, maximum
Normal	Mean standard deviation
Log normal	Mean standard deviation
Triangular	Minimum, most likely, maximum
Beta	Alpha, beta
Geometric	Probability
Truncated normal	Mean, standard deviation, minimum, maximum
Truncated log normal	Mean, standard deviation, minimum, maximum

The built-in probabilistic inputs in Real Cost 2.5 software are: discount rate, agency construction cost, activity service life, and agency maintenance cost. The software allows the user to assign probability distributions to other desired inputs as well. Moreover, when performing a probabilistic analysis, RealCost is able to create reproducible results (i.e., the randomness associated with the simulation numbers can be eliminated). If random results are chosen, the computer will generate a seed value (the value that the simulation starts with) from its internal clock. However, when reproducible results are chosen, the analyst specifies a specific seed value. This value is used in all simulations. This causes the same set of random numbers to be generated by the computer allowing the analyst to perform separate simulation runs to compare multiple alternatives.

The discount rate probability distribution function considered in this study has uniform distribution with minimum value equal to 3% and maximum value equal to 8%. Minimum discount rate equal to 3% is based on office of budget and management guideline (circular A-94) and maximum discount rate equal to 8% is based on real discount rate history (NCHRP 483). Based on NDOR cost data, normal probability distribution function with 10% variation of mean value is considered in analysis. For instance, agency cost for alternative 1 in example 1 (chapter 4) were equal to $603,950. Therefore, mean value and standard deviation for this alternative is calculated to be 603,950 and $60.395, respectively.

5.3. Deck Overlay Decision

Probability distribution function for bare deck is considered as normal distribution (Hatami and Morcous, 2011). Table 5-2 lists mean value and standard deviation for bare deck at different condition rating.

Table 5-2: Mean value and standard deviation for bare deck at different condition rating

Bare Deck	State Bridges – From 1998 to 2010					
Condition Rating	9	8	7	6	5	4
Number of Data	2530	3191	988	1096	896	280
Average Age	6.7	16.6	34.0	37.5	44.0	46.4
STDEV	4.6	7.6	9.5	9.9	10.3	10.5
COV	67.7%	45.9%	28.1%	26.5%	23.5%	22.5%

Because there is limited data for SFO, EPO and PO performance, triangular probability distribution functions are considered. Table 5-3 shows the probability distribution functions for SFO, EPO and PO.

Table 5-3: Probability distribution functions for SFO, EPO and PO

Type of Overlay	Triangular Probability Distribution Function		
	Minimum (years)	Most Likely (years)	Maximum (years)
Silica Fume Overlay (SFO)	20	25	30
Epoxy Coated Overlay (EPO)	5	10	15
Polyester Overlay (PO)	12	16	20

It is assumed that the structural life of the deck will extend for 25, 10, and 16 years by applying the SFO, EPO, and PO at each condition, respectively. The results from deterministic analysis for EPO and PO have shown that realistic service life for EPO and PO are 15 and 20 years, respectively. Table 5-4 shows the revised probability distribution function used in this analysis.

Table 5-4: Probability distribution function for SFO, EPO and PO

Type of Overlay	Triangular Probability Distribution Function		
	Minimum (years)	Most Likely (years)	Maximum (years)
Silica Fume Overlay (SFO)	20	25	30
Epoxy Coated Overlay (EPO)	10	15	20
Polyester Overlay (PO)	15	20	25

The problem investigated in this example is the selection of lowest LCC alternative among the following alternatives: 1) bare deck; 2) SFO on bare deck at condition 5; 3) SFO on bare deck at condition 6; 4) EPO on bare deck at condition 7; and 5) PO on bare deck at condition 7. Figure 5-1 shows the distribution of agency cost for these alternatives.

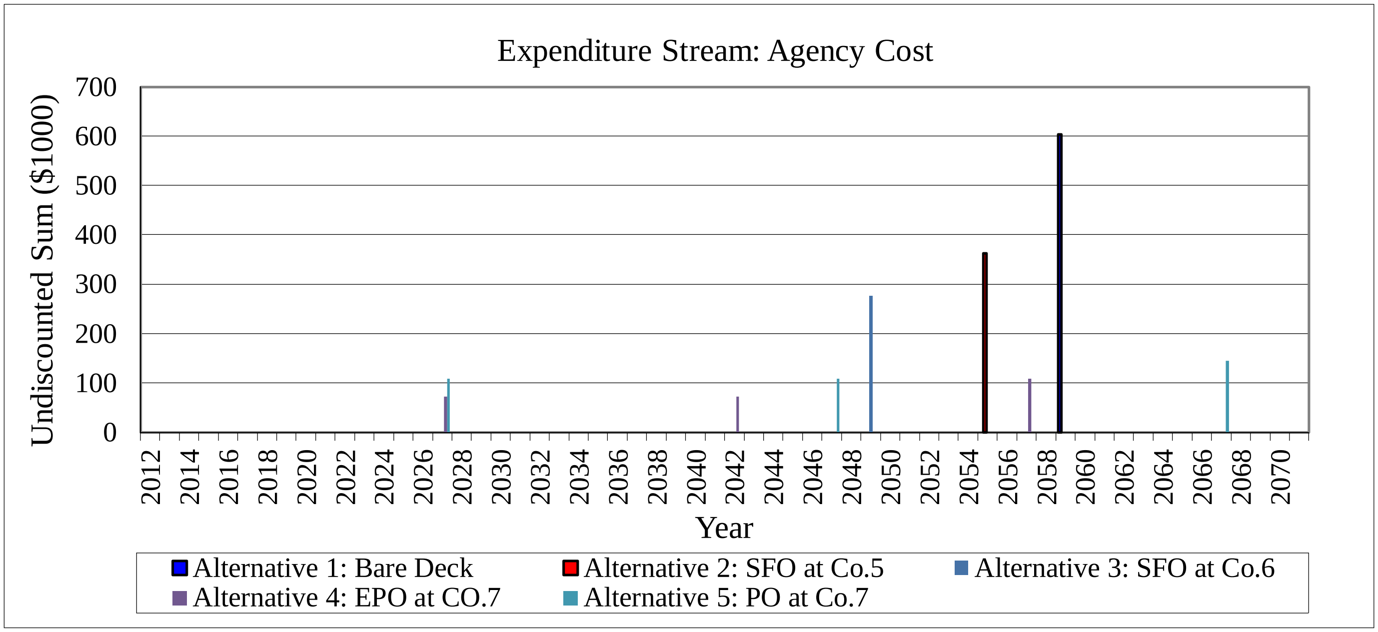

Figure 5-1: Distribution of agency cost for alternatives 1 to 5 in deck overlay example

The results of deterministic analysis show that EPO on bare deck at condition 7 has the lowest LCC. Table 5-5 shows the results of NPV and EUAC for alternatives 1 to 5 using the probabilistic analysis. These results plotted in 5-2 indicate that the same conclusion.

Table 5-5: LCCA results for deck overlay alternatives

Total Cost	Alternative 1: Bare Deck	Alternative 2: SFO at Co.5	Alternative 3: SFO at Co.6	Alternative 4: EPO at CO.7	Alternative 5: PO at Co.7
	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)
Undiscounted Sum	$326.46	$333.38	$277.82	$253.66	$253.66
Present Value	$138.05	$116.47	$111.12	$105.12	$118.48
EUAC	$4.99	$4.21	$4.02	$3.80	$4.28

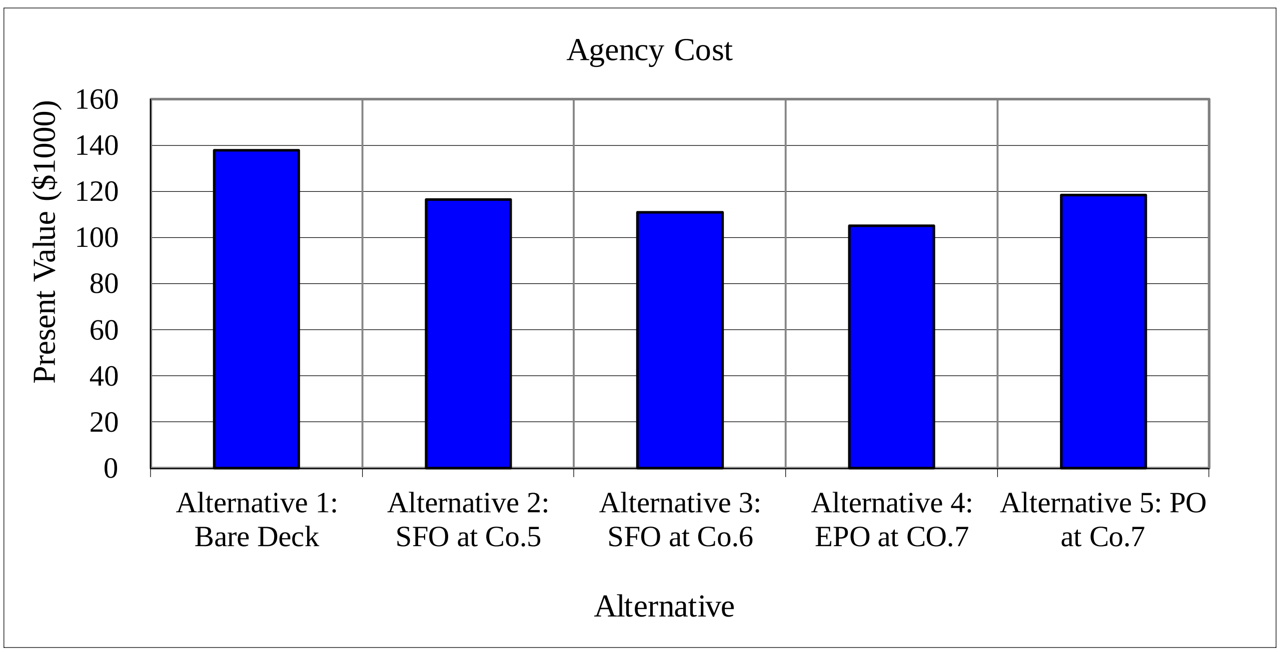

Figure 5-2: Net present value for alternatives 1 to 5 in deck overlay example

The agency costs include the initial construction cost, cost for rehabilitation, and cost for maintenance activities carried out during the life time of the deck. The cumulative distribution graphs are obtained by implementing several iterations of the inputs using Monte Carlo simulation technique in RealCost. The analysis period over which the life cycle costs are calculated for the design alternatives is 60 years and with discount rate of 3%. Figure 5-3 shows the cumulative distribution of the agency costs for all the deck overlay alternatives. The bare deck (alternative 1) is the most expensive alternative and the EPO on bare deck at condition 7 (alternative 4) is the most economical alternatives. The results show a 90% probability (cumulative) for the EPO on bare deck at condition 7 to yield the lowest costs to the agency.

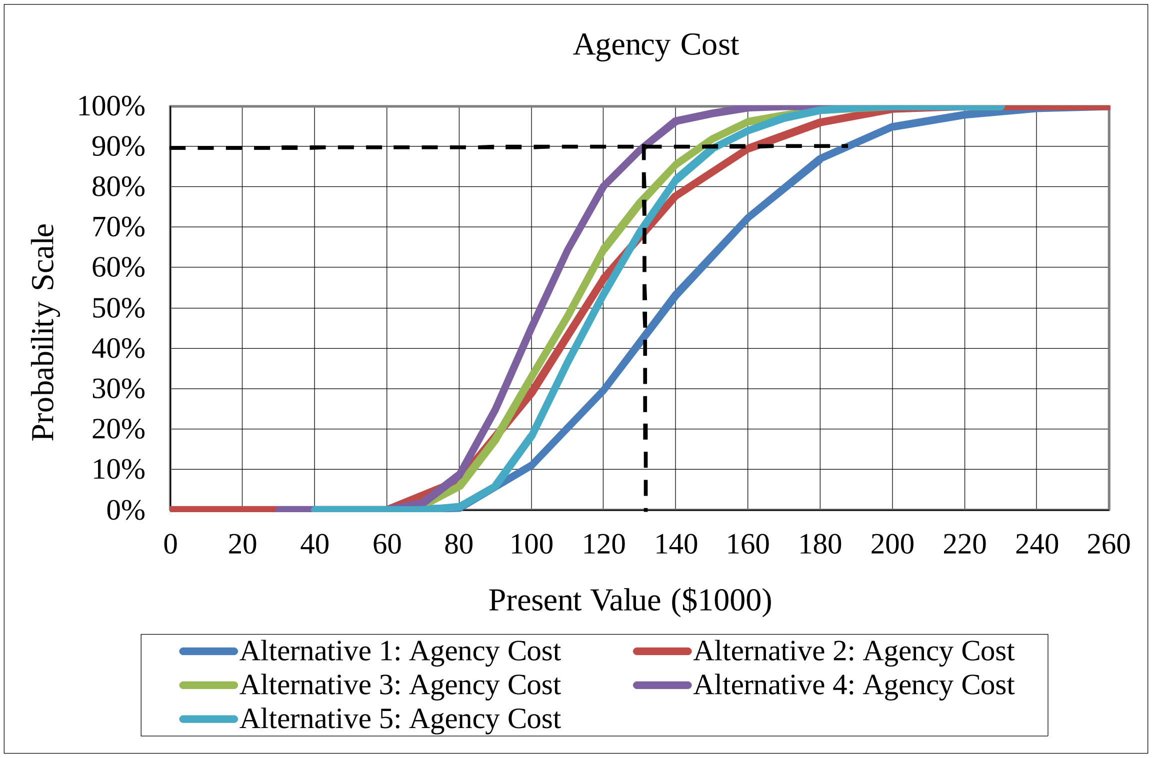

Figure 5-3: Relative cumulative probability distributions of the deck overlay alternatives

Figure 5-3 also shows that the bare deck has higher life cycle agency costs than the other design alternatives. Another way to read the plot is that, for a net present value of $130,000 there is a 40% probability that the bare deck can be constructed at that cost. There is a 90% probability that the EPO on bare deck at condition 7 can be constructed for the same cost. The probabilities for the SFO on bare deck at condition 6 and PO on bare deck at condition 7 for a net present value of $130,000 are 77% and 70%, respectively.

Table 5-6 shows the mean, standard deviation, minimum and maximum values of the agency costs obtained through running a probabilistic analysis using RealCost software for the deck overlay alternatives. Figure 4 plots the probability distribution of the NPV for each of the five investigated alternatives. It indicates that EOP on bare deck at condition 7 (alternative 4) has the highest probability of having less NPV than the other deck overlay alternatives followed by SFO on bare deck at condition 6 (alternative 3).

Table 5-6: Mean distributions of costs for deck overlay example (Monte Carlo simulation values)

Total Cost (Present Value)	Alternative 1: Bare Deck	Alternative 2: SFO at Co.5	Alternative 3: SFO at Co.6	Alternative 4: EPO at CO.7	Alternative 5: PO at Co.7
	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)	Agency Cost ($1000)
Mean	$140.68	$118.63	$113.52	$104.12	$120.40
Standard Deviation	$33.52	$29.76	$24.58	$18.93	$22.35
Minimum	$67.71	$57.35	$59.45	$63.28	$76.45
Maximum	$257.88	$214.94	$196.88	$163.13	$194.84

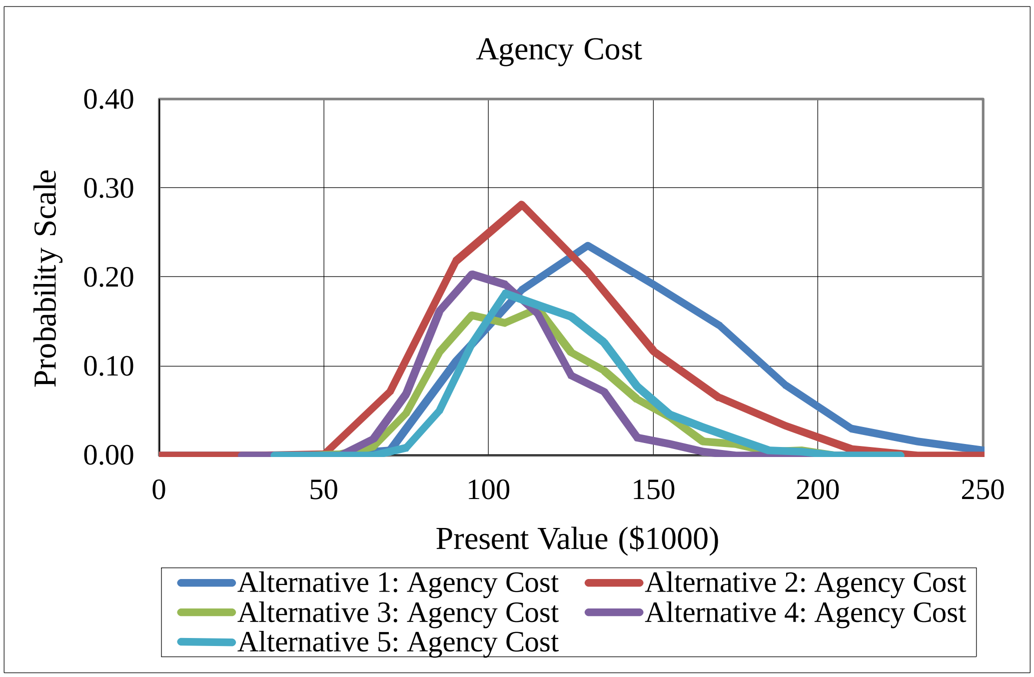

Figure 5-4: Agency cost distributions of deck overlay alternatives

The correlation coefficient plots, known as the tornado plots, are part of the sensitivity analysis. As there are several inputs involved in the computation of the total costs, a sensitivity analysis study is conducted to find out the inputs that have a dominant effect on the final output. Any input with a correlation value less than 0.10 is considered ineffective and not to have a significant effect on the final output. A positive correlation value can be understood as having a directly proportional effect on the output, similarly a negative correlation value can be considered as having an inversely proportional effect on the output. The tornado plot in Figure 5-5, indicates that discount rate has highest negative correlation to the output meaning that with an increase in the discount rate there would be a decrease in the overall costs. Cost of deck replacement (agency cost in activity 2) has a more positive effect on the total costs than any other input. The 0.45 correlation value for deck replacement means that if agency cost moves one standard deviation in either direction, the present value of the bare deck will move 0.45 of standard deviation in the same direction. In case of a negative correlation value, as in the discount rate, if it moves one standard deviation in either direction, the present value will move 0.88 standard deviations in the opposite direction. Figures 5-6, 5-7, 5-8, and 5-9 show similar plots for other alternatives.

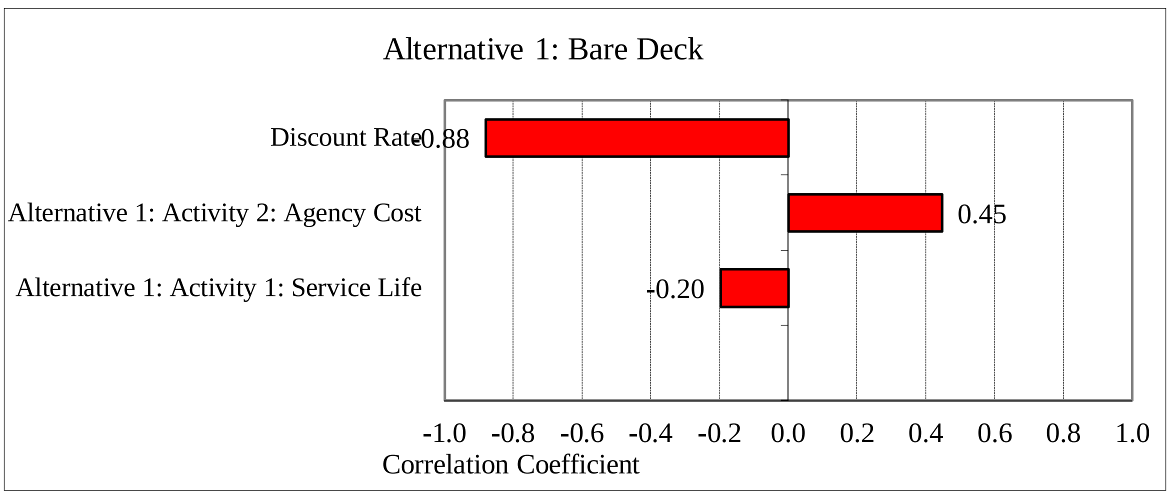

Figure 5-5: Correlation coefficient plots for alternative 1 (bare deck) in deck overlay example

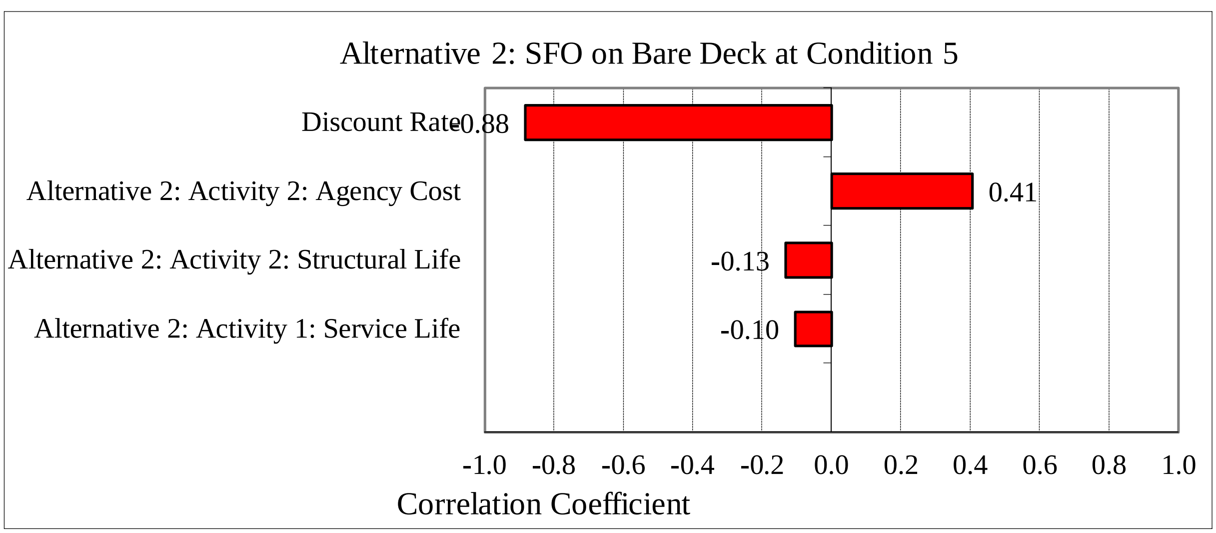

Figure 5-6: Correlation coefficient plots for SFO on bare deck at condition 5

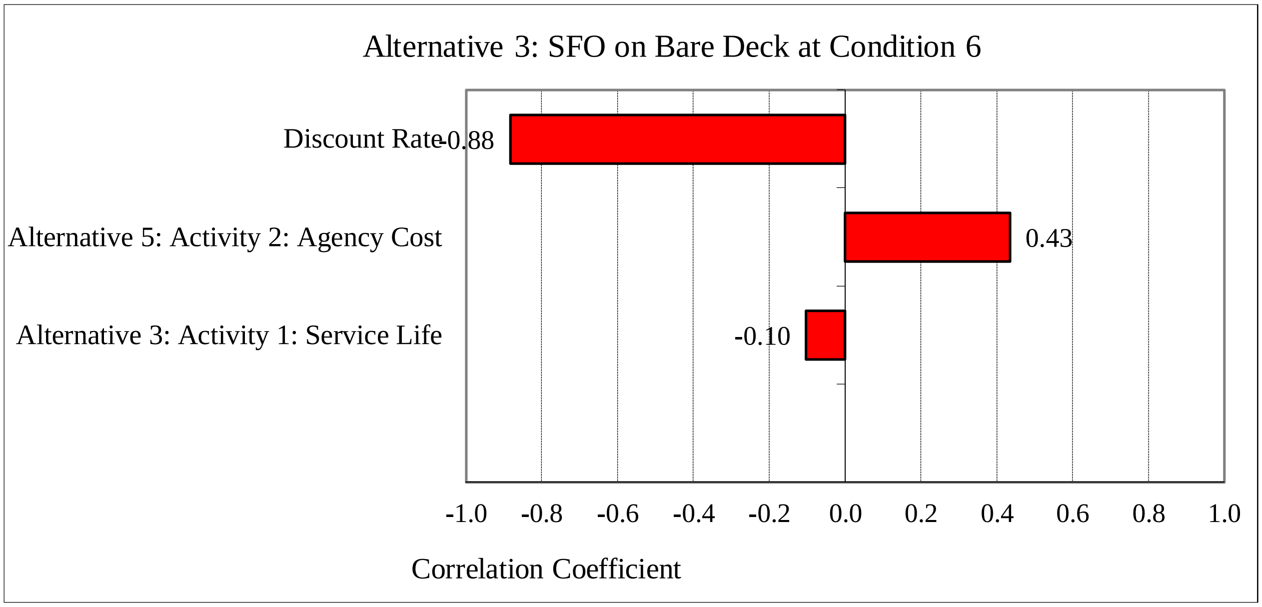

Figure 5-7: Correlation coefficient plots for SFO on bare deck at condition 6

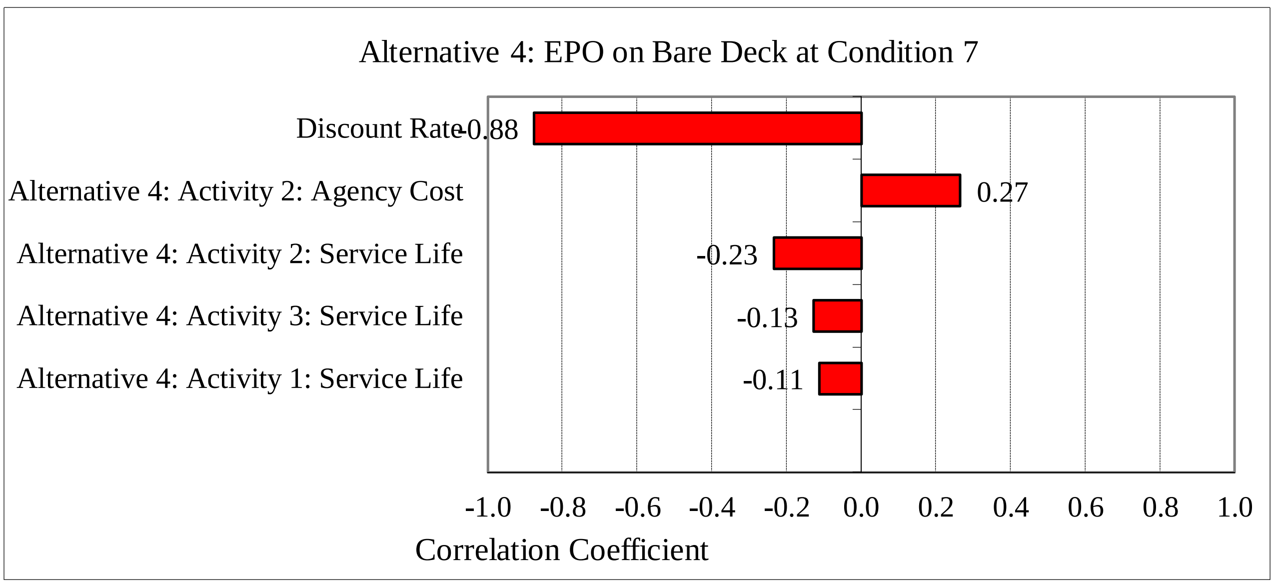

Figure 5-8: Correlation coefficient plots for EPO on bare deck at condition 7

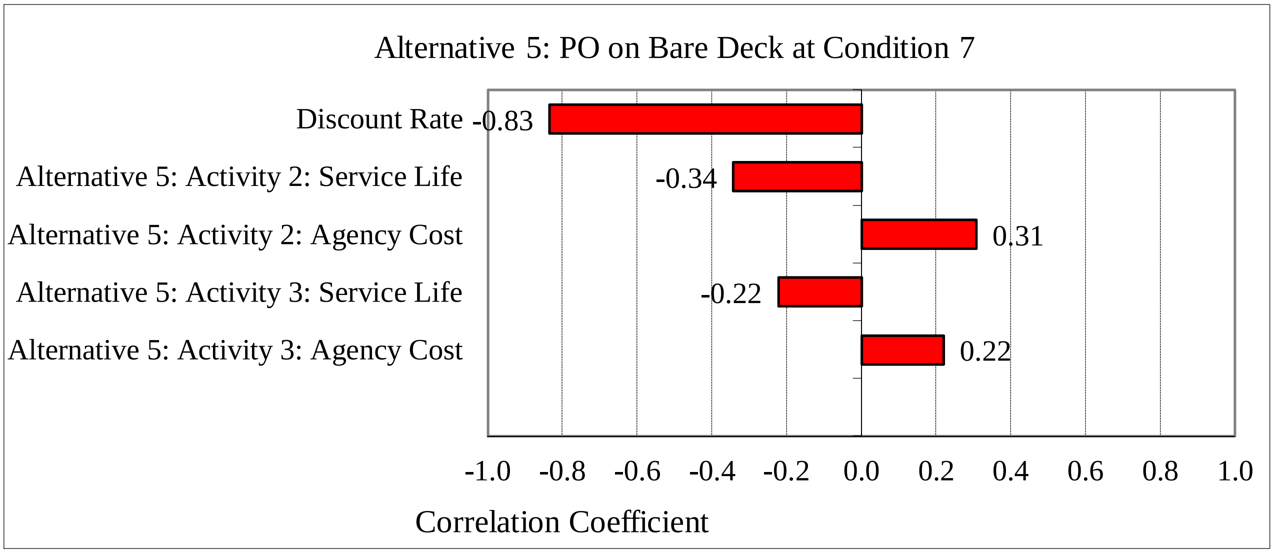

Figure 5-9: Correlation coefficient plots for PO on bare deck at condition 7

5.4. Expansion Joint Replacement Decision

The problem investigated in this example is the selection of lowest LCC alternatives among two alternatives: 1) replacing the abutment expansion joint and relocating at the grade beam, and 2) replacing the abutment expansion joint at the same place. Deterministic analysis shows that alternative 2 has the lowest LCC. Figure 5-10 shows the cumulative distribution of the agency costs for the two alternatives. This figure clearly shows that replacing the abutment expansion joint at the same place (alternative 2) is the economical alternative. The results show a 90% probability (cumulative) for the alternative 2 to yield the lowest agency costs. Table 5-7 shows the mean, standard deviation, minimum and maximum values of the agency costs obtained through running a probabilistic analysis using RealCost software for the expansion joint replacement decision. Figure 5-11 shows the probability distribution of agency cost of each alternative. As shown in this figure, replacing the abutment expansion joint at the same place (alternative 2) has less present value for a given probability than replacing the abutment expansion joint and relocating at the grade beam.

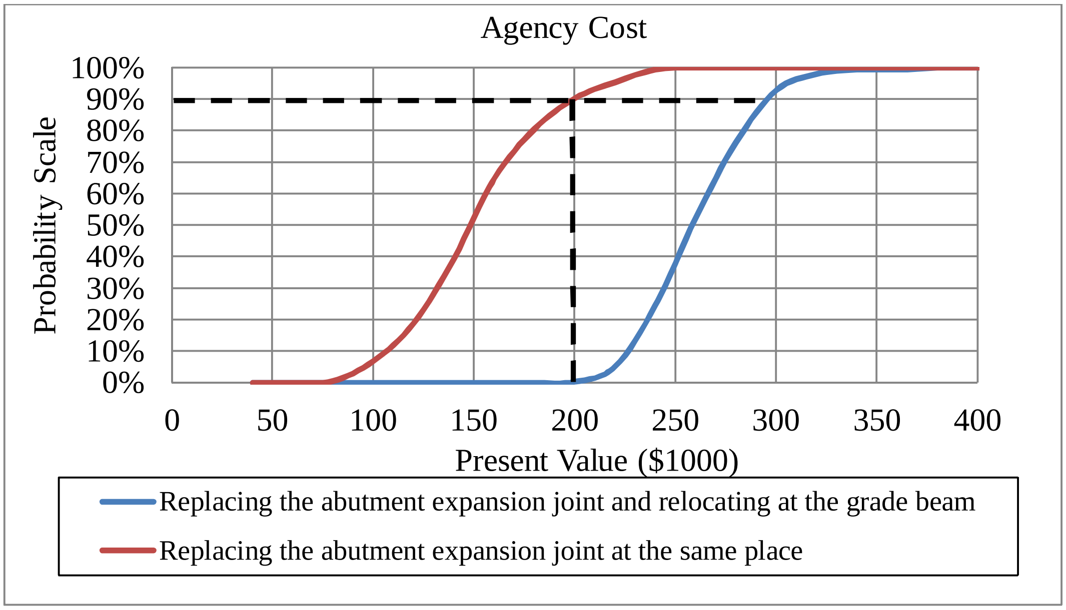

Figure 5-10: Relative cumulative probability distributions of the deck overlay alternatives

Table 5-7: Mean distributions of costs for expansion joint example (Monte Carlo simulation)

Total Cost (Present Value)	Alternative 1: Relocating abutment expansion joints at the grade beam	Alternative 2: Replacing abutment expansion joints at the same place
	Agency Cost ($1000)	Agency Cost ($1000)
Mean	$260.35	$150.77
Standard Deviation	$27.08	$35.15
Minimum	$199.53	$73.45
Maximum	$374.63	$253.01

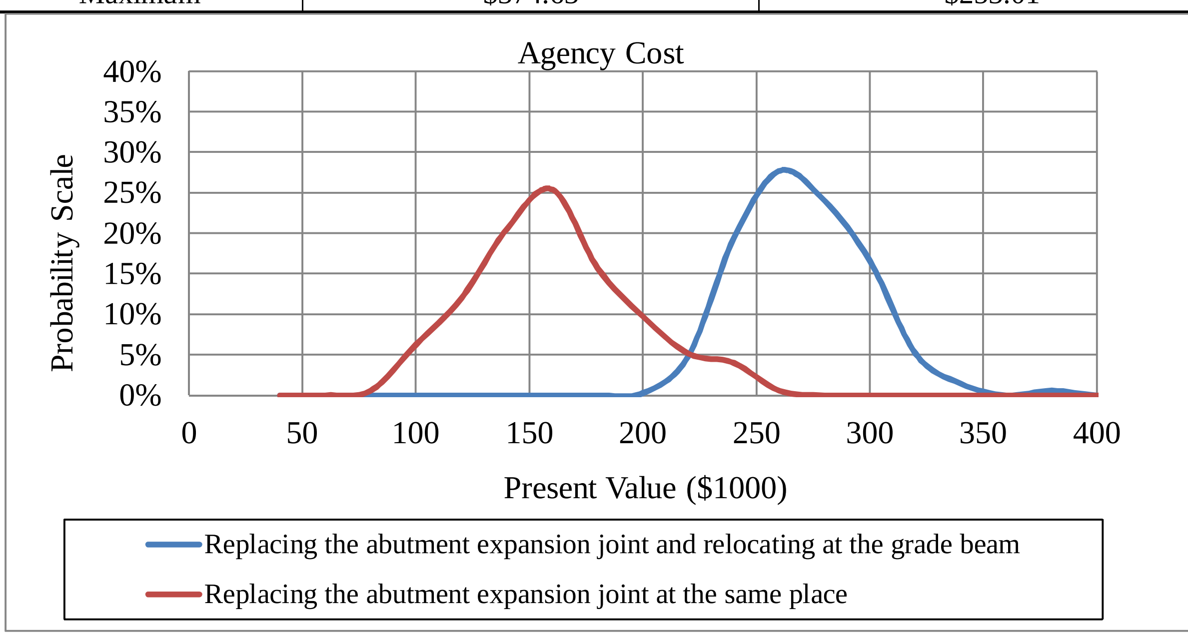

Figure 5-11: Agency cost distributions of expansion joint replacement alternatives

Figure 5-12 shows the tornado graph for replacing the abutment expansion joint and relocating at the grade beam (alternative 1). This figure shows that initial construction cost (agency cost of activity 1) has 99% effect on the total costs than any other input which means that if initial construction cost in alternative 1 moves one standard deviation in either direction, then the present value of replacing the abutment expansion joint and relocating at the grade beam will move 0.99 of standard deviation in the same direction. Structural life of activity 1 has a negative correlation to the output, meaning that with an increase in the structural life there would be a decrease in the overall costs.

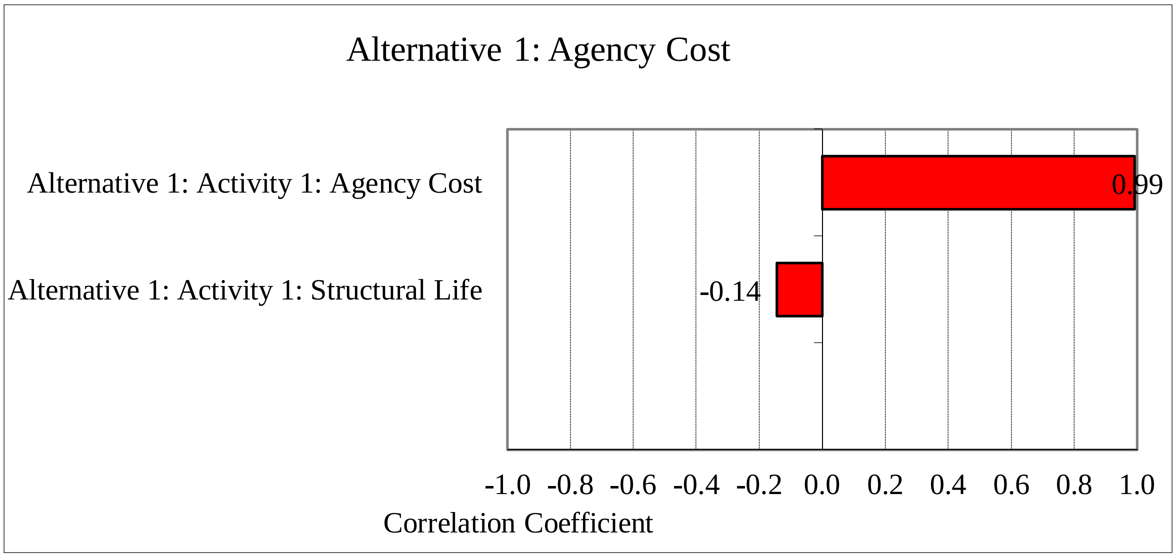

Figure 5-12: Correlation coefficient plots for replacing the abutment expansion joint and relocating at the grade beam

The sensitivity analysis results for replacing the abutment expansion joint at the same place is shown in Figure 5-13. The results show that service life of bridge deck and discount rate have the highest negative correlation to the output meaning that with an increase in these parameters there would be a decrease in the overall costs. Cost of bearing replacement and superstructure repair (agency cost in activity 2) have a more positive effect on the total costs than any other input.

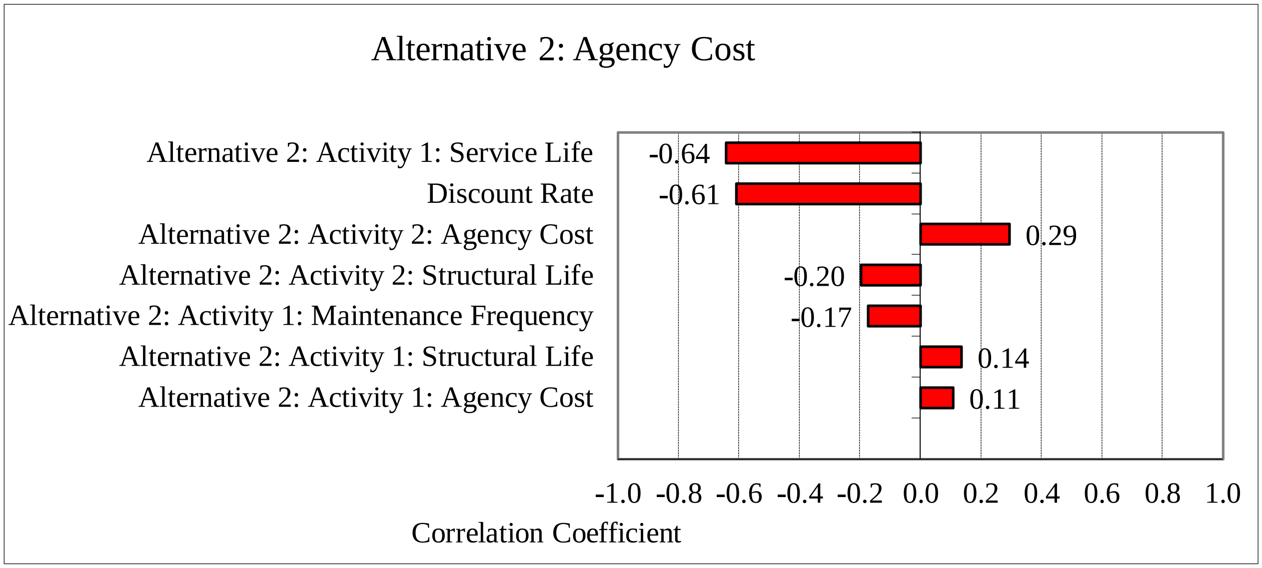

Figure 5-13: Correlation coefficient plots for replacing abutment expansion joint at the same place

5.5. Deck Widening VS Deck Replacement

The problem is to compare deck widening versus deck replacement in 5 different bridges. Information on these bridges and deterministic analysis results are presented in chapter 4. The deterministic analysis indicates that deck widening has a lower net present value than deck replacement. Figure 5-14 shows the cumulative distribution of the agency costs for deck widening and deck replacement using probabilistic analysis. This figure clearly shows that the deck replacement has significantly higher life cycle agency cost than the deck widening. For a net present value of $6,000,000 there is a 90% probability that the deck widening can be constructed at that cost. However, there is a 0% probability that the deck can be replaced with the same cost. Table 5-8 shows the mean, standard deviation, minimum and maximum values of the agency costs obtained through running a probabilistic analysis using RealCost software.

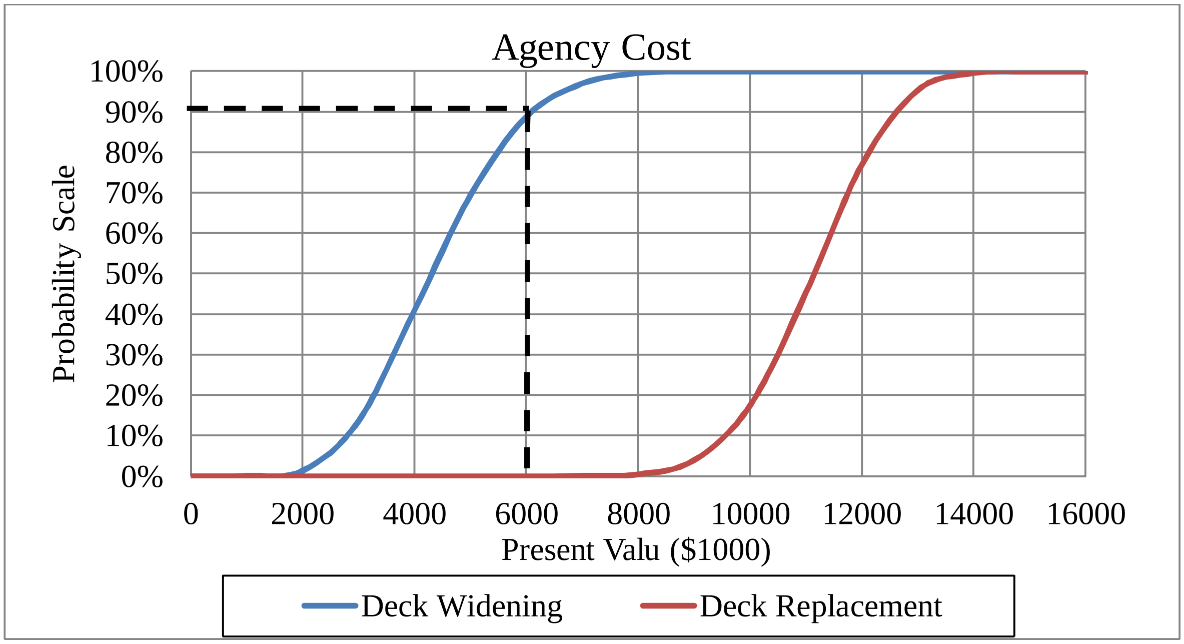

Figure 5-14: Relative cumulative probability distributions for deck widening and replacement

Table 5-8: Mean distributions of costs for deck widening versus replacement

Total Cost (Present Value)	Alternative 1: Deck Widening	Alternative 2: Deck Replacement
	Agency Cost ($1000)	Agency Cost ($1000)
Mean	$4,391.11	$11,094.25
Standard Deviation	$1,270.95	$1,175.72
Minimum	$685.94	$6,928.08
Maximum	$8,951.50	$14,287.98

Figure 5-15 presents the agency cost distribution of deck widening and deck replacement. The mean distributions highlight the mean value of the normally distributed present values of costs. As each value represents a possible scenario, considering three standard deviations to the either side of the mean makes sure that each and every possible cost scenario is taken into account during the risk analysis. As shown in figure 5-15, deck widening has a lower present value than the deck replacement for any given probability.

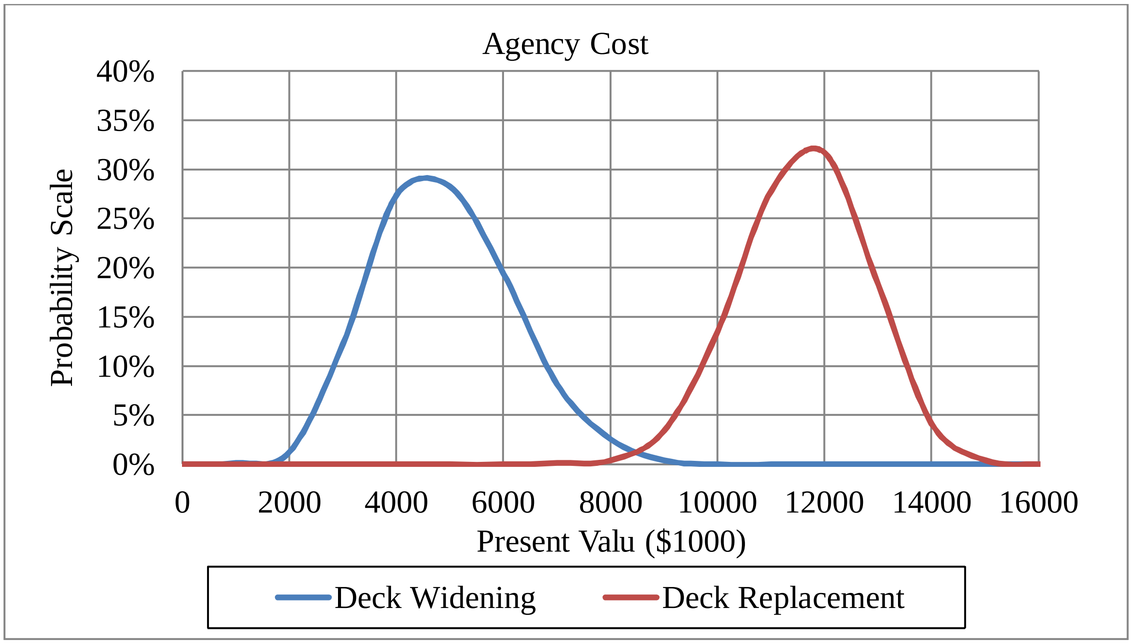

Figure 5-15: Agency cost distributions of deck overlay alternatives

Looking at the deck widening tornado plot in Figure 5-16, service life has highest negative correlation to the output meaning that an increase in the service life causes a decrease in the cost. Cost of the deck widening has positive effect on the total costs than any other input, meaning that if the deck widening agency cost moves one standard deviation in either direction then the present value of the bare deck moves 0.24 of standard deviation in the same direction.

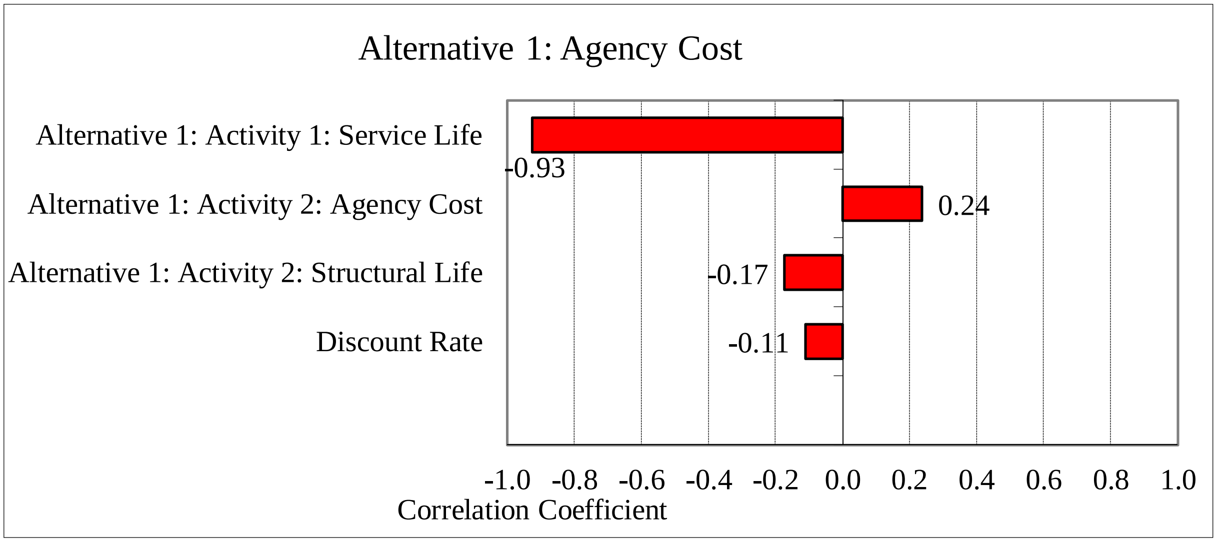

Figure 5-16: Correlation coefficient plots for deck widening

The sensitivity analysis result for the deck replacement is shown in Figure 5-17. Cost of deck replacement has the highest correlation to the output meaning that an increase in the cost of deck replacement causes an increase in total cost. Service life of deck has a negative correlation meaning that an increase in the service life of deck causes a decrease in total cost.

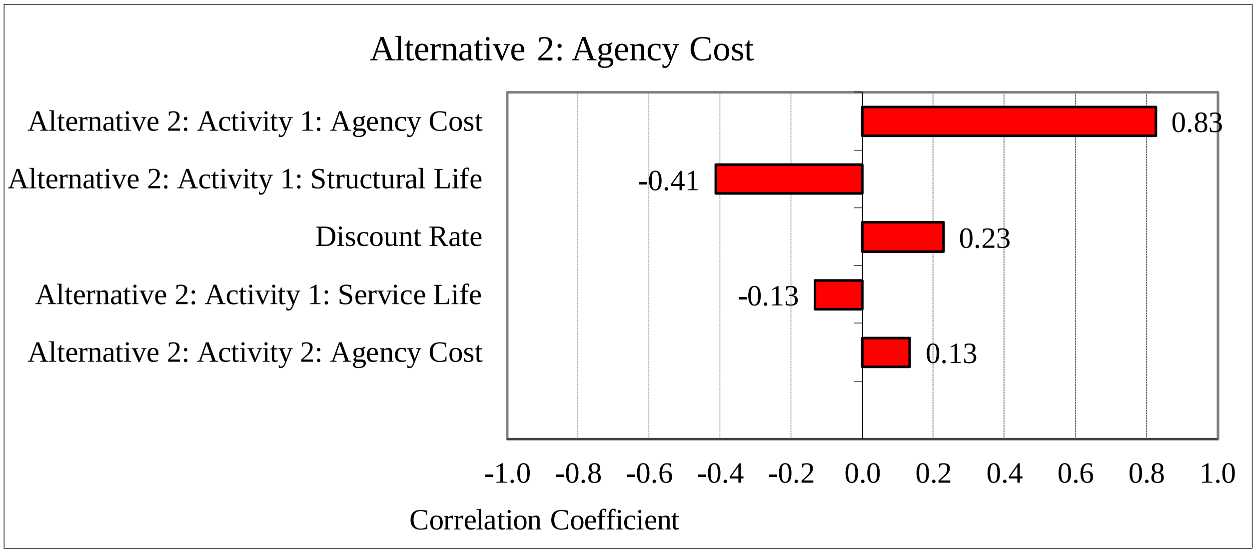

Figure 5-17: Correlation coefficient plots for deck replacement

5.6. SUMMARY

Probabilistic analysis conducted using RealCost software yielded similar results to the deterministic analysis conducted in chapter 4. In the deck overlay decision example, bare deck, SFO on bare deck at condition 5 and 6, EPO and PO on bare deck at condition 7 were compared. Results showed that EPO has the lowest net present value. For the expansion joint replacement decision example, replacing abutment expansion joints at the same place had a lower net present value than the relocating abutment expansion joints at the grade beam. For the deck widening versus deck replacement example, deck widening had a lower net present value. The difference between the deterministic and probabilistic results in all examples is in the range of $1,000-$3,000.

Also for the deck overlay decision example, the sensitivity analysis indicated that discount rate has the highest negative correlation to the output followed by structural service life. Agency cost has the highest positive correlation to the output. For the expansion joint example, agency cost has the highest positive correlation and service life has a negative correlation to the output in relocating abutment expansion joints at the grade beam alternative. However, in the replacing abutment expansion joints at the same place alternative, discount rate has the highest negative correlation to the output followed by service life, while agency cost has the highest positive correlation to the output. For the deck widening versus deck replacement example, agency cost has the highest positive correlation and service life has the highest negative correlation to the output.

6 CONCLUSIONS

Deterministic and probabilistic LCCA using the RealCost software was conducted for three different decision examples: deck overlay decision, expansion joint replacement decision, and deck widening versus deck replacement decision. For the deck overlay decision, bare deck, silica fume overlay (SFO) on bare deck at condition 5, SFO on bare deck at condition 6, epoxy polymer overlay (EPO) and polyester overlay (PO) on bare deck at condition 7 were considered. For the expansion joint replacement decision, replacing abutment expansion joints at the same place and relocating them at the grade beam were compared. For the deck widening versus deck replacement decision, analysis was conducted on five bridge projects. The main conclusions from these examples can be summarized as follows:

1) SFO on bare deck at condition 6 has a lower net present value than bare deck and SFO on bare at condition 5.
2) EPO on bare deck at condition 7 has a lower net present value than bare deck, SFO on bare deck at condition 5 and 6, and PO on bare deck at condition 7.
3) Minimum required service life of EPO and PO to delay a more expensive action are between 11 to 14 and 17 to 22 years, respectively depending on the type of the action being compared to.
4) Replacing abutment expansion joints at the same place has a lower net present value than relocating them at the grade beam despite the fact that it causes deterioration of girder ends and bearings at a higher rate.
5) Deck widening has a lower net present value than deck replacement for the given agency cost and service life.
6) Probabilistic analysis yields results that are consistent with those of the deterministic analysis.
7) Based on the results of the sensitivity analysis, it was found the agency cost has the highest positive correlation to the output, while service life and discount rate have the highest negative correlation to the output.

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