A Briefing on Life-Cycle Cost Analysis of New Bridge Design Alternatives

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The second Strategic Highway Research Program (SHRP2) is a national partnership of key transportation organizations: the Federal Highway Administration, American Association of State Highway and Transportation Officials, and Transportation Research Board. Together, these partners are deploying products that will help the transportation community enhance the productivity, boost the efficiency, increase the safety, and improve the reliability of the nation's highway system.

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1 Introduction

This document has been developed to promote the concept of integrating the principles of Life Cycle Cost Analysis (LCCA) with Service Life Design (SLD) of bridges. The primary focus of this brief is on the application of the LCCA during bridge design. While life cycle cost (LCC) is not the focus of the R19A SLD project, this brief aims to demonstrate the importance of considering both the initial cost and cost of ownership in bridge SLD. The brief includes a worked LCC example for maintenance of a bridge and an example wherein LCCA is used to evaluate two potential design features of a bridge.

1.1 Background

The life cycle of a bridge involves the following phases in the life of the structure:

- Design
- Construction
- Maintenance
- Demolition

The first life cycle phase is design for both structural integrity and durability. The latter is also known as SLD, a rational engineering approach to specify and provide durable structural materials and component details to resist deterioration resulting from the prevailing environmental exposure conditions.

LCCA is an engineering economic analysis tool that allows transportation officials to quantify the differential costs of alternative investment options for a given project. At a project level, LCCA of alternative new bridge designs seeks to quantify the differential costs associated with differing design features to allow optimization of costs.

Figure 1 shows a graphical representation of the events making up the life cycle of a bridge. The horizontal axis represents time and identifies activities occurring in each phase. The vertical axis represents the condition of the structure. A design condition is planned that may be exceeded, achieved, or not achieved during construction. The condition changes with time during service, as assessed through a schedule of necessary inspections and/or monitoring (indicated as 'Inspection' on Figure 1) and periodic monetary investments are made to help preserve the structure (that is, maintain or improve the condition) through cyclical and condition-based maintenance or replacement of replaceable components. LCCA may be used to schedule and quantify these activities and investments to help owners make decisions throughout the life of the structure.

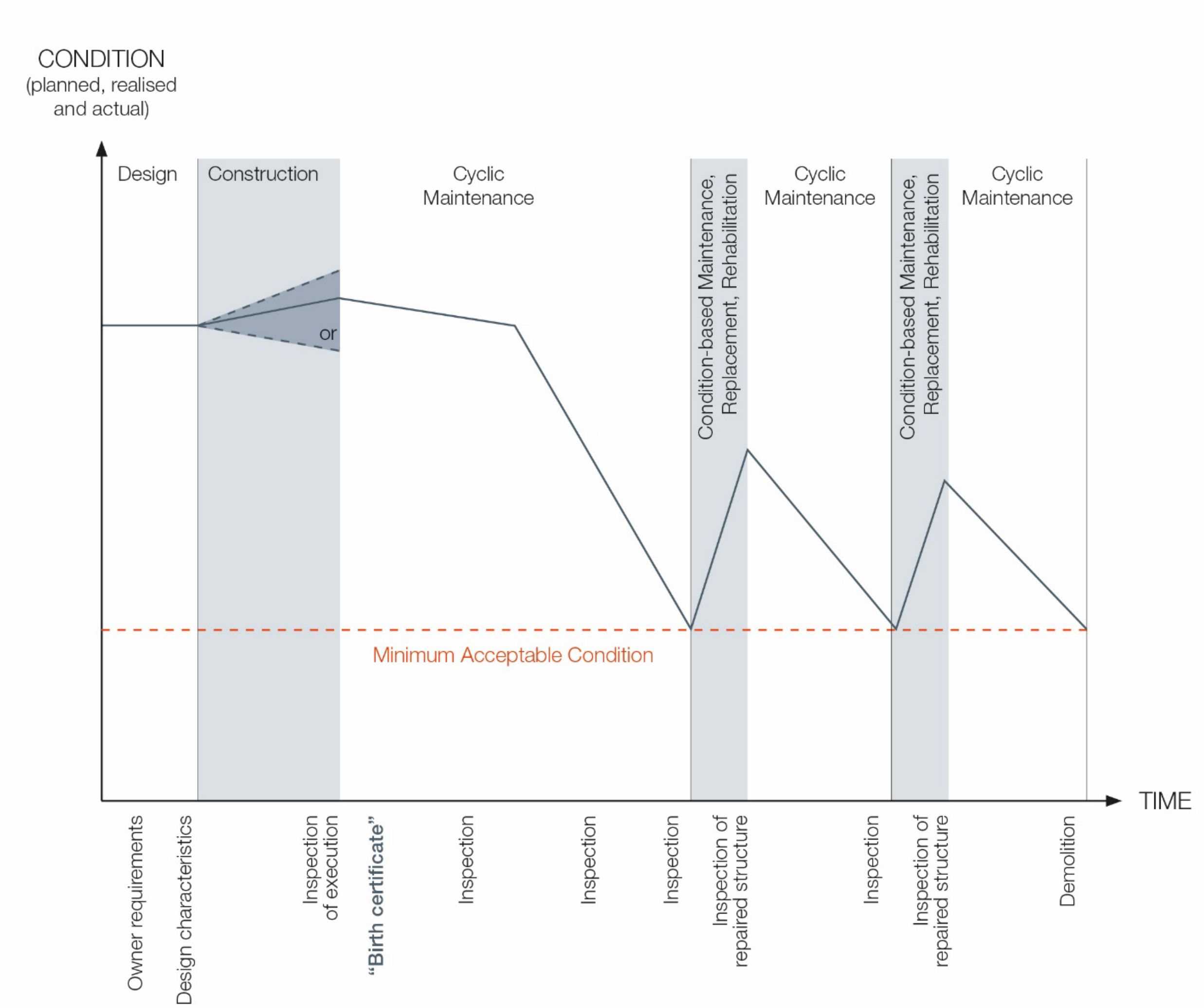

Figure 1: Complete Service Life (adapted from Gehlen, 2006, [19])

The Federal Highway Administration (FHWA) has produced two documents that describe the goals of performing a LCCA on a transportation project: the LCCA Fact Sheet [9] and Primer [10]. They can be found on the FHWA website at:

https://www.fhwa.dot.gov/infrastructure/asstmgmt/lcca.cfm

The key features identified in these documents are that LCCA can be used to study new construction projects and to examine preservation strategies for existing transportation assets. LCCA can consider all agency expenditures and user costs throughout the life of an alternative, not only initial investments. As it is generally the transportation official's policy decision to include user costs in decision-making, comparisons may be made both with and without consideration of user costs.

The following steps define the LCCA Methodology:

1. **Establish alternative design and preservation strategies**. Project teams using the LCCA process first define reasonable design and preservation strategy alternatives. For each proposed alternative, they identify initial construction activities, the necessary future maintenance activities, and the timing of those activities. At least two mutually exclusive options must be considered, and the economic difference between alternatives is assumed to be attributable to the total cost of each.
2. **Determine activity timing**. From this information, a schedule of activities is constructed for each project alternative. After the component activities for each competing project alternative have been identified, each alternative's maintenance plans are developed. Effectively, this plan results in a schedule of when the future maintenance activities will occur, when agency funds will be expended, and when and for how long the agency will establish work zones.
3. **Estimate agency costs**. Next, activity costs are estimated. Best practice LCCA calls for including direct agency expenditures (for example, construction or maintenance activities). LCCA does not require that all costs associated with each alternative be calculated. Only costs that demonstrate the differences between alternatives need be explored.
4. **Estimate user costs**. User costs are costs to the public resulting from work zone activities, including lost time and vehicle expenses. In LCCA, user costs of primary interest include vehicle operating costs, travel time costs, and crash costs. Such user costs typically arise from the timing, duration, scope, and number of construction, preservation, and replacement work zones characterizing each project alternative. Because work zones typically restrict the normal capacity of the facility and reduce traffic flow, work zone user costs are caused by speed changes, stops, delays, detours, and incidents.
5. **Determine LCC**. Once the expenditure streams have been determined for the different competing alternatives, the objective is to calculate the total LCCs for each alternative.

As the Primer [10] neither includes any references to or examples of a bridge LCCA, nor do any of the publication links on the referenced FHWA webpage, examples of a bridge LCC calculation and an LCCA of two different bridge deck solutions are provided herein.

The principles of LCCA are described in standards and guidelines, such as ISO 15686, Part 5, EN 60300-3-3, the LCCA Primer by FHWA [10], Guidelines for LCCA - Final report by FHWA, and NHCRP Report 483 Bridge Life Cycle Cost Analysis. For additional references on LCCA beyond the FHWA documents, readers are referenced to the following sources: the Green Book by Davis Langdon; the National Cooperative Highway Research Program (NCHRP) Synthesis 494 on Management of Highway Assets published in 2016 [18], which refers to bridge LCCA work performed by the Florida Department of Transportation (DOT) on system-wide bridge management issues of in-service structures; and *fib* Bulletin 71 [17] on integrated life cycle assessment of concrete structures, which provides an example LCCA for selection of reinforcement type and use of cathodic protection based on European experience. It is outside the scope of this document to further describe these references.

1.2 Purpose

LCCA can be used as a supporting tool in bridge SLD to assess alternatives and optimize, based on minimum cost or maximum service life durations. This report will concentrate on optimizing alternatives by minimum cost for the same service life duration. The intention of this report is to review LCC strategies and activities, present a step-by-step approach together with an example LCC calculation of a complete bridge, and an example of how LCCA can be used as a decision-making tool for the selection of materials and details for durability.

1.3 Scope

Based on the background and purpose previously identified, the following items are expanded upon herein:

- Summarization of the full life-cycle considerations required to achieve the desired service life duration for a bridge. As described in Section 1.1, this summary will identify a schedule of necessary inspection, special durability monitoring, cyclical and condition-based maintenance, and component replacement activities.
- An example LCC report for a bridge showing the anticipated maintenance activities to be performed during the specified service life, and associated agency costs.
- An example LCCA for alternative components in a bridge. This will compare only the costs that demonstrate the difference between the alternatives. For any future activities requiring lane closures or detours, Work Zones and associated User Costs will be developed. User Costs will include delay costs only (vehicle operating costs, travel time costs) based on available national data and assumed values (for example, detour distance).
- Summarization of how LCCA may be considered together with the R19A SLD project.

2 Principles in Life Cycle Cost Analysis

2.1 Definition of Service Life, Design Life, and Life Cycle

The term 'service life' generally relates to the time from which a bridge, or a bridge component, is constructed until a point where it no longer serves its original purpose in a satisfactory manner.

This 'terminal point' is not necessarily well-defined by a standard or reference definition and can depend on the practice of the bridge's Owner. NCHRP Report 483 [1] defines service life as *'the time between a bridge's construction and its replacement or removal from service*' which takes place when the bridge is '*(1) no longer needed or (2) unsafe, obsolete, or otherwise unable to provide the services expected of it even with repairs*'. Other references and design codes have slightly different definitions stated as follows:

- American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) [2]: *Service life – The period of time that the bridge is expected to be in operation*.
- The Federal Highway Administration (FHWA) [16]: Service life - The service life is the period for which a component, element, or bridge provides the desired function and remains in service with appropriate preservation activities.
- American Concrete Institute (ACI) 365 [3]: *Service life (of building component or material) is the period of time after installation (or in the case of concrete, placement) during which all the properties exceed the minimum acceptable values when routinely maintained*.
- CSA Group (formerly Canadian Standards Association) A23.1-14 and S6-14 [4],[5]: *Service life is the time during which the structure performs its design function without unforeseen maintenance or repair*.
- *fib* Bulletin No. 34, *Model Code for Service Life Design* [6]: *Design Service Life – assumed period for which a structure or a part of it is to be used for its intended purpose*.
- *fib, Model Code for Concrete Structures 2010* [20]*: Service Life – The period for which the required performance of a structure or structural element is achieved, when it used for its intended purpose and under the expected conditions of use*.
- ISO 16204 Durability – Service Life Design of Concrete Structures [21]: *Design service life – assumed period for which a structure or a part of it is to be used for its intended purpose with anticipated maintenance, but without major repair being necessary*;
- SHRP2 Renewal Project Brief – Designing Bridges for Service Life, 2013: *Service Life. The time duration during which the bridge element, component, subsystem, or system provides the desired level of performance or functionality, with any required level of repair and/or maintenance; Target Design Service Life. The time period during which the bridge element, component, subsystem, or system is expected to provide the desired function with a specified level of maintenance established at the design or retrofit stage*.

These definitions are all associated with the length of time that a structure is in use. However, none of them specify an expected time or associated reliability and statistical basis for that time. In contrast, AASHTO LRFD [2] defines Design Life as:

> *Period of time on which the statistical derivation of transient loads is based: 75 years for these Specifications.*

AASHTO LRFD Commentary C1.3.2.1 further states:

> *The Strength I Limit State in the AASHTO LRFD Design Specifications has been calibrated for a target reliability index of 3.5 with a corresponding probability of exceedance of 2.0E-04 during the 75-year design life of the bridge.*

Design Life is focused on structural loading and strength properties remaining the same throughout the 75-year duration. Load and resistance factors for structural design in AASHTO LRFD were calibrated to the 75-year period, but deterioration of the structure over time was not explicitly considered. Service Life Design is a durability related concept associated with preventing excessive deterioration that directly affects the ability of the structure to remain in use and recognizing that its condition changes over time. Unfortunately, there is no direct relationship between the AASHTO LRFD definitions for Service Life and Design Life. This has caused confusion in the bridge community. One key cause of the confusion is that the AASHTO LRFD Design Life is 75 years, whereas much of the SHRP2 documentation has suggested a service life of 100 years or more. Terminology such as Design Service Life and Target Design Service Life, cause further confusion by combining the words “Design” and “Service”, with “Life”. For this document, the term Design Life (as defined by AASHTO LRFD) has very limited meaning and will be used sparingly. To avoid confusion, when discussing what the desired design or actual achieved life for a structure is, the term Service Life will be used.

All structural components of a bridge are designed to equations calibrated to the 75-year Design Life. Ideally, all components would also be designed to achieve a service life of 75 years, as a minimum. As previously stated, the Service Life may be 100 years or more. The two definitions (i.e., Design Life and Service Life) were not necessarily developed at the same time or with the same goals, and it is generally possible for the major structural components like piles, footings, columns, pier caps, girders, and decks to achieve a desired Service Life of 100 years. However, it is not always feasible for other components. Historically, it is known that some components of a bridge deteriorate in much less time than the established Service Life. This includes bearings, expansion joints, drainage systems, coating systems, and deck overlays. Fortunately, these components can often be replaced with minimal effects to traffic, and thus a shorter life can be specified. Therefore, all components need not have the same Service Life.

Whereas Design Life and Service Life relate to *time*, 'life cycle' relates to the *sequence of actions, events and outcomes* that lead to termination of the Service Life [1]. In this way, LCCA is also concerned with determining which maintenance and replacement tasks and sequence are expected to yield the least LCC over the Service Life of the bridge.

2.2 Why Perform Life Cycle Cost Analysis?

The Service Life of different bridge components depends on their rate of deterioration, which again depends on their environmental exposure. For example, the part of a concrete pier directly exposed to de-icing salts is expected to deteriorate faster than the part of the pier only indirectly exposed to de-icing salts. Concrete exposed to direct de-icing salts can potentially deteriorate from alkali-aggregate reactions, freeze-thaw, scaling, carbonation-induced corrosion, and chloride-induced corrosion, whereas scaling is not expected for concrete exposed indirectly to de-icing salts. For steel components, the environmental exposure of the component influences how fast the steel deteriorates due to corrosion.

Throughout the Service Life of the bridge, bridge components need preservation and maintenance actions to counter the effects of deterioration and restore components to an acceptable condition [7]. Certain bridge components might even need replacement if their Service Life is less than that of the bridge (see Section 2.1). Thus, a bridge represents a long-term, multi-year investment and the cost to an agency for a bridge is never a one-time expenditure because expenses to preserve and maintain the desired performance levels must be expected throughout its life cycle [1].

LCCA is a process of identifying the least cost alternative and associated preservation and maintenance strategy of competing design alternatives to achieve a specific Service Life [8]. Thus, an LCCA can assist decision makers in comparing alternative strategies for managing a bridge [1]. Decisions on the initial construction of a new bridge are crucial to the expected maintenance needs throughout the service life of the bridge. The purpose of a project-level LCCA as discussed in this document is to quantify and identify the least cost alternative. It is noted that even though relatively high cost maintenance actions can be recommended from LCCA, these costs could be less than the premature replacement of a bridge because of the lack of maintenance and subsequent early onset of deterioration.

LCCA may also be used to evaluate competing design alternatives, as exemplified in Chapter 7. In such cases, the bridge's service life is typically used as the analysis period. The competing design alternatives should first be benchmarked for suitability (that is, each design alternative must first show it reliably achieves project requirements such as service life, structural stability, and desired level of maintenance) before consideration in an LCCA. Further, it is important to understand the risk and reliability associated with each design alternative and that these may likely differ amongst the design alternatives. These vital considerations shall not be overlooked in the completion of an LCCA. In case the variation in the LCC for several design solutions is limited, other indicators should be used to assess the optimal solution.

2.3 Present Value

Since constructing and managing a bridge covers a timeframe of 75 or more years, those costs need to be converted to a form that allows them to be compared. The value between a dollar today and a future dollar is different. Economists distinguish the value between a dollar today and one in the future through a process called discounting. Discounting involves calculating the range of values of a dollar over a time horizon to find their present value.

The relationship between the amount of a future expenditure and its equivalent present value, (PV) is calculated from the following expression using a real discount rate (r) [10].

$$PV = C_n * 1/(1+r)^n \quad (1)$$

where:

C_n = Cost of expenditure at year n, (in today's dollars)
r = real discount rate
n = year in the future when cost will be incurred

Additional discussion of discounting and the above equation can be found in the Primer [10].

The LCC is then calculated as the sum of the PVs of accumulated costs (C_n) incurred at time t, over a period of time (T) as given by the following formula:

$$PV_{LCC} = \sum_{t=0}^{T} C_n * 1/(1+r)^n \quad (2)$$

wherein each time-step considers costs associated for that year.

The real discount rate used in the analysis of public investments represents the opportunity cost that tax payers incur for not being able to use the tax dollars for their discretionary consumption preferences. Studies of consumer behavior over the past 50 years show that society would require a real rate of between 2% and 4%. In cases where borrowed funds are used to fund initial construction, preservation or maintenance activities, the real discount rate would represent the borrowing rate of the borrowed funds. The *real* discount rate does not include inflation. Thus, by using the real discount rate in equation (1), estimates of future costs can be made in current dollars.

Because of the significance of the selected real discount rate on the LCCs, typically a value is set in project requirements by the Owner. The choice of real discount rate has a huge influence on the outcome of the LCCA and therefore should be chosen carefully. Low real discount rates favor current expenditures whereas high rates reduce the present value of future costs and consequently tend to favor options with low capital cost, short life and high recurring cost.[1] Selecting the most appropriate real discount rate is not easy or clear. Sometimes it is necessary to carry out LCCA with two or three different real discount rates to assess the sensitivity of the analysis [7]. The real discount rate can be estimated using current financial-market conditions or set by agency policy. For LCCA of bridge structures, the standard is to use a real discount rate of 2% to 4% per year [1].

3 Maintenance of Bridge Components

Maintenance of bridge components influences the rate of their deterioration; thus, the level of maintenance has a large influence on the service life of the component and hence on the bridge. Maintenance-related terminology, definitions, and informative examples are summarized, based on definitions in the FHWA Bridge Preservation Guide [16], in Table 1.

Table 1: Maintenance-related Terminology

Term	Definition	Informative examples
Condition-based Maintenance	Condition-based maintenance activities are performed on bridge components or elements in response to known defects. Condition-based maintenance improves the condition of that portion of the element but may or may not result in an increase in the component condition rating. Replacement of replaceable components (see Section 2.4) is part of condition-based maintenance	• Repair/replacement of crash barrier(s) and steel coatings, in response to reaching end of service life • Repair or replacement of strip seals in expansion joints • Bearing restoration (cleaning, lubrication, resetting, replacement) • Spot/zone/full painting of steel elements
Cyclical Maintenance	Maintenance activities performed on pre-determined intervals that aim to preserve and delay deterioration of bridge elements or component conditions.	• Cleaning of dirt, debris, bird droppings from structural steel • Flush drains • Cleaning of expansion joints and bearings • Periodic application of grease, lubricants where appropriate • Repair of concrete surfaces due to mechanical damages or local surface spalls

[1] In other words, low discount rates favor performing work and incurring costs now rather than allowing further deterioration and incurring more expensive work needs later, high discount rate favors deferring work although this will result in more expensive work needs later.

Table 1: Maintenance-related Terminology

Term	Definition	Informative examples
		• Apply sealers to concrete surfaces
Maintenance	Work performed to maintain the condition of the bridge or respond to specific conditions or events that restore the bridge to a functional state of operations. Maintenance is a general term and encompasses routine, preventative, cyclical, and condition-based maintenance activities as well as preservation, rehabilitation and replacement. Rehabilitation, prior to reaching the required service life is commonly referred to as 'major maintenance'.	See other definitions for examples of individual maintenance types
Preservation	Actions or strategies that prevent, delay, or reduce deterioration of bridges or bridge elements; restore the function of existing bridges; and keep bridges in good or fair condition. Preservation actions include cyclical maintenance, condition-based maintenance, and preventative maintenance, the latter being a form of preservation intended to extend service life.	See definitions of cyclical maintenance, condition-based maintenance, and preventative maintenance for informative examples
Preventative Maintenance	A proactive and cost-effective approach to extend the service life of a bridge. Preventative maintenance is typically not foreseen as part of the service life design of new structures.	• Application of cathodic protection to arrest ongoing reinforcement corrosion • Electrochemical chloride extraction from concrete • Mechanical strengthening of the bridge or component
Rehabilitation	Major work required to restore the structural integrity of a bridge, as well as work necessary to correct major safety defects.	• Partial or complete deck replacement • Superstructure replacement, • Substructure/culvert strengthening or partial/full replacement.
Replacement	Total replacement of an existing bridge with a new facility in the same general corridor.	Not applicable for service life design of new structures
Routine Maintenance	Work performed in reaction to an event, season, or activities that are done for short-term operational need	• Trash, litter, and dead animal removal • Snow removal/application of salt/de-icing chemicals

Table 1: Maintenance-related Terminology

Term	Definition	Informative examples
	that do not have preservation value. This work requires regular reoccurring attention.	• Graffiti removal • Hazardous material removal • Asphalt patch with no membrane on concrete deck • Accident damage to bridge and its appurtenances • Storm damage

Among other aspects, cyclical maintenance includes the process of repairing or modifying a bridge or its components to reinstate a desired useful condition, including replacing worn parts. This type of maintenance is performed at predefined intervals (for example, 5 or 10 years) and covers tasks such as, strip seal replacement of expansion joints, extensive coating touch-up (at 10 years) or a full overcoat of coating systems (at 15 to 20 years), or maintenance of sliding materials for bearings. Routine maintenance typically occurs at a greater frequency and, by definition, does not have a preservation value.

Replacement describes the complete removal of a component (for example, bearing, crash barrier, and surface coating), followed by reinstallation of a new component.

Depending on the purpose of a specific LCC calculation(s), costs associated with the specific maintenance types from Table 1 should be included as described further in subsequent sections and chapters of this document.

3.1 Deterioration and Exposure Zones

As background for the planning of maintenance, the exposure conditions and corresponding likely deterioration mechanisms should be understood. An important aspect of maintenance planning is to identify the exposure zone of the different components under consideration. For example, the following exposure zones can be assumed for bridge components: atmospheric, de-icing salts (direct or indirect), water level or tidal zone, submerged, and buried. Other exposure zones could be applicable depending on the bridge location and environment. The exposure conditions of a bridge component (or parts of it) define which exposure zone it belongs to. The following definitions are examples of what can be used for a bridge in a mild environment exposed to de-icing salts:

- Atmospheric: Exposed to airborne chlorides. Temperature and humidity variations, including freeze-thaw.

- Direct de-icing salts: Exposed to alternating wetting and drying, freeze/thaw with direct exposure to de-icing salts, and temperature variations.
- Indirect de-icing salts: Exposed to alternating wetting and drying, freeze/thaw with indirect exposure to de-icing salts, leakage from deck joints, and temperature variations.
- Water level or tidal zone: Exposed to atmospheric conditions and alternating wetting and drying from a body of water (could be fresh water or salted water), temperature variations, possibly ice abrasion.
- Submerged: Permanently submerged in water.
- Buried: Permanently buried in soil.

Based on experience and knowledge about steel and concrete technology, it is possible to decide which typical damages are to be expected for the different bridge components belonging to the different exposure zones. For example, a concrete surface in a direct de-icing salt zone (for example a concrete deck) is much more vulnerable to scaling than a concrete surface in an atmospheric exposure zone (for example part of a concrete pier), and thus, a higher level of maintenance is to be planned for the concrete deck than for the concrete pier in this example.

3.2 Level of Maintenance

Two questions are relevant to answer when considering maintenance of bridges: *do all bridges need maintenance* and *when is maintenance of bridge (components) necessary*?

When designing new bridges, it is often advantageous to carefully plan expected maintenance tasks throughout the service life of the bridge. Planning is advantageous because the target service life of modern bridges cannot be met without carefully maintaining the bridge components, which starts right after opening the bridge.

It is often a subjective decision – usually based on experience – to assess the deterioration level that should prompt maintenance. Maintenance actions can either be performed before the condition of a specific component/material is so poor that maintenance is required or at preset intervals while the component is still in good or fair condition. The minimal acceptable condition for a bridge component and the desired condition can vary substantially [7], often maintenance is planned for a condition between these two limits.

The total LCC of a specific bridge component (and of the entire bridge) depends on the chosen maintenance schedule. Long intervals between maintenance tasks typically lead to increased LCC because deterioration of the component has had time to develop, which is not cost-effective. But very short intervals between maintenance tasks is not cost-effective either because a certain deterioration level is needed before it is worth spending money on rectification, particularly considering that maintenance may require partial closures and incurrence agency costs due to mobilization and maintenance of traffic, and user costs due to delay. The most optimal interval between maintenance tasks is found by repeating the LCCA for different maintenance schedules and thereby predicting the lowest cost-scenario. If the condition of the bridge component, using this maintenance schedule, provides an acceptable level of condition after maintenance, it is accepted. In this way, the maintenance schedule for a bridge structure throughout its service life can be decided. Figure 2, which is adapted from Hurt and Schrock [7], visualizes this balance between LCC and the condition of the bridge component.

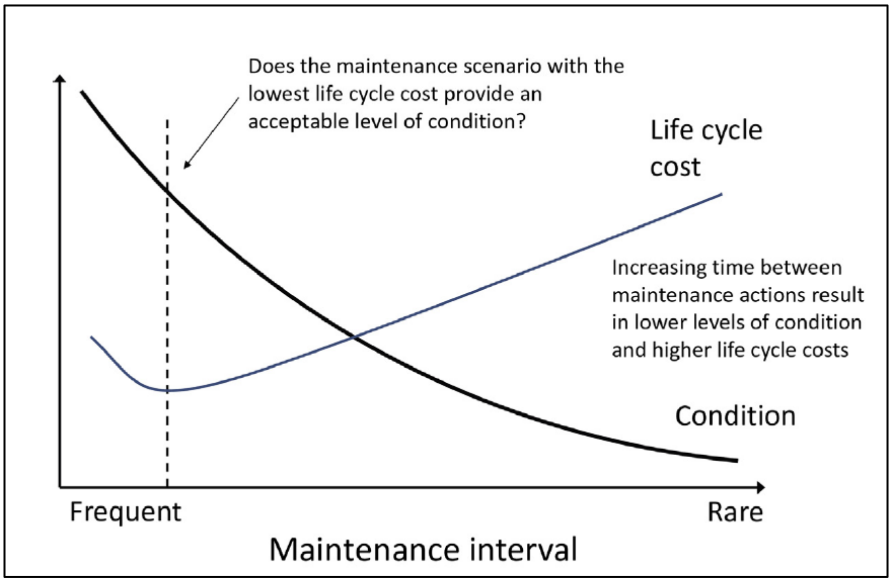

Figure 2: Life Cycle Cost and condition of bridge as a function of maintenance interval [7]

However, in some situations there can be special needs or reasons for differing from the optimal maintenance scenario if, for example, the bridge's Owner needs a very high level of functionality at a particular location [7]. In such case, LCC must be expected to increase.

4 Costs During Bridge Service Life

Many costs are involved with the service life of a bridge and when performing LCCA it should be carefully considered and clearly stated which costs are part of the analysis. When comparing different design options, an LCCA should be focused on differential costs tied to design options being considered and not costs that would be incurred no matter the option chosen. On top of costs directly related to maintaining the bridge throughout its service life, the following other costs can also be considered:

- Costs related to initial construction.

- Costs related to demolition of the bridge (at termination of its service life).
- Residual value of components with remaining service life at the end of the bridge's service life.
- Costs associated with inspections or daily operations of the bridge.
- Costs associated with traffic disruption, delays.

The choice to include or exclude these costs in the LCCA will depend on the specifics of the project and the LCCA shall clearly indicate which costs are considered.

4.1 Unit Costs

The total costs related with the planned maintenance tasks are based on *unit costs*. Unit costs describe the cost of a maintenance task on a unit rate basis for a specific component. This could, for example, be a concrete surface repair with a unit cost of $60 per square feet ($ft^2$) or a replacement of a disc bearing with a unit cost of $20,000/bearing. The unit costs have a great influence on the outcome of LCCA and should be decided carefully.

Preferably, unit costs are estimated from experience from previous similar projects. Cost information can come from a variety of sources, including cost estimating consultants, contractors, vendors, and designers [8]. Some US states have also assembled historic data and developed unit-costs that are available online for estimating purposes [1].

However, it can be difficult to predict the exact unit costs because many factors influence how much a certain maintenance task will cost. For example, if work on several bridges can be combined into a single project, the unit costs can be minimized, or if the work involves larger quantities, it may attract more bidders and, consequently, more competitive bids [7]. The LCCA can include a cost contingency, added as a separate cost item, if the uncertainty on the different unit costs is deemed too high. Alternatively, in case of high uncertainty for a specific unit cost, a sensitivity analysis may be completed using minimum, average, and maximum expected unit cost values so that this uncertainty is considered in deciding which solution is most cost-effective.

5 Step-by-Step Instruction for Life Cycle Cost Analysis

Based on the LCCA background provided in the previous chapters, a step-by-step instruction on how to perform a high-level LCCA is suggested herein. If each step is carefully followed, the result is the total cost (given as present value) that should be expected to maintain the desired standard of the bridge throughout its entire service life. This step-by-step guide only considers costs involved in maintenance tasks throughout the entire service life of the bridge. While this example does not include initial costs for construction or other activities (for example, cost of daily operation and inspections, and demolition) in the bridge's life cycle, the basic approach of the step-by-step instructions herein can be applied for other activities.

The step-by-step instructions are as follows:

1. Clarify which components need maintenance within the service life of the bridge.
2. Identify the exposure zones for the different components and determine which deterioration is expected to take place for the different components.
3. Identify which type of maintenance tasks each component needs during the service life based on the expected deterioration and component service life and define these tasks for each of the components from Step 1.
4. Decide the frequency of each of the individual tasks from Step 3.
5. Determine the number/quantity of each of the components from Step 1.
6. Determine the unit cost for each of the specific tasks from Step 3.
7. Sum the entire maintenance cost per year considering each task from Step 3 from year 1, until termination of the bridge service life, the task frequency of each individual task from Step 4, the quantity from Step 5, and the unit price from Step 6.
8. Determine the present value cost for each task from Step 3 from year 1 until termination of the bridge service life by using equation (1) on the values from Step 7.
9. Determine the total present value cost for each component for all tasks throughout the entire service life of the bridge by adding the values from Step 8.
10. Determine the total present value cost for the entire bridge by adding the present value of all components from step 9 using equation (2).

The tools presented on the following two pages are helpful when performing LCCA. The use of these tools is exemplified in Chapter 6.

<u>Component:</u>

Condition-based maintenance:

Description:

Duration of cycle (years):

Cycle starting at year:

Quantity:

Unit cost (2018$):

Activity cost per time (2018$): (quantity x unit cost)

Total PV (2018$):

Cyclical maintenance:

Description:

Duration of cycle (years):

Cycle starting at year:

Quantity:

Unit cost (2018$):

Activity cost per time (2018$): (quantity x unit cost)

Total PV (2018$):

Replacement:

Description:

Duration of cycle (years):

Cycle starting at year:

Quantity:

Unit cost (2018$):

Activity cost per time (2018$): (quantity x unit cost)

Total PV (2018$):

TOTAL LCC for (component) in PV 2018$:

Component: Real Discount Rate:						
Year	Condition-based Maintenance		Cyclical Maintenance		Replacement	
	Unit Cost (2018$)	PV (2018$)	Unit Cost (2018$)	PV (2018$)	Unit Cost (2018$)	PV (2018$)
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
:						
:						
:						
:						
99						
100 (service life of bridge)						
Total						

6 Example of Life Cycle Cost Analysis

To exemplify the use of the LCCA step-by-step instruction and background outlined in the previous chapters, a detailed LCC of a bridge is performed and described in this chapter. Only one maintenance schedule is planned and analyzed; however, LCCA could be completed by considering multiple maintenance schedules. It is left to the reader to investigate alternative LCCA scenarios.

The bridge analyzed in this chapter represents a fictitious example and should only be considered as such. The main purpose of this document is to outline the general principles of LCCA such that the reader becomes familiar with the main principles and is capable of transferring these to other bridge structures in the future. Thus, it is the overall procedures rather than the details of the chosen example that are interesting and those that should be the focus when studying the example. In the remaining document, the bridge analyzed will be referred to as 'the Bridge'.

6.1 Overall Arrangement of the Bridge

The Bridge crosses a river and consists of a main span and approach spans for a total length of 1,850 feet (ft) as shown on Figure 3. The river is fresh water with no significant ice loads in the winter (no ice abrasion occurs at the piers). The climate is mild with periods of snow and freeze-thaw cycles; de-icing salts are applied on the Bridge.

There are four piers in the river, one pier on land, and two semi-integral abutments. There are four expansion joints: one modular joint at each Piers 3 and 4, and one strip seal joint at the ends of the approach slabs of abutments 1 and 2.

Foundations consist of piles comprised of a permanent steel casing filled with reinforced concrete.

The main span unit is a tied arch structure of 830 ft. The deck roadway width is 48 ft on average with a shared use path on the side. The deck system is comprised of a post-tensioned reinforced concrete deck and steel stringers spanning in the longitudinal direction. The wearing surface is bare high-performance concrete, no asphalt and/or waterproofing membrane is used. Stringers are supported on elastomeric bearings at floor beams which span in the transverse bridge direction. The arch ribs are welded steel box sections. Tie chords are rectangular box sections that connect the knuckles at the arch ends. All structural steel is weathering steel. Because use of uncoated weathering steel is not recommended when exposed to de-icing chemicals, the arch ribs and tie chords are painted to protect them from corrosion. Figure 3 shows a typical cross section of the main span.

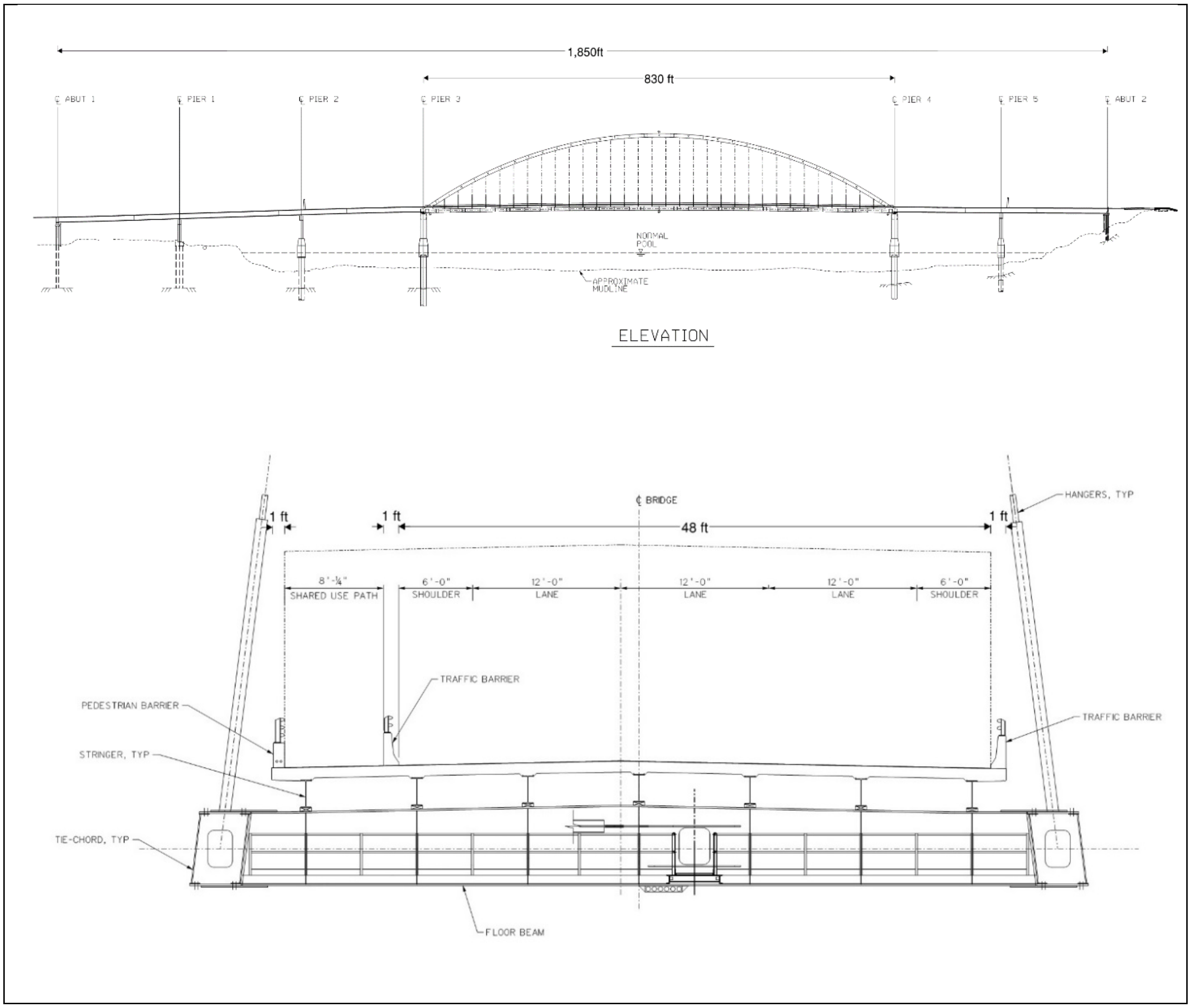

Figure 3: Typical cross section of main span

There are 32 hanger cables on each arch. The cables are 15 strands 0.6-diameter weldless low-relaxation strands. The individual strands are sheathed by polyethylene with corrosion-inhibiting grease or wax. The cables are contained within an un-grouted heavy-duty co-extruded polyethylene (HDPE) pipe.

The approach structures consist of weathering steel plate girders with a concrete deck for a total length of 645 ft on the northern side and 375 ft on the southern side of the bridge. The ends of the steel plate girders are encased in the concrete abutments and an additional foot in length is painted to protect the girders from corrosion. For the same reason, the steel girders are painted at expansion joint locations within 10 ft from the joint. Concrete barriers are installed along the entire length of the bridge.

The Project Criteria require the structures to meet a minimum service life of 100 years for non-replaceable components and define minimum service life for each of the replaceable components as shown in Table 2.[2]

Table 2: Summary of Minimum Service Life Requirements of Bridge Components

Non-Replaceable Components	Minimum Service Life (years)
Foundations, abutments, piers, structural steel, and deck	100
Replaceable Components	**Minimum Service Life (years)**
Bridge bearings	50
Expansion joints	30
Bridge barriers	60
Drainage system	75
Access: access ladders, platforms, and lifts	60
Painting	25
Cables and hangers	60

6.2 Step-by-Step Example of Life Cycle Cost Analysis

The following LCCA of the Bridge follows the step-by-step instruction introduced in Chapter 5.

6.2.1 Components Considered in Life Cycle Cost Analysis (Step 1)

Components considered in the LCCA are replaceable components with a service life less than that of the bridge and non-replaceable components that are expected to require maintenance to achieve the desired service life of the bridge. The components considered are those included in Table 2.

6.2.2 Exposure Zones for Components (Step 2)

To assess which type of maintenance the different bridge components need, the exposure zones must first be defined. The exposure zones for the Bridge have been defined as follows:

[2] It is noted that the service lives for replaceable component are for demonstration purposes only in this example, and more detailed discussion on the selection of service life requirements for replaceable components may be found in the SHRP2 R19A "AASHTO Service Life Design for Bridges - Summary Guide".

- Buried: zones permanently buried in soil (wing walls and abutment surfaces exposed to soil, foundations)
- Submerged: zones permanently submerged in river water (steel casing of foundations)
- Water level: zones not permanently submerged in river water, subject to wet-dry cycles, approximately from bottom of pile caps to 100-year flood water level (pile caps and pedestals)
- Direct de-icing salts: zones directly exposed to the use of de-icing salts (top surface of decks, traffic barriers, and pedestrian barriers)
- Indirect de-icing salts: zones subject to runoff water or spray containing de-icing salts, assumed here as areas under and within 10 ft of expansion joints and zones within 35 ft vertically of a roadway (*structural steel including arch ribs next to joints, portion of structural steel that extends beyond the exterior stringer; top of pier column, lower part of cable hangers*)
- Atmospheric: zones not exposed to soil, river water, or de-icing salts (*arch rib, upper part of cable hangers, upper bracing, steel more than 35 ft vertically above the roadway level, structural steel more than 10 ft horizontally from expansion joints, piers, abutments, wing wall surfaces not in previous exposure zones*)
- Interior: zones completely sheltered and inside closed sections (*inside surface of tie-chords and arch ribs*)

A convenient way of visualizing these exposure zones is by use of a color code as shown on Figure 4 and Figure 5.

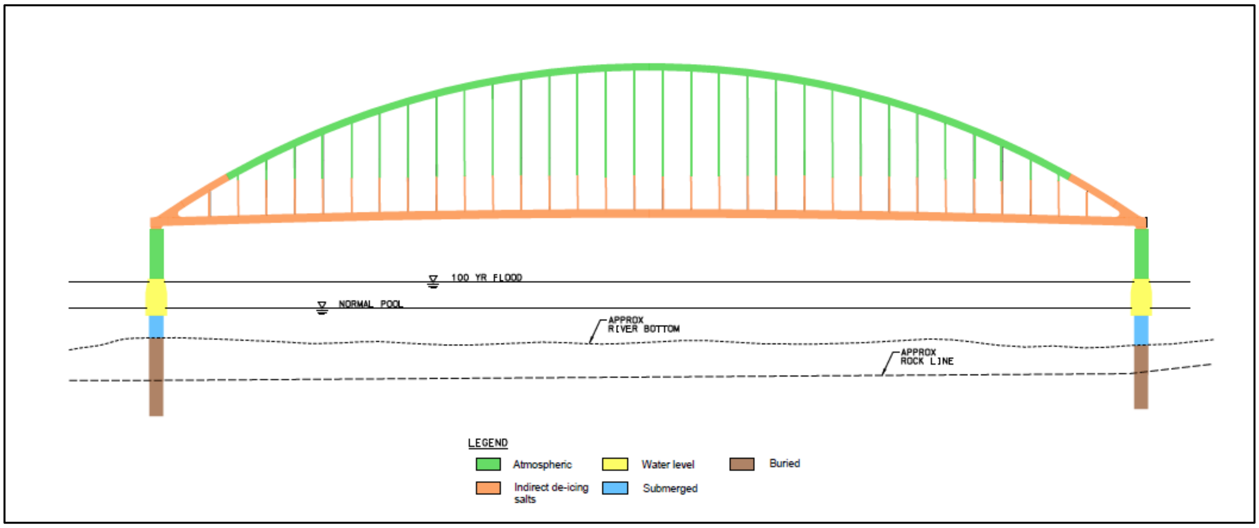

Figure 4: Color code used to visualize exposure zones for main span of the Bridge

Based on the exposure zone, the deterioration mechanisms most likely to occur for each component can be identified. The same component can have different maintenance tasks for different exposure zones. Listing all possible deterioration mechanisms and maintenance tasks for the Bridge is outside the scope of this document; instead the following are a few examples:

- Concrete exposed to indirect de-icing salt or at the water level is more prone to minor damages because of corrosion or freeze-thaw and thus an allowance for repair of the concrete (patching) will be included.

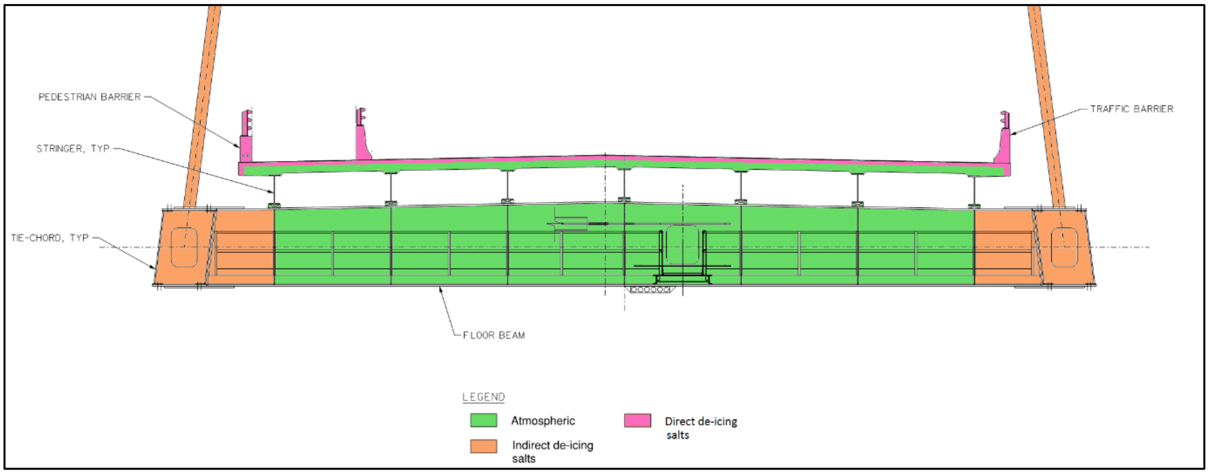

Figure 5: Color code used to visualize exposure zones for main span cross section of the Bridge

- The submerged part of the piles is not expected to need maintenance as sufficient corrosion allowances were used in the design to provide adequate protection during the target service life.
- The part of the arch rib in the indirect de-icing salt zone is more sensitive to corrosion than the part in the atmospheric zone; thus, different maintenance strategies (typically different frequencies) will be planned for these two exposure zones.

6.2.3 Maintenance Tasks for Each Component (Step 3)

The necessary maintenance tasks are planned from the damage mechanisms identified in the previous step.

To make the following guidance of Step 3 throughout Step 9 as clear as possible, the following sections only relate to the component 'Cables and Hangers' because a description of all components would be too comprehensive; however, the same procedure as outlined in the following is also followed for the remaining components listed in Table 2. On pages 35-37, an overall summary of all components is made.

Cables and hangers are present in the atmospheric zone as well as in the indirect de-icing salts zone, and it must be expected that corrosion therefore can occur if, for example, the HDPE tubes are damaged (at least for the part of the cables exposed to salts). Therefore, regular repair of HDPE tubes and sealing should be planned. Moreover, because the cables are exposed to large tensile forces, it might be necessary to make minor adjustments of them whenever necessary. Furthermore, the cables should be cleaned whenever needed. This can be summarized as follows:

- Condition-based maintenance based on observations from routine inspection: minor adjustments and cleaning of the cables.
- Cyclical maintenance: minor repairs of sealing, grease, drainage, HDPE tube, bolts, and coating.

As for replacement, cables have a minimum service life less than that of the bridge (see Table 2) and replacement of all the cables will therefore be assumed.

6.2.4 Frequency of Each Maintenance Task (Step 4)

For the purpose of this example and to yield a conservative LCC, the condition-based maintenance of cables and hangers is assumed to be needed based on the outcome of routine inspections every two years.

Minor repairs of sealing, grease, drainage, HDPE tube, bolts, and coating are planned to take place in a 5-year cycle. However, it is not expected that these cyclical maintenance tasks become relevant until the bridge has an age of 25 years.

The service life of cables and hangers is a minimum of 60 years according to Table 2. Therefore, is it assumed that all cables must be replaced when the bridge is 60 years old. However, this is a conservative assumption as the cables will likely not be in such condition to require replacement at once.

6.2.5 Quantities of Components (Step 5)

In this example, the quantities of components or extent of tasks are either given with the units of length ('ft'), area ('ft^2'), or number of items ('ea'). Other units could be used to suit the project.

For condition-based maintenance, the quantity is often set to 1 because the unit cost is given as a lump sum. This is because condition-based maintenance often covers small non-periodic tasks which individually are difficult to price. Instead, the total expected cost is estimated, as also seen in the next section (Section 6.2.6).

Determination of quantities connected with surface areas such as, structural steel to be painted or concrete areas exposed to certain deterioration mechanisms requires calculations. To obtain the most accurate quantities, it is necessary to review design drawings of the structure. For other components such as bearings or joints, the quantity can be determined by simply counting the number of items.

It is typically convenient to begin this step by determining the *total* quantities of the different components. Sometimes, different maintenance tasks have been identified for different exposure zones of the same component and in such case, the quantities must be divided between the different exposure zones. For the Bridge, the total quantities shown in Table 3 have been determined for the different exposure zones.

Table 3: Total Quantities for Different Components of the Bridge for the Different Exposure Zones

Component	Buried / Submerged	Water Level	Interior	Atm.	Indirect De-icing	Direct De-icing
Land structures (Pier 1 and abutments)* (ft^2)	Not calculated	5,703				
Pier 2+3+4+5* (ft^2)	Not calculated	40,846				
Top deck roadway and pedestrian surface main and approach spans (ft^2)						104,063
Structural steel to be painted (ft^2)			103,782	62,795	50,037	
Total barrier length (ft)						5,550
Cables and hangers (ea)				64		
Elastomeric bearings on appr. span (ea)				42		
Elastomeric bearings on stringers (ea)				231		
Arch disc bearings (ea)				4		
Modular expansion joints (ea)					2	
Strip seal expansion joints (ea)					2	
Scuppers (ea)				90		

* The exposure zones 'water level, interior', 'atmospheric', 'indirect de-icing salts', and 'direct de-icing salts' are considered under one for land structures and piers because the maintenance tasks defined for these exposure zones are assumed to be the same. There is uncertainty related to the amount of maintenance specific to each zone, instead one maintenance regime is assumed for these structures. No maintenance tasks are considered for the buried exposure zone and therefore areas are not calculated.

After determining the total quantities, it should be determined how much of the total quantity needs maintenance during the considered maintenance task. This is typically given as a certain percentage. For example, how much of the total deck surface is expected to need minor repair annually, or how many bearings are expected to be replaced every 50 years?

For this example, it is assumed that 50% of the total roadway and pedestrian deck area is repaired in each cycle (every 30 year), that 0.1% of the surface area of the piers is repaired in each cycle (each year), and that 10% of the concrete barriers is repaired in each cycle (every 15 year). Assumptions like these are typically decided based on experience from previous similar projects and/or based on the Owner's practices. The assumptions for this example may not be suitable for other projects.

As for the cables and hangers, it is assumed that all 64 cables and hangers need minor repair every 5 years as part of cyclical maintenance. It is also assumed that all 64 cables and hangers need replacement after 60 years even though this is a very conservative assumption as also discussed in Section 6.2.4. The quantity of the yearly condition-based maintenance is set to 1 since the unit cost is a lump sum.

6.2.6 Unit Costs of Maintenance Tasks (Step 6)

The unit costs should always be consistent with the unit of the quantities determined in Step 4. As discussed in Chapter 4, the unit cost should be carefully considered since it greatly influences the total LCC.

The unit costs of the maintenance tasks identified for the cables have been assessed from reference projects, where the same types of cables were used. Table 4 shows the assumed unit costs.

Table 4: Unit Costs for Maintenance Tasks for Cables and Hangers

Maintenance	Unit	Unit Cost (2018$)
Condition-based Maintenance	Lump sum	$6,500
Cyclical Maintenance	ea	$1,560
Replacement	ea	$156,000

6.2.7 Activity Cost per Time for Each Maintenance Task (Step 7)

The activity cost per time for each maintenance task for each component is simply determined by multiplying the quantity from Step 5 with the unit cost from Step 6 at the frequency from Step 4 For the cables and hangers, the activity cost per time is determined as shown in Table 5.

Table 5: Calculations of Maintenance Cost for Cables and Hangers.

Maintenance	Calculation	Activity Cost per Time (2018$)
Condition-based Maintenance	1 x $6,500	$6,500
Cyclical Maintenance	64 x $1,560	$99,840
Replacement	64 x $156,000	$9,984,000

6.2.8 Present Value Cost for Each Year (Step 8)

The activity costs should be transformed into present value to account for the 'time value of money'. This is done by applying equation (1) to the costs in Table 5 for each year the specific task is planned to take place. For example, at year 40 condition-based maintenance and cyclical maintenance is planned to take place. Assuming a real discount rate of 2.9%, the present value for the maintenance tasks in year 40 is as shown in Table 6. Similar calculations are performed for all other relevant years from year 1 to termination of the service life of the bridge.

Table 6: Calculations of Present Value for Cables and Hangers at Year 40.

Maintenance	Calculation	Present Value (2018$)
Condition-based Maintenance	$\$6,500 \times (1+0.029)^{-40}$	$2,072
Cyclical Maintenance	$\$99,840 \times (1+0.029)^{-40}$	$31,819

6.2.9 Total Present Value Cost for Each Maintenance Task (Step 9)

After having determined the present value cost for each year for each maintenance task, the total present value cost for each maintenance task can be determined by simply adding the present value costs per year (from year 1 to termination of the service life of the bridge) for each maintenance task.

6.2.10 Example of Help Tools

The sample tables shown on pages 20 through 22 are effective help tools when trying to obtain a good overview of the LCCA. Steps 3 through 9 give the input values for the table on page 20 as follows:

Component: Cables and hangers

Condition-based maintenance:

Description: Cleaning and minor adjustment, based on outcome of routine inspection (every two years).	
Duration of cycle (years):	2
Cycle starting at year:	2
Quantity:	1 (lump sum)
Unit cost (2018$):	6,500
Activity cost per time (2018$):	6,500
Total PV (2018$):	**103,760**

Cyclical maintenance:

Description: Minor repair of sealing, grease, drainage, HDPE tube, bolts, and coating.	
Duration of cycle (years):	5
Cycle starting at year:	25
Quantity:	64 (ea)
Unit cost (2018$):	1,560
Activity cost per time (2018$):	99,840
Total PV (2018$):	**323,830**

Replacement:

Description: Replacement of cables.	
Duration of cycle (years):	60+
Cycle starting at year:	60
Quantity:	64 (ea)
Unit cost (2018$):	156,000
Activity cost per time (2018$):	9,984,000
Total PV (2018$):	**1,796,313**

TOTAL LCC for cables and hangers in PV 2018$: 2,223,903

The table on page 22 is helpful when determining the PV costs for each year (Step 8) and the total PV cost for each maintenance task (Step 9) as shown in Table 7. The total PV for each maintenance task is then input to the table right above.

Table 7: Calculation of Present Value at Each Year for Maintenance and Replacement of Cables and Hangers.

Component: Cables and hangers Real Discount Rate: 2.9%						
Year	Condition-based Maintenance		Cyclical Maintenance		Replacement	
	Unit Cost (2018$)	PV (2018$)	Unit Cost (2018$)	PV (2018$)	Unit Cost (2018$)	PV (2018$)
1						
2	6,500	6,139				
3						
4	6,500	5,798				
5						
6	6,500	5,475				
7						
8	6,500	5,171				
9						
10	6,500	4,884				
:	:	:				
25			99,840	48,856		
26	6,500	3,091				
27						
28	6,500	2,919				
29						
30	6,500	2,757	99,840	42,349		
31						
:	:	:				
60	6,500	1,169	99,840	17,963	9,984,000	1,796,313
61						
62	6,500	1,104				
:	:	:				
:	:	:				
100	-	-	-	-		
Sub-Total	318,500	103,760	1,497,600	323,830	9,984,000	1,796,313
Grand Total	103,760 + 323,830 + 1,796,313 = 2,223,903					

6.2.11 Complete Overview of Maintenance for the Bridge

To complete the LCCA for the whole bridge structure, the Component Summary Table and Component Calculation Table similar to those provided in Section 6.2.10 must be filled out for each component identified in Step 1. The following pages show the identified maintenance tasks and corresponding total PVs for all the components identified in Section 6.2.1.

For this example, assumptions regarding the level of maintenance were made. Ideally, the level of maintenance planned during the bridge service life should be consistent with the Owner's best practices. In addition, calculations and costs are shown to the exact dollars to help the read follow through the example. However, calculations may be rounded up to the nearest $100 or $1000 depending on the level of confidence for the unit costs.

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Condition-based and Routine Maintenance *(the latter is marked with * below)*

Concrete

Component: Bridge deck (main + approach spans)
Description: Condition-based maintenance is not anticipated or very minor. Ignored for this example.

Component: Concrete barriers*
Description: Repair of damaged sections as needed (for example due to impacts).

Duration of cycle:	1
Cycle starting at year:	1
Quantity:	1 (lump sum)
Unit cost (2018$):	750
Activity cost (2018$):	750
Total PV (2018$):	**24,336**

Component: Land structures (Pier 1 and abutments)
Description: Condition-based maintenance is not anticipated or very minor. Ignored for this example.

Component: Piers 2-3-4-5
Description: Condition-based maintenance is not anticipated or very minor. Ignored for this example.

Structural Steel

Component: Cables and hangers
Description: Cleaning and minor adjustments.

Duration of cycle:	2
Cycle starting at year:	2
Quantity:	1 (lump sum)
Unit cost (2018$):	6,500
Activity cost (2018$):	6,500
Total PV (2018$):	**103,760**

Component: Painting, interior
Description: Touch-ups of paint (5%), overcoat (100%), and repaint (100%, last year of replacement: 48).

Duration of cycle:	48
Cycle starting at year:	26 (touch-up) / 35 (overcoat) / 48 (repaint)
Quantity:	5,189 ft2 / 103,782 ft2 / 103,782 ft2
Unit cost (2018$):	9.6 / 16.8 / 32.4
Activity cost (2018$):	49,815 / 1,743,530 / 3,362,521
Total PV (2018$):	**29,696 / 803,586 / 852,564**

Component: Painting, atmospheric
Description: Touch-ups of paint (5%), overcoat (100%), and repaint (100%, last year of replacement: 76).

Duration of cycle:	38
Cycle starting at year	21 (touch-up) / 28 (overcoat) / 76 (repaint)
Quantity:	4,396 ft2 / 62,795 ft2 / 62,795 ft2
Unit cost (2018$):	9.6 / 16.8 / 32.4
Activity cost (2018$):	42,198 / 1,054,953 / 2,034,552
Total PV (2018$):	**30,963 / 633,697 / 918,256**

Component: Painting, indirect de-icing salts
Description: Touch-ups of paint (5%), overcoat (100%), and repaint (100%, last year of replacement: 66).

Duration of cycle:	33
Cycle starting at year:	18 (touch-up) / 24 (overcoat) / 33 (repaint)
Quantity:	5,004 ft2 / 50,037 ft2 / 50,037 ft2
Unit cost (2018$):	9.6 / 16.8 / 32.4
Activity cost (2018$):	48,035 / 840,614 / 1,621,183
Total PV (2018$):	**44,243 / 652,218 / 876,846**

Other Components

Component: Bearings (disc)
Description: Maint. of sliding material, repair of coating.

Duration of cycle:	25
Cycle starting at year:	25
Quantity:	4 (ea)
Unit cost (2018$):	13,600
Activity cost (2018$):	54,400
Total PV (2018$):	**46,021**

Component: Drainage
Description: Overhaul, spot coating repair, tighten loose fasteners.

Duration of cycle:	10
Cycle starting at year:	10
Quantity:	90 (ea)
Unit cost (2018$):	200
Activity cost (2018$):	18,000
Total PV (2018$):	**50,242**

Component: Expansion joints (modular/strip seal)
Description: Maint. of moving parts (incl. springs), repair of strip seal, and repair of coating.

Duration of cycle:	10
Cycle starting at year:	10
Quantity:	2 (ea) / 2 (ea)
Unit cost (2018$):	28,600 / 14,300
Activity cost (2018$):	57,200 / 28,600
Total PV (2018$):	**159,657 / 79,829**

Component: Access systems
Description: Touch-ups of coatings and minor repair.

Duration of cycle:	5
Cycle starting at year:	5
Quantity:	1 (lump sum)
Unit cost (2018$):	15,000
Activity cost (2018$):	15,000
Total PV (2018$):	**89,323**

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Cyclical maintenance

Concrete

Component: Bridge deck (main + approach spans)
Description: Repair of concrete surface spalls and other concrete deterioration and any localized reinforcement deter.

Duration of cycle:	30
Cycle starting at year:	30
Quantity:	51,839 ft^2 (50% of total)
Unit cost (2018$):	60
Activity cost (2018$):	3,121,875

Component: Concrete barriers
Description: Repair due to scaling, corrosion etc.

Duration of cycle:	15
Cycle starting at year:	15
Quantity:	555 ft (10% of total)
Unit cost (2018$):	100
Activity cost (2018$):	55,500
Total PV (2018$):	**85,759**

Component: Land structures (Pier 1 and abutments)
Description: Repair of concrete deterioration.

Duration of cycle:	1
Cycle starting at year:	1
Quantity:	5.7 ft^2 (0.1% of total)
Unit cost (2018$):	100
Activity cost (2018$):	570
Total PV (2018$):	**18,505**

Component: Piers 2-3-4-5
Description: Repair of concrete deterioration.

Duration of cycle:	1
Cycle starting at year:	1
Quantity:	40.8 ft^2 (0.1% of total)
Unit cost (2018$):	100
Activity cost (2018$):	4,085
Total PV (2018$):	**132,541**

Structural Steel

Component: Cables and hangers
Description: Minor repair of sealing, grease, drainage, HDPE tube, bolts and coating.

Duration of cycle:	5
Cycle starting at year:	25
Quantity:	64 (ea)
Unit cost (2018$):	1,560
Activity cost (2018$):	99,840
Total PV (2018$):	**323,830**

Component: Painting, interior
Description: N/A (Per definitions in Section 3.0, maintenance of paint is condition-based in all cases)

Component: Painting, atmospheric
Description: N/A (Per definitions in Section 3.0, maintenance of paint is condition-based in all cases)

Component: Painting, indirect de-icing salts
Description: N/A (Per definitions in Section 3.0, maintenance of paint is condition-based in all cases)

Other Components

Component: Bearings
Description: Cleaning, spot repair of coating.

Duration of cycle:	1
Cycle starting at year:	1
Quantity:	1 (lump sum)
Unit cost (2018$):	17,500
Activity cost (2018$):	17,500
Total PV (2018$):	**568,846**

Component: Drainage
Description: Cleaning and small repair work.

Duration of cycle:	1
Cycle starting at year:	1
Quantity:	1 (lump sum)
Unit cost (2018$):	4,600
Activity cost (2018$):	4,600
Total PV (2018$):	**149,262**

Component: Expansion joints
Description: Cleaning and spot repair of coating.

Duration of cycle:	1
Cycle starting at year:	1
Quantity:	1 (lump sum)
Unit cost (2018$):	1,000
Activity cost (2018$):	1,000
Total PV (2018$):	**64,896**

Component: Access systems
Description: Ad hoc minor repair.

Duration of cycle:	1
Cycle starting at year:	1
Quantity:	1 (lump sum)
Unit cost (2018$):	5,000
Activity cost (2018$):	5,000
Total PV (2018$):	**162,241**

Replacement

Concrete

Component: Bridge deck (main + approach spans)
Description: No replacement anticipated.

Component: Concrete barriers
Description: Replacement of 100% of the barriers.

Duration of cycle:	60
Cycle starting at year:	60
Quantity:	5,550 ft
Unit cost (2018$):	313
Activity cost (2018$):	1,737,150
Total PV (2018$):	**312,547**

Component: Land structures (Pier 1 and abutments)
Description: No replacement anticipated.

Component: Piers 2-3-4-5
Description: No replacement anticipated.

Structural Steel

Component: Cables and hangers
Description: Replacement of all cables and hangers.

Duration of cycle:	60
Cycle starting at year:	60
Quantity:	64 (ea)
Unit cost (2018$):	156,000
Activity cost (2018$):	9,984,000
Total PV (2018$):	**1,796,313**

Component: Painting, interior
Description: N/A (Per definitions in Section 3.0, maintenance of paint is condition-based in all cases)

Component: Painting, atmospheric
Description: N/A (Per definitions in Section 3.0, maintenance of paint is condition-based in all cases)

Component: Painting, indirect de-icing salts
Description: N/A (Per definitions in Section 3.0, maintenance of paint is condition-based in all cases)

Other Components

Component: Bearings (disc/elastomeric)
Description: Replacement of bearings.

Duration of cycle:	50
Cycle starting at year:	50
Quantity:	4 (ea) / 273 (ea)
Unit cost (2018$):	20,000 / 3,000
Activity cost (2018$):	80,000 / 819,000
Total PV (2018$):	**19,157 / 196,117**

Component: Drainage
Description: Replacement of scuppers.

Duration of cycle:	75
Cycle starting at year:	75
Quantity:	90 (ea)
Unit cost (2018$):	4,100
Activity cost (2018$):	369,000
Total PV (2018$):	**43,239**

Component: Expansion joints (modular / strip seal)
Description: Replacement of expansion joints.

Duration of cycle:	30
Cycle starting at year:	30
Quantity:	2 (ea)/ 2 (ea)
Unit cost (2018$):	53,900 / 41,800
Activity cost (2018$):	107,800 / 83,600
Total PV (2018$):	**73,348 / 56,882**

Component: Access systems
Description: Replacement of ladders, platforms etc.

Duration of cycle:	60
Cycle starting at year:	60
Quantity:	1 (lump sum)
Unit cost (2018$):	100,000
Activity cost (2018$):	100,000
Total PV (2018$):	**17,992**

6.2.12 Total Present Value Cost for Entire Bridge (Step 10)

Finally, the total PV cost for the entire bridge structure is determined by summation of all total PV costs for each component. In the present example, the total PV cost to be expected for maintenance tasks during the 100-year service life of the bridge structure is approximately $11.5M. It is noted that user cost is not included in this example.

6.3 Visual relation of Life Cycle Cost

Note, it is a good idea to visually interpret the results from the finalized LCCA to obtain a much better overview than what is provided from the tabulated results.

6.3.1 Pie Chart

If the costs themselves are less important than the distribution of the costs among the different components, a pie chart might be the most optimal way of visualizing the results. Figure 7 shows the results from the tables on pages 35-37 in a pie chart.

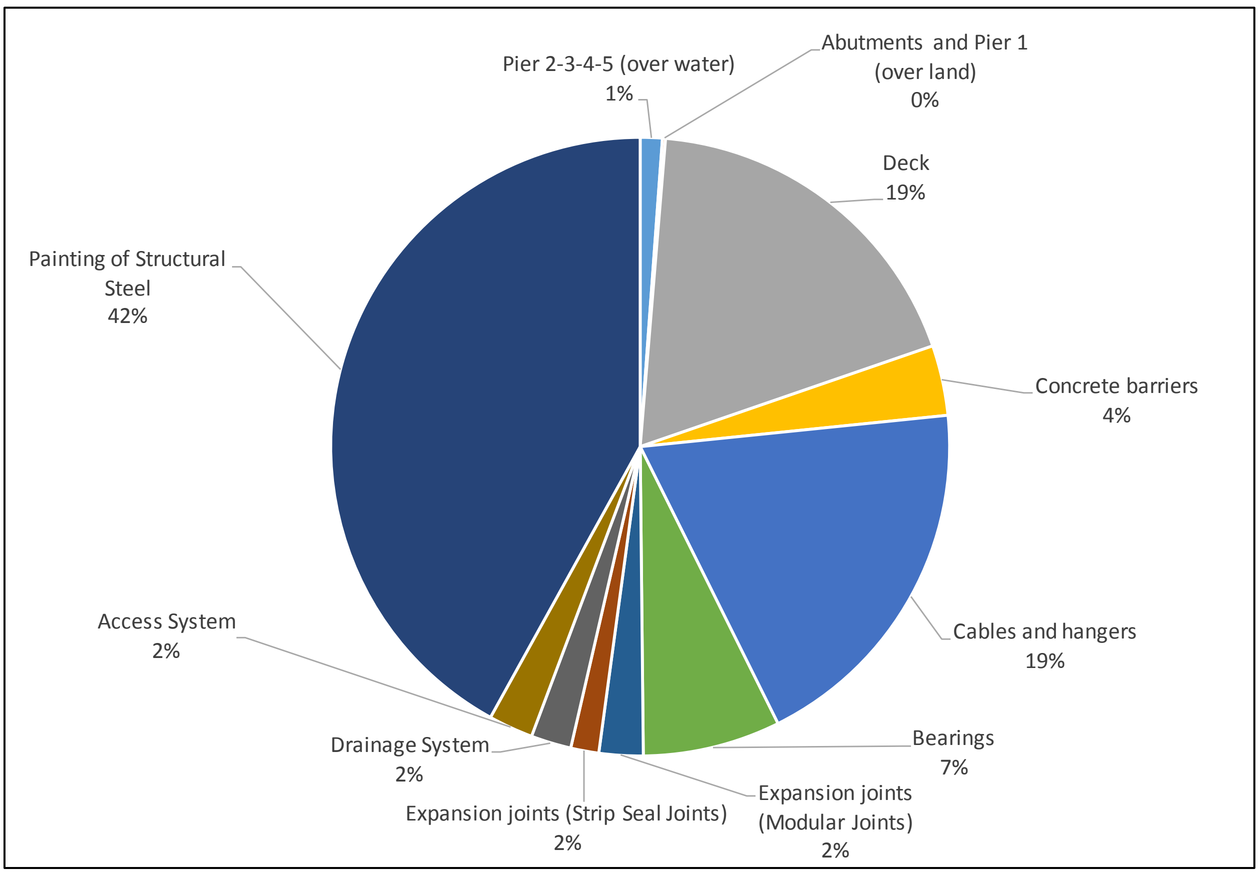

Figure 6. Pie chart visualization of the finalized LCCA

The painting of structural steel and maintenance and replacement of bearings, deck, cables and hangers account for almost 90% of the PV amount, whereas other components, such as maintenance for the abutments, piers, access components, or the drainage system, do not contribute significantly to the total LCC. Thus, if LCC is to be reduced, emphasis should be placed on, for example, bearings, rather than on the drainage system.

6.3.2 Accumulated Costs

Another way of visualizing LCCA is by showing the costs per year together with the total accumulated cost. In contrast to the pie chart, this type of interpretation does not distinguish one component from the other but only considers the total costs per year. Figure 8 shows such depiction based on the results from the tables on pages 35.

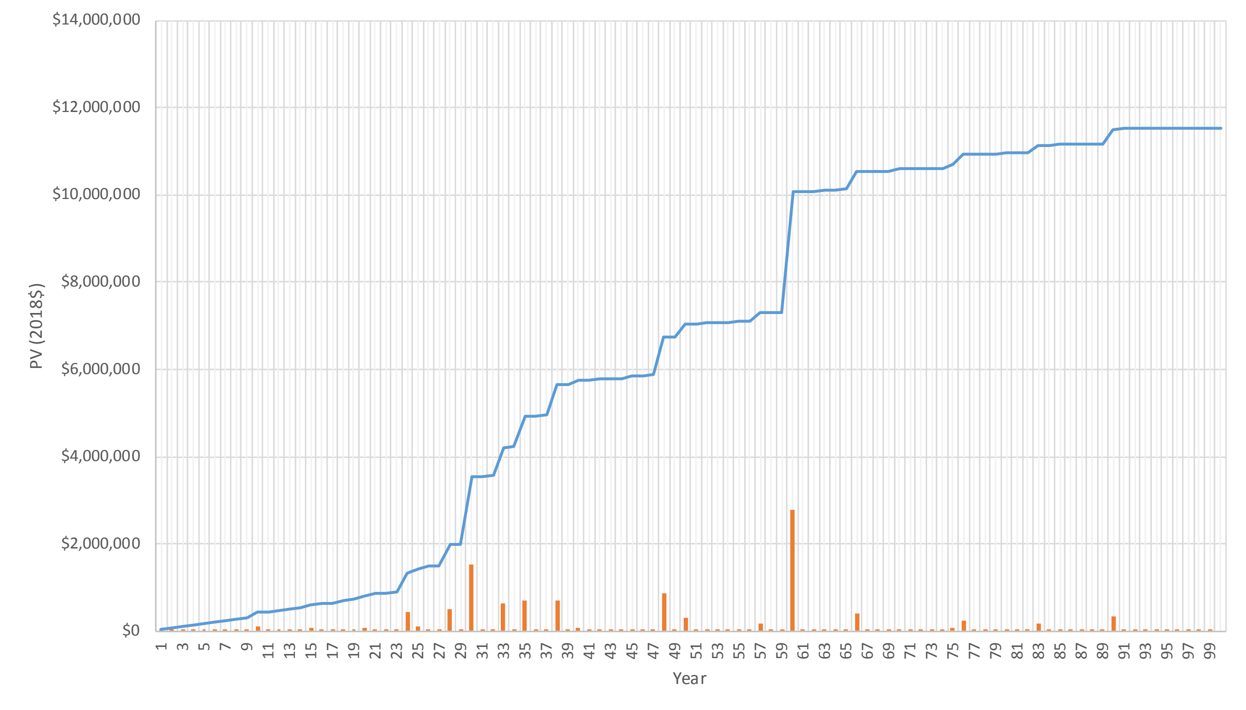

Figure 7. Life Cycle Costs per year and accumulated costs. Values are shown as present values

This type of visualization is useful when trying to get an overview of which years large maintenance jobs are expected to take place. For example, Figure 8 shows that in the LCCA, large maintenance expenses are expected around year 25, 50, and 60. These observed 'jumps' often build on assumptions such as all cables being replaced after 60 years. As stated previously, however, this is a conservative assumption because the cables will probably not get replaced all at once and not all cables may need a replacement, so in reality the curve is expected to be smoother than what is seen on Figure 8.

7 Cost Comparison of Different Design Solutions

Where the previous chapters have outlined the necessity of LCCA and shown how to perform LCCA, this chapter exemplifies another main purpose of LCCA: to provide a tool for cost comparison to select the most cost-effective solution among several alternative design solutions. As described in Section 2.2, before LCCA considerations, the suitability of the individual design alternatives with regard to achieving basic project requirements shall first be addressed. Any design alternatives subject to initial consideration, that were found to not comply with basic project requirements, shall be eliminated from further consideration in a LCCA. The most cost-effective solution is obtained by exploring LCCA of the different suitable design configurations and finding the right balance between initial costs, maintenance costs, user costs, and the condition of the bridge (see also Figure 2). Even for the same initial design configuration, different maintenance schedules can be considered and LCCA of each design can help decide which is the most cost-effective. This chapter shows an example of cost-comparison of a selected element/component of a short-span highway bridge. All steps to perform such cost comparison are available in the previous chapters of this guideline.

When carrying out a cost-comparison by use of LCCA, it is very important to be critical when assessing the final cost results. Keep in mind that the final result, with regard to cost, is very sensitive to several factors, especially the unit costs (see Section 4.1).

7.1 Example of Cost Comparison

This example concerns the decision on which types of overlay to be used for a new highway bridge structure (in the following description referred to as 'the Highway Bridge’) with a target service life of 100 years. The Highway Bridge is to be built and opened in 2020 and PVs are based on year 2018 (that is, year of design). It is assumed that the average daily traffic is 25,000 vehicles, 9% of those being trucks, and that this number remains constant with time. The Highway Bridge is a concrete slab bridge with a total road width of 92 ft and a total length of 131 ft. The bridge carries three lanes and one shoulder in each direction, one lane being an exit lane during normal conditions for the cloverleaf ramps that connects traffic on the highway bridge with the under passing road in both directions (see Figure 9). Two different types of overlay are considered for the bridge:

- Option 1: Waterproofing and asphalt overlay
- Option 2: Concrete overlay (2.5 inches)

It has been determined that the initial cost for placing an asphalt overlay + waterproofing is $120,000, whereas the initial cost for placing a 2.5-inch-thick concrete overlay is $40,000.

7.1.1 Maintenance Costs

The maintenance tasks identified and expected for the two different overlay solutions are outlined in Table 8. Inspections and cyclical maintenance tasks, such as cleaning, are not considered in this example because they are expected to be the same for both options.

Table 8. Maintenance Schedule by Option.

Year	Option 1 - Waterproofing and Asphalt Overlay	Option 2 - Concrete Overlay
15	Replacement of asphalt	-
25	Replacement of waterproofing and asphalt	Roughening of the surface (milling)
40	Replacement of asphalt	-
50	Replacement of waterproofing and asphalt	Replacement of concrete overlay
65	Replacement of asphalt	-
75	Replacement of waterproofing and asphalt	Replacement of concrete overlay
90	Replacement of asphalt	-

Each individual task in Table 8 can be further detailed and divided into subtasks. For example, Table 9 shows the subtasks for replacement of waterproofing and asphalt (Option 1) and for replacement of concrete overlay (Option 2). Similarly, subtasks can be defined for the replacement of asphalt, and milling of existing concrete overlay.

Table 9. Detailed Procedure for Maintenance Tasks.

	Option 1 - Waterproofing and Asphalt Overlay	Option 2 - Concrete Overlay
Maintenance task	Replacement of waterproofing and asphalt	Replacement of concrete overlay
Detailed maintenance procedure	1. Surface removal 2. Partial depth repairs 3. Deck surface preparation 4. Deck waterproofing 5. Asphalt supply, application	1. Concrete removal 2. Partial depth repairs 3. Supply high performance concrete (HPC) deck overlay 4. Placement of HPC deck overlay

Using the step-by-step instruction outlined in Chapter 5, LCCA can be performed for each identified maintenance subtask. The use of the instruction is exemplified for the subtask 'surface removal' for Option 1 – Replacement of waterproofing and asphalt, in the following cyclical maintenance table:

Description: Surface removal (Option 1)

Duration of cycle (years): See Table 8

Cycle starting at year: See Table 8

Quantity: 92 ft x 131 ft = 12,052 ft^2

Unit cost (2018$): 6.5$/ft^2

Activity cost per time (2018$): 12,052 ft^2 x 6.5$/ft^2 = 78,338$

Total PV (2018$): 160,455

The unit cost used in the calculation for surface removal in this cyclical maintenance table is based on experience from previous reference projects. The total PV given in the cyclical maintenance table, is found by using equation (1) and the Component Calculation Table sample provided in Section 5 (page 22), assuming a real discount rate of 2.9%. For example, at year 15:

$$PV = \$78,338 * 1/ (1 + 0.029)^{15} = \$51,020$$

Table 10. Calculation of Present Value at Each Year for Maintenance and Replacement of Overlay.

Component: Overlay Real Discount Rate: 2.9%		
Year	Surface removal (option 1)	
	Unit Cost (2018$)	PV (2018$)
1	-	-
:	-	-
15	78,338	51,020
:	-	-
25	78,338	38,334
:	-	-
40	78,338	24,966
:	-	-
50	78,338	18,759
:	-	-
65	78,338	12,217
:	-	-
75	78,338	9,180
:	-	-
90	78,338	5,978
:		
100	-	-

Component: Overlay Real Discount Rate: 2.9%		
Year	Surface removal (option 1)	
	Unit Cost	PV
	(2018$)	(2018$)
Total	548,366	160,455

In a similar manner, the total PV is determined for all other subtasks in Table 9 and maintenance tasks in Table 8. The result is shown in Table 11, which also shows the total PV cost for each option.

Table 11. Total Present Value Cost for Option 1 – Waterproofing and Overlay and Option 2 – Concrete Overlay for the Highway Bridge.

Option 1 - Waterproofing and Asphalt Overlay		Option 2 - Concrete Overlay	
Maintenance task	Total PV (2018$)	Maintenance task	Total PV (2018$)
Surface removal (See Table 8)	160,455	Deck surface roughening (Year 25)	10,961
Partial depth repairs (every 25 years)	94,749	Concrete removal (Years 50 and 75)	79,887
Deck surface preparation (every 25 years)	18,950	Partial depth repairs (Years 50 and 75)	101,803
Deck waterproofing (every 25 years)	71,063	Supply HPC deck overlay (2.5 inch) (Years 50 and 75)	3,355
Asphalt supply+application (every 10 to 15 years)	70,376	Placement of HPC deck overlay (Years 50 and 75)	3,195
TOTAL	**415,573**	**TOTAL**	**199,202**

7.1.2 Road User Costs

On top of the direct maintenance costs provided in Table 11, indirect costs such as maintenance of traffic and mobilization during maintenance can also be part of the LCC comparison of the two options. This is typically done by considering Road User Costs (RUCs). RUCs are added vehicle operating costs, travel delay costs, crash costs, and emission costs to highway users resulting from construction, maintenance, or rehabilitation activity. Moreover, RUC can include offsite components such as noise, and business and local community impacts [11]. Considerations on additional delay because of congestion and nighttime closures can also be included in a more refined RUC analysis. Advanced tools are available for such detailed analyses, for example, A Case Study on Sr-91 Corridor Improvement Project [12] and CO^3 User Manual [13], and for this example, RUCs include travel delay costs caused by the establishment of either a detour or work zones.

In this example, RUC for car and truck travel delays are found using the Ohio DOT's Innovative Contracting Manual [14]. The values are from 2008 and the Consumer Price Index (CPI) is used to convert the costs to 2018 values. The CPI used is the "Historical Consumer Price Index for All Urban Consumers (CPI-U): U. S. city average, all items" which can be found on www.bls.gov/cpi. To further extrapolate the values to future years, a 3% increase per year is assumed based on the recent average over the past decade or so. This increase is also based on the previously mentioned CPI data. Table 12 summarizes the RUC for cars and trucks in 2018 values.

Table 12. Road User Costs Per Hour for Cars and Trucks According to Ohio DOT [14]. The Values From 2008 are Extrapolated to Future Years by Use of the Consumer Price Index.

Year	Car	Truck
2018	$23.09	$62.33

During maintenance of the bridge deck, according to the tasks specified in Table 6, two different traffic control alternatives are considered for both Option 1 – Waterproofing and asphalt overlay and Option 2 – Concrete overlay:

- Complete closure (detour): The bridge is completely closed during maintenance and traffic is redirected along an alternative route as shown on Figure 9. This detour is 2.6 miles long compared to the original travel distance of 1.1 miles along the highway. A reduced speed of 40 miles per hour (mph) is allowed on the detour route compared to the speed of 55 mph allowed on the highway.

Figure 8. Map of redirected traffic for complete closure of the Highway Bridge. The original route (green, solid line) is 1.1 miles long and the detour route (red, dashed line) is 2.6 miles long.

- Partial closure (lane restriction): The bridge is partially closed during maintenance with two narrowed lanes (for example, 10 foot width) shifted, using the exit lane for through traffic, to prevent closure of through lanes. A 1.1 mile long work zone is assumed in which the speed is reduced from 55 mph to 30 mph.

Table 13 shows assumptions on the expected duration of closures for either complete or partial closure of the Highway Bridge. In general, all durations assume summer work and no extra time for delays (for example, weather). The duration for replacement of waterproofing assumes an epoxy + bitumen sheet membrane system.

Table 13. Duration of Closure for Either Complete or Partial Closure of the Highway Bridge by Option.

Option 1 – Waterproofing and Asphalt Overlay			Option 2 – Concrete Overlay		
Task	Traffic Control	Duration (days)	Task	Traffic Control	Duration (days)
Replacement of asphalt (every 10 to 15 years)	Complete closure (detour)	3	Roughening of the surface (milling) (Year 25)	Complete closure (detour)	1
	Partial closure (lane restrictions)	6		Partial closure (lane restrictions)	2
Replacement of waterproofing, asphalt and asphalt (every 25 years)	Complete closure (detour)	14	Replacement of concrete overlay (Years 50 and 75)	Complete closure (detour)	16
	Partial closure (lane restrictions)	20		Partial closure (lane restrictions)	38

The RUC analysis can now be performed based on the following parameters:

- RUC for the year of maintenance (cars and trucks)
- Average daily traffic (cars and trucks)
- Duration of closure
- For complete closure: Length of normal route and detour route, and speed on normal route and detour route

- For partial closure: Length of work zone, original posted speed, and work zone posted speed

Several online tools are available for computing the total RUC based on these parameters. One such example can be found at Ohio DOT's website [15] and has been used to determine the RUC for Option 1 – Waterproofing and asphalt overlay and Option 2 – Concrete overlay. As an example of the RUC calculations, Table 14 shows RUC for Option 2, deck surface roughening at year 2045 with full bridge closure and Table 15 shows RUC for Option 1, replacement of asphalt at year 2035 with partial bridge closure. All costs are presented as 2018 values.

Table 14. Calculation of RUC for Surface Roughening at Year 2045 with Full Bridge Closure for Option 2 – Concrete Overlay by Use of Calculation Tool found at Ohio DOT's Website [15].

Work Zone User Cost Calculations (Year 2018)		
Detour (Using Distance & Speed)		
User Input:		
Construction Calendar Year:	2045	
	Car	B/C Truck
ADT of Detoured Section:	22,727	2,273
Length of Normal Route (Miles):	1.1	
Length of Detour Route (Miles):	2.6	
Avg Posted Speed on Normal Route (MPH):	55	
Avg Posted Speed on Detour Route (MPH):	40	
Duration of Closure (Days):	1	
Calculated Values:		
Cost per Hour:	$23.09	$62.33
Travel Time Along Normal Route (Secs):	72	72
Travel Time Along Detour Route (Secs):	234	234
Delay (Secs):	162	162
Delay (Hours):	0.045	0.045
Delay Cost per Vehicle:	$1.04	$2.81
Delay Cost per Day:	$23,617.50	$6,375.85
Delay Cost for Closure Duration:	$23,617	$6,376
Total Delay Cost for Closure Duration:	**$29,993**	
Average Delay Cost per Day:	**$29,993**	

Table 15. Calculation of RUC for Replacement of Asphalt at Year 2035 with Partial Bridge Closure for Option 1 – Waterproof and Asphalt Overlay by Use of Calculation Tool found at Ohio DOT's Website [15].

Work Zone User Cost Calculations (Year 2018)		
No Lanes Closed		
User Input:		
Construction Calendar Year:	2035	
	Car	B/C Truck
ADT of Section:	22,727	2,273
Length of Work Zone (Miles):	1.1	
Original Posted Speed (MPH):	55	
Work Zone Posted Speed (MPH):	30	
Duration of Work Zone (Days):	6	
Calculated Values:		
Cost per Hour:	$23.09	$62.33
Travel Time Pre-Work Zone (Secs):	72	72
Travel Time During Work Zone (Secs):	132	132
Delay (Secs):	60	60
Delay (Hours):	0.017	0.017
Delay Cost per Vehicle:	$0.38	$1.04
Delay Cost per Day:	$8,747.22	$2,361.42
Delay Cost for Work Zone Duration:	$52,483	$14,169
Total Delay Cost for Work Zone Duration:	$66,652	
Average Delay Cost per Day:	$11,109	

RUC at the different years of maintenance must be converted into PVs similar to the maintenance costs in Section 7.1.1. Using a real discount rate of 2.9%, the total delay costs from Table 14 and Table 15 can be converted into PV as shown in Table 16.

Table 16. Calculations of Present Value for Total Delay Costs in Table 14 and Table 15.

Total Delay Cost Example For	Calculation	Present Value (2018$)
Option 2, surface roughening, year 2045, partial closure (Table 14)	$29,993 x (1+0.029)$^{-25}$	$14,677
Option 1, replacement of asphalt, year 2035, full closure (Table 15)	$66,652 x (1+0.029)$^{-15}$	$43,409

Similar calculations are carried out for all other years shown in Table 8. A summary of the present value RUC for Options 1 and 2 are as shown in Table 17 and Table 18, respectively. The future RUCs are affected by average daily traffic (ADT) at the time of maintenance. However, for simplicity in this example and to focus on the impact discounting has on the PV of future costs, calculations assume the average daily traffic remains constant with time. As the different maintenance options involve activities at different years, the expected ADT at the time of maintenance should be accounted for in real-time on local traffic forecasting models, for example.

Table 17. Comparison of RUC for Complete or Partial Closure of the Highway Bridge for Option 1 - Waterproofing and Asphalt Overlay. RUC are shown as Present Value Costs.

Year	Task	Complete Closure (Detour)		Partial Closure (Lane Restrictions)	
		Duration (days)	Total RUC (PV 2018$)	Duration (days)	Total RUC (PV 2018$)
2020	Bridge constructed				
2035	Replacement of asphalt	3	$58,602	6	$43,409
2045	Replacement of waterproofing and asphalt	14	$205,480	20	$108,719
2060	Replacement of asphalt	3	$28,677	6	$21,242
2070	Replacement of waterproofing and asphalt	14	$100,551	20	$53,201
2085	Replacement of asphalt	3	$14,033	6	$10,395
2095	Replacement of waterproofing and asphalt	14	$49,204	20	$26,034
2110	Replacement of asphalt	3	$6,867	6	$5,087
TOTAL COST			**$463,413**		**$268,087**

Table 18. Comparison of RUC for Complete or Partial Closure of the Highway Bridge for Option 2 - Concrete Overlay. RUC are shown as Present Value Costs.

Year	Task	Complete Closure (Detour)		Partial Closure (Lane Restrictions)	
		Duration (days)	Total RUC (PV 2018$)	Duration (days)	Total RUC (PV 2018$)
2020	Bridge constructed				
2045	Replacement of asphalt	1	$14,677	2	$10,872
2060	Replacement of waterproofing and asphalt	16	$93,368	38	$85,122
2095	Replacement of asphalt	16	$45,689	38	$41,654
TOTAL COST			**$153,734**		**$137,648**

For both Options 1 and 2, partial closure of the Highway Bridge is the most cost-effective traffic control alternative and therefore recommended. As stated previously, the calculations in Tables 17 and 18 are simplified and a more refined analysis, including items such as traffic congestion and forecasted ADT at the time of maintenance, could be included if a higher level of detail is needed.

7.1.3 Cost Comparison

It is now possible to perform a cost-comparison by including initial construction costs, expected maintenance costs, and road user costs. Table 19 summarizes the LCCA for Options 1 and 2.

Table 19. Comparison of Total Costs in Present Value (PV 2018$) for Option 1 – Waterproofing and Asphalt Overlay and Option 2 – Concrete Overlay for the Highway Bridge.

	Option 1 – Waterproofing and Asphalt Overlay	Option 2 – Concrete Overlay
Initial construction costs	$120,000	$40,000
Maintenance costs	$415,573	$199,202
SUM	**$535,573**	**$239,202**
Road user costs	$268,087	$137,648
Total PV cost (2018$)	**$803,660**	**$376,850**

The results summarized in Table 19 indicate in this example case, Option 2 yields the lowest total PV cost and would be recommendable based on the described LCCA approach. However, final decisions on which option to choose could also consider other factors such as user comfort and noise level, bridge type, safety aspects, and best practices used by the Owner.

8 Summary

This document provides a succinct introduction to LCCA of bridge structures along with worked examples. The main purpose of the document is to present those unfamiliar with LCCA the why, how, and when to perform LCCA of bridge structures. The main conclusions and highlights of the material presented herein are summarized as follows:

- The purpose of LCCA is to specify an economically efficient set of actions and their timing during the bridge's life cycle, to achieve the desired service life, and thereby ensuring longevity of the bridge structure. Moreover, cost comparison based on LCCA can be used to select the most cost-effective solution by finding the right balance between initial costs, maintenance costs, and the desired condition of the bridge.
- Maintenance of bridge components greatly influences the rate of their deterioration. Maintenance costs (assuming proper regular maintenance) are typically less than the costs of prematurely replacing a bridge because the lack of maintenance has led to early deterioration and decay.
- To carry out LCCA, it is necessary to be familiar with several fields, concepts, and terms such as service life, life cycle, maintenance, real discount rate, and PV. These terms are defined throughout this document.
- The planned maintenance tasks of different bridge components are closely related to the exposure zones and level of expected deterioration of the components. Based on these factors, the necessary maintenance precautions can be planned. It is important to carefully identify maintenance tasks and the related unit costs as this greatly influences in the outcome of LCCA. This is further discussed in Chapters 3 and 4.
- Step-by-step instructions and help tools for performing LCCA of bridges is introduced in Chapter 5.
- A detailed worked LCC calculation example of a major bridge is presented in Chapter 6. The example covers numerous bridge components, typical maintenance tasks, and walks the reader through the steps introduced in Chapter 5. Chapter 6 also discusses how to best visualize the results from the LCC calculation.
- The advantages of performing cost comparison of different design solutions through the use of LCCA are described in Chapter 7, where two different design solutions for the overlay of a short-span highway bridge are analyzed by also including considerations on road user costs.

9 References

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