BridgeLCC 1.0 Users Manual

Life-Cycle Costing Software for Preliminary Bridge Design

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Abstract

BridgeLCC 1.0 is user-friendly software developed by the National Institute of Standards and Technology to help bridge designers determine the cost effectiveness of new, alternative construction materials. The software uses a life-cycle costing methodology based on the ASTM standard for life-cycle costing (E 917) and a cost classification scheme developed by NIST. This user manual describes the functions and settings in BridgeLCC and includes an example study which illustrates the use of the software.

BridgeLCC is designed to run on Windows™ 3.x, Windows™ 95/98, and Windows™ NT 4.0. Although BridgeLCC is specifically tailored to highway bridges, it can also be applied to pavements, piers, and other civil infrastructure.

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1.0 Introduction

1.1 Background

The Building and Fire Research Laboratory, one of seven laboratories at the National Institute of Standards and Technology, performs research in diverse areas of building research such as material science, structural design, automated construction, and the effects of fire on building systems. The material science research in particular develops, tests, and creates measurement standards for "new-technology" construction materials such as high-performance concrete and fiber-reinforced-polymer (FRP) composites.

Part of this materials research is developing and providing industry with tools that can estimate and compare the life-cycle cost—the total cost over the intended life—of one construction material with another. The most basic comparison is between a material currently being used—herein called the "base case" material—and an new-technology material. Since the particular use of the material determines its life-cycle cost, costs are usually compared by considering their use in a specific "prototypical" structure, such as "a 322-foot long by 42-foot wide two-lane highway overpass." The engineer, in effect, goes through the process of designing, building, maintaining, and eventually disposing of two functionally equivalent bridges made of the competing, alternative materials.

BridgeLCC is user-friendly, Windows™ software specifically designed to help these engineers with these comparisons. The engineer compiles the costs of building, maintaining, and then disposing of each of the two above-mentioned bridges. These costs include project costs incurred by the agency responsible for the structure (agency costs), costs incurred by drivers on the highway that are inconvenienced by bridge construction and other bridge activity (user costs), and user costs incurred by third parties who are not direct users of the structure but are impacted by bridge activity (third-party costs). Each of these types of costs are compiled over the life or "life cycle" of each structure.

BridgeLCC uses a life-cycle costing methodology based on the ASTM practice for measuring the life-cycle costs of buildings and building systems (ASTM E 917) and a cost classification scheme developed by NIST. The practice insures that the cost calculations follow accepted practice; the scheme helps the engineer account for all project costs and to properly categorized them.

Once the costs are compiled, the engineer compares the life-cycle costs of the two bridges. The structure with the lowest life-cycle cost, all other factors being equal, is the cost-effective bridge. The engineer uses the cost classification to compare breakdowns of costs according to who pays the costs, when the costs occur, and what part of the project generated the costs. The engineer compares the technical advantages and disadvantages of each material in life-cycle cost terms.

The life-cycle costs are first based on the engineer's "best guess" of what the costs of each material are. If one or more of an alternative's costs are highly uncertain, the user can also assign to each cost a range of possible costs (e.g, instead of costing $15 per square foot, it can cost anywhere between $10 and $20 per square foot) and run Monte Carlo simulations, generating a range of possible life-cycle costs. This

allows the engineer to see to what extent cost uncertainties affect whether the particular structure is cost-effective for all possible cost outcomes.

To give an example of how BridgeLCC organizes and displays costs, Figure 1 shows the BridgeLCC **Cost Summary** window. This window serves as the command center where the current life-cycle cost totals are displayed and buttons start the most common tasks.
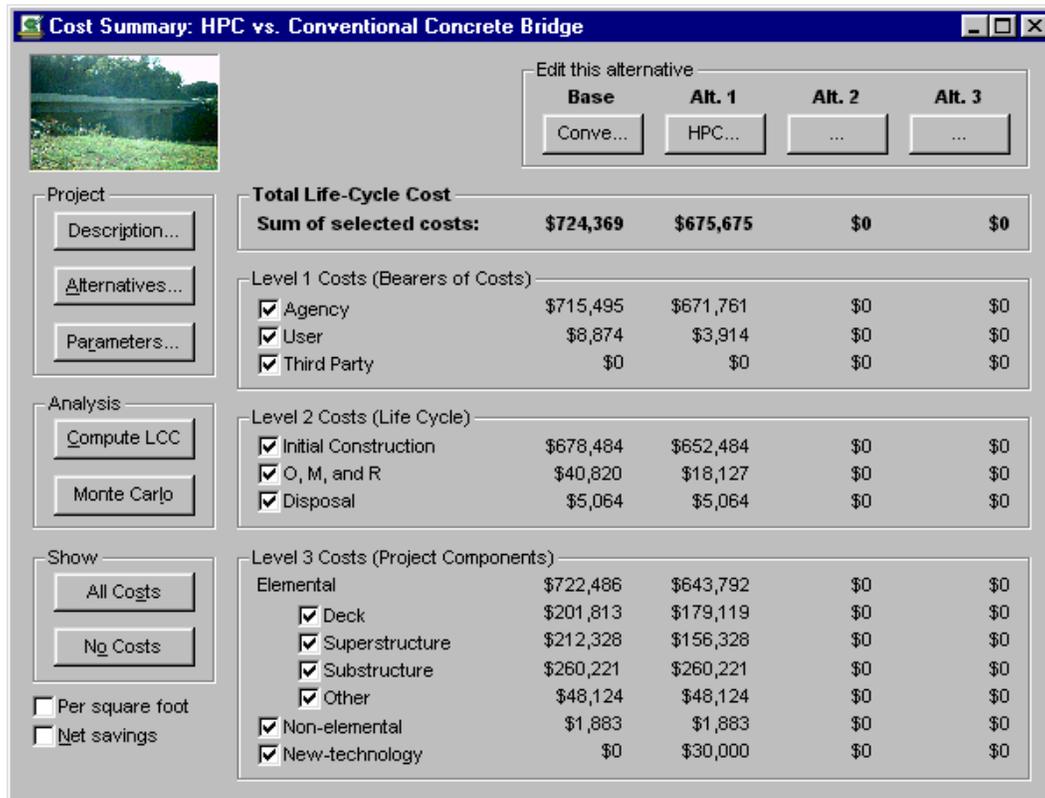
Figure 1. Cost Summary Window

The top row, titled **Sum of selected costs**, lists the sum of costs currently entered for each alternative. Below this line, the window shows this total divided three ways according to three groups: **Bearers of Costs**, **Life Cycle,** and **Project Components**. Note that the sum of each category cost equals the **Sum of selected costs**.

In the upper-right section, the **Edit this alternative** group box contains pushbuttons for accessing the two project alternatives, **"Conve..."** and **"HPC..."** (which are shortened versions of the alternative names "Conventional-Concrete Bridge" and "HPC Bridge").

The check boxes in the **Level 1**, **Level 2**, and **Level 3** cost categories allow the user to edit, compute, and display results for a subset of costs. For example, to work with only the engineer's estimates of these

two structures, the user check-marks the **Agency** box in the **Level 1** group, the **Initial Construction** box in the **Level 2** group, and all four **Element** boxes in the **Level 3** group. Now, the **Cost Summary** window displays only this engineer's estimates for each alternative bridge, as a total in the **Sum of selected costs** line and by cost types in the **Level 1**, **Level 2**, and **Level 3** cost categories. All subsequent windows, graphs, and reports will display only this subset of costs.
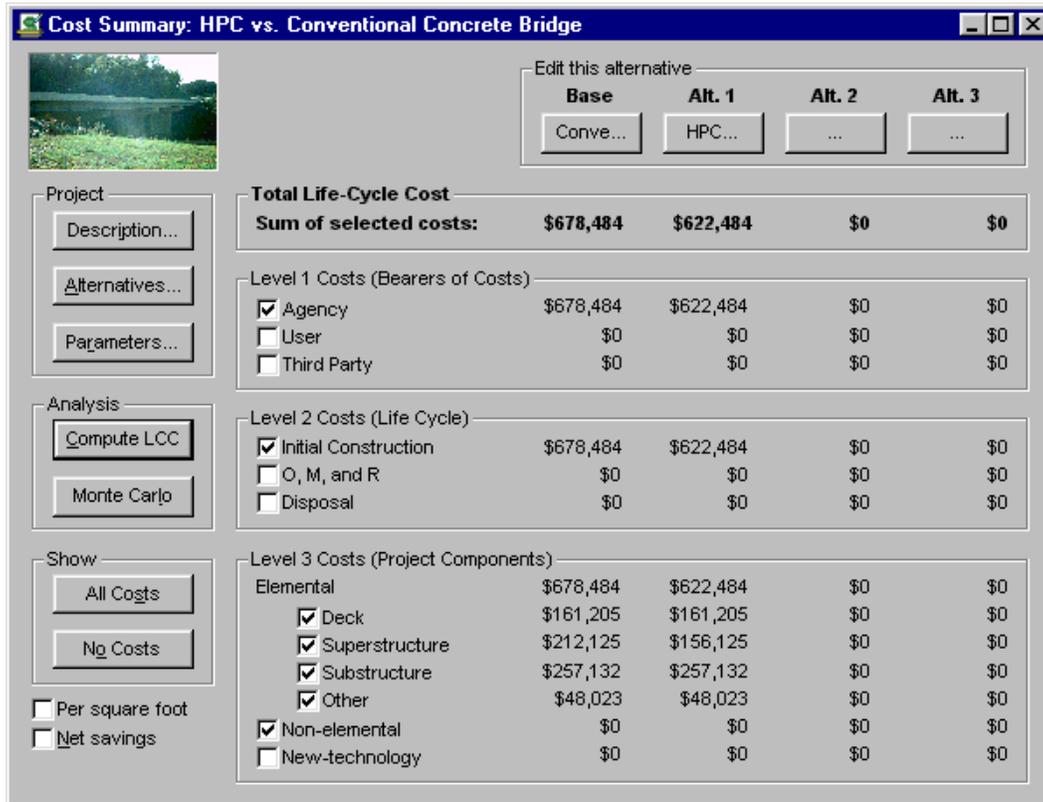
Figure 2. Cost Summary Window Showing the Engineer's Estimate

From the **Cost Summary** window, and from the **LCC Steps** window (LCC stands for life-cycle cost) shown later, the user can perform most of the steps required to complete a life-cycle cost analysis. From these windows the engineer can access other windows which will allow him or her to

- describe the overall project and the alternatives under consideration;
- set project-wide parameters such as the interest rate for discounting future costs to the present, the average traffic levels at the bridge's location, and the value of driver's time;
- input and edit individual costs for each alternative bridge;
- run simulations in which one or more of the costs is uncertain; and
- document the steps in the analysis and the results obtained.

1.2 The Economic Foundation of BridgeLCC

BridgeLCC uses the life-cycle cost (LCC) model described in Ehlen and Marshall (1996).[1] This model is consistent with the standard practice for measuring life-cycle costs (E-917) published by the American Society for Testing and Materials.[2]

Competing construction materials are assessed by comparing their life-cycle costs when performing the same particular function, say when used for constructing, maintaining, and eventually disposing of a two-lane highway bridge. The LCC model shows for each alternative material all of the relevant costs for the given function. The alternative that performs the function for the minimum life-cycle cost is the economically efficient choice, other things being equal. The model uses ASTM-standard formulas for discounting future costs to their present-value equivalents. Additional formulas are provided for computing the costs to drivers during bridge work (but this does not prevent users from specifying their own user costs).[3]

BridgeLCC can also perform Monte Carlo simulations of probabilistic life-cycle cost outcomes, based on uncertainty regarding the quantity or unit cost of a project task (e.g., the cost to construct a deck, in dollars per square meter). The user can choose the relative uncertainty of each cost. Using either uniform or normal (Gaussian) distributions for the individual costs, the Monte Carlo simulations produce cumulative distribution functions of life-cycle cost, allowing the user to see the range of potential life-cycle cost outcomes for each alternative.

1.3 Organization of this Manual

BridgeLCC is designed to be a user-friendly, intuitive tool for estimating the life-cycle costs of bridges. The manual begins with two chapters which describe the basic functions and options in BridgeLCC. It follows with a chapter about the online help in BridgeLCC and a chapter presenting an example life-cycle cost analysis.

Specifically, Chapter 2 provides a description, by function, of how to use BridgeLCC. This includes how to start an analysis, how to edit costs and project parameters, and how to produce life-cycle cost tables, graphs, and printed reports. Chapter 3 highlights several key BridgeLCC options that make analysis more comprehensive and productive. Chapter 4 describes the BridgeLCC online help which provides information about each window, about life-cycle costing terminology, and about the default bridge elemental classification. Chapter 5 provides an example of how to apply the tools described in Chapters 2 through 4. It illustrates a case study comparison of high-performance and conventional concrete bridges (The BridgeLCC file of this analysis, CASE-1.LCC, can be found in your BridgeLCC directory).

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[1] Ehlen, Mark A., and Marshall, Harold E. 1996. *The Economics of New-Technology Materials: A Case Study of FRP Bridge Decking.* NISTIR 5864. Gaithersburg, MD: National Institute of Standards and Technology.

[2] For a description of various economic methods for assessing the relative cost effectiveness of projects, see American Society of Testing and Materials, *ASTM Standards on Building Economics,* Third Edition, Philadelphia, PA, 1994.

[3] See Appendix B for the discounting and user cost formulas used in BridgeLCC.

Appendix A outlines the life-cycle methodology in BridgeLCC. Appendix B lists the BridgeLCC discounting and user cost formulas. Appendix C provides blank worksheets for listing costs prior to entering them into BridgeLCC.

The manual assumes that the reader has a working knowledge of how to use Microsoft® Windows™, such as how to find files and copy them, and to print results to a printer. If you are not familiar with Windows™, please consult a Windows™ users guide or operating system manual before proceeding.

The BridgeLCC users manual uses some standard window nomenclature, shown in Figure 3.
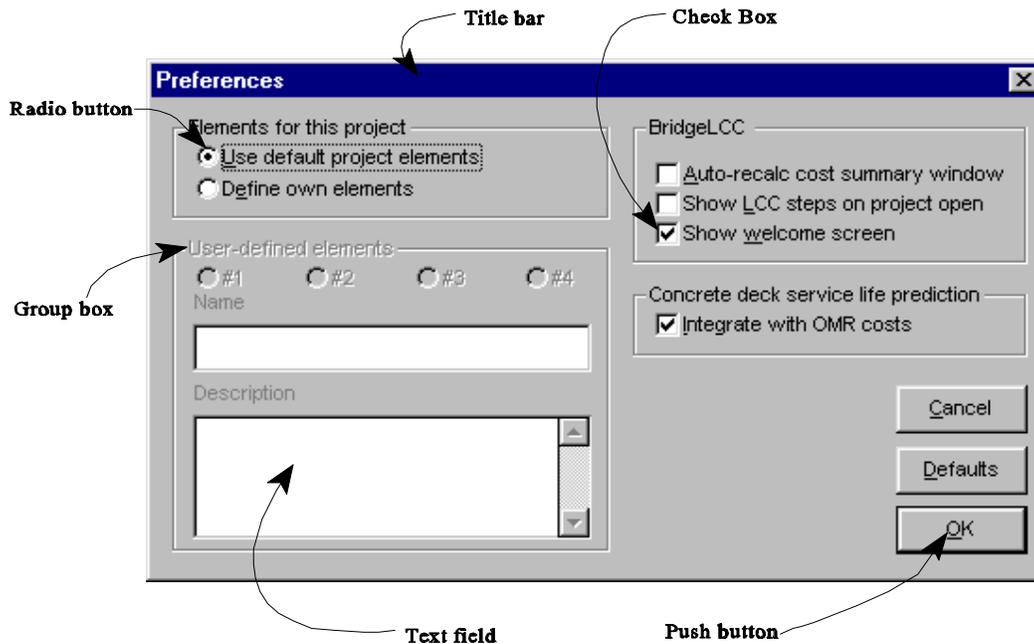
Figure 3. The Names of Common Window Items

The manual also uses some typographical conventions. Menu and window items are shown in **bold,** and menu items in a task are separated with "/" slashes. For example, to open a stored analysis, the user is asked to select **File/Open Existing Analysis...**, that is, to first click "File" and then click "Open Existing Analysis" from the "File" submenu. Similarly, if the user is asked to push a window button labeled "OK," the user is asked "to push the **OK** button." The names of the windows themselves are also in **bold**; e.g., the window in Figure 3 is the **Preferences** window (which is accessed by selecting **File/Preferences...** from the menu.) Filenames are shown in UPPER-CASE type, for example, the analysis file that comes with BridgeLCC is CASE-1.LCC.

Special notes	Special notes are highlighted with a box similar to the "Special notes" box to the left of this paragraph. These notes provide useful hints and warnings about the possible misuse of BridgeLCC.

This manual is intended to act as the software help system found in many Windows™ programs. Since Adobe® Acrobat™ PDF files have full search and keyword capabilities, a PDF of this users manual is included with BridgeLCC (it is the file MANUAL.PDF and should be in the BridgeLCC directory of your computer). For information about Adobe® PDF files and how to obtain Adobe® Acrobat™, access the Adobe® web site, http://www.adobe.com/prodindex/acrobat/readstep.html.

2.0 Using BridgeLCC

This chapter describes the three functional tasks necessary to perform a life-cycle cost analysis with BridgeLCC: (1) starting an analysis, (2) inputting and editing project data, and (3) computing and interpreting the life-cycle cost results. Each function is described with the first-time user in mind, and is supported with pictures of BridgeLCC screens and specific instructions on how to accomplish the tasks. Once these tasks are understood, read Chapters 3 and 4 for a description of additional BridgeLCC capabilities.

2.1 Installing and Starting BridgeLCC

BridgeLCC can be installed either from compact disk (CD) or by downloading the software from the BridgeLCC web site, http://ehlen.nist.gov/BridgeLCC/welcome.html. BridgeLCC is designed to run in Windows™ 3.x, Windows™ 95/98, or Windows™ NT 4.0. The computer should have at least a 486-66MHZ processor, 8 megabytes of RAM, 15 megabytes of available hard disk space, and a video card that supports 800x600 resolution (though 1024x768 is highly recommended).

2.1.1 Installing BridgeLCC

To install BridgeLCC from CD, insert the disk, access it with either File Manager (Windows™ 3.x) or Internet Explorer (Windows™ 95/98 and NT), and double-click on SETUP.EXE. To install from the Internet, download BRIDGE10.EXE to a clean directory (one with no files in it; create one if necessary), then double-click on the file. This will expand a self-extracting ZIP file into a set of installation files. Next, double-click on SETUP.EXE. BridgeLCC will then run through its installation program, during which it will ask you for the directory to which you want to install BridgeLCC.

Win 3.1	Modify the CONFIG.SYS file so that it includes a FILES=50 statement (do not modify this file if you are already specifying more than 50 files).

2.1.2 Starting BridgeLCC

To start BridgeLCC:

In Windows 3.x:
Access Program Manager, open the BridgeLCC group, and double click on the BridgeLCC button.

In Windows 95/98 and NT:
Access the BridgeLCC button via the Start/Programs/BridgeLCC 1.0 menu in the lower left-hand corner of the screen.

The first time BridgeLCC runs it must create a set of supporting subdirectories and files. Installation will have completed successfully if the opening screen, shown in Figure 4, has a picture of a bridge in the middle. If the opening screen shows only a black box, then select the **Exit** button and restart BridgeLCC.

Figure 4. Welcome Window

The **Welcome** window has three buttons: **Overview**, **Start**, and **Exit**. The **Overview** button provides a brief discussion of the purpose and scope of BridgeLCC; this is intended for users that are not familiar with life-cycle costing methods and analysis. Select the **Start** button to enter BridgeLCC. Select the **Exit** button to leave BridgeLCC.

2.2 Starting an Analysis

2.2.1 Opening an Existing Analysis

To open an existing analysis, such as the included case study, choose **File/Open Existing Analysis...** from the menu, and then select one of the *.LCC files below the **File name** area (Figure 5). If necessary, change drives or folders to access the file. If you receive an "UnZip error", the file has a damaged directory. To repair the file, run "FIXLCC FILENAME", when FILENAME.LCC is the file that will not open. You will now have a repaired version of your file called FIXED.LCC.
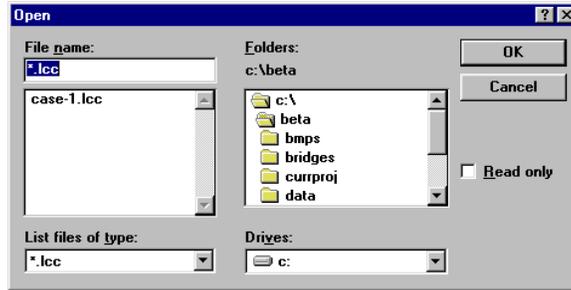
Figure 5. Open Window

Once the analysis has been opened, the **Cost Summary** window will display (see Figure 1); by default, the **LCC Steps** window will also display in the upper-right corner. See section 2.2.4 for a description of the **LCC Steps** window.

2.2.2 Starting a New Analysis

A new analysis is started by selecting **File/Start New Analysis...** from the menu (if an analysis is already open, you must first close it by selecting **File/Close Analysis** from the menu.) BridgeLCC will then walk through two "wizard" windows which allow you to input the initial basic set of information needed for an analysis. These two wizard windows are shown in Figure 6.
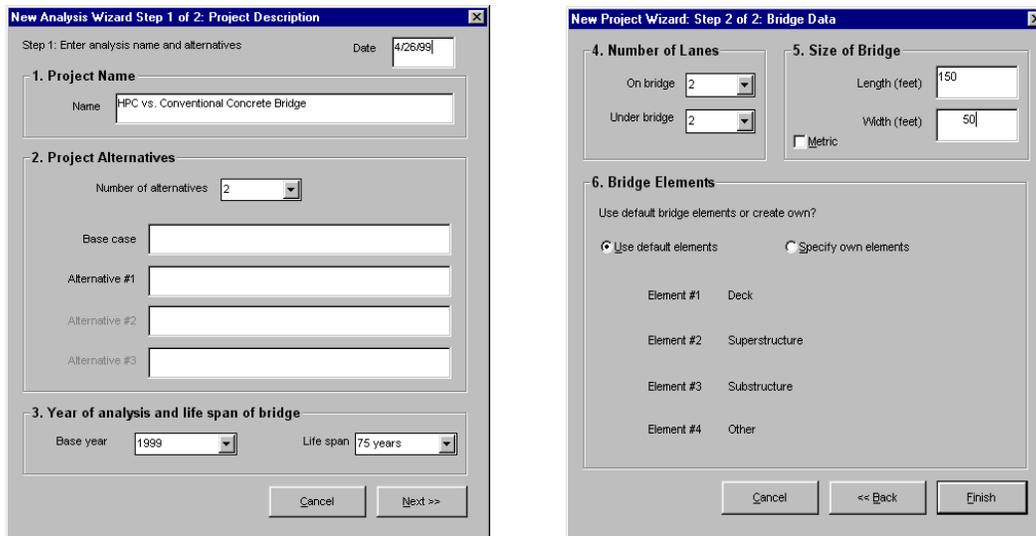
Figure 6. New-Analysis Wizard Windows

Use the first wizard window to name and date the analysis, to choose the number of alternatives to be compared and to name them, and to define the study period. Use the second wizard window to document the number of lanes, to give dimensions to the structure (these may vary slightly between alternatives),

and either to use the default bridge elements (Deck, Superstructure, Substructure, and Other) or to specify your own elements. Department of transportation (DOT) will often have their own set of elements such as Superstructure, Substructure, and Approaches. The descriptions of the default bridge elements are given in the lower portion of the **Edit Cost** window and in the cost classification section of the **Help** window (accessed by selecting **Help/Help Topics...** from the menu and pressing the **Cost Classification** button at the top of the window).

Once you have completed the two form windows, BridgeLCC will ask for a filename for the analysis, create the new analysis file, and then display the **Cost Summary** window (by default, the **LCC Steps** window will also display; this window is described in section 2.2.4).

2.2.3 The Cost Summary Window

The **Cost Summary** window serves two important functions. First, it summarizes the current state of the cost calculations. The middle to lower-right area of the window lists, by cost type, the life-cycle cost of each project alternative. In Figure 7, these alternatives are listed as **"Conve..."** for the base case and **"HPC..."** for alternative #1 (the words "Conve..." and "HPC..." are abbreviations of the alternatives' full names).

Cost Summary: HPC vs. Conventional Concrete Bridge

Edit this alternative

	Base	Alt. 1	Alt. 2	Alt. 3
	Conve...	HPC...	...	...

Total Life-Cycle Cost

	Base	Alt. 1	Alt. 2	Alt. 3
Sum of selected costs:	$724,369	$675,675	$0	$0

Level 1 Costs (Bearers of Costs)

☑ Agency	$715,495	$671,761	$0	$0
☑ User	$8,874	$3,914	$0	$0
☑ Third Party	$0	$0	$0	$0

Level 2 Costs (Life Cycle)

☑ Initial Construction	$678,484	$652,484	$0	$0
☑ O, M, and R	$40,820	$18,127	$0	$0
☑ Disposal	$5,064	$5,064	$0	$0

Level 3 Costs (Project Components)

Elemental	$722,486	$643,792	$0	$0
☑ Deck	$201,813	$179,119	$0	$0
☑ Superstructure	$212,328	$156,328	$0	$0
☑ Substructure	$260,221	$260,221	$0	$0
☑ Other	$48,124	$48,124	$0	$0
☑ Non-elemental	$1,883	$1,883	$0	$0
☑ New-technology	$0	$30,000	$0	$0

Project: Description... / Alternatives... / Parameters...
Analysis: Compute LCC / Monte Carlo
Show: All Costs / No Costs
☐ Per square foot
☐ Net savings

Figure 7. Cost Summary Window

The current total for each alternative bridge is listed in the **Total Life Cycle Cost** group, while the lower **Level 1**, **Level 2**, and **Level 3** groups show the breakdown of the total by cost category. For example, the current total for Alternative #1, "HPC," is $675,675. Looking at the **Level 1** breakdown of costs, $671,760 of this cost is Agency costs, i.e., is incurred by the agency that builds, maintains, and disposes of the structure; the remaining $3,914 is User costs, i.e., costs incurred by drivers on the bridge.

Similarly, looking at the **Level 2** breakdown of costs, of the $675,675 total, $652,484 occurs during initial construction, $18,127 occurs during operation, maintenance, and repair (OM&R); and $5,064 occurs during disposal of the structure. Finally, looking at the **Level 3** breakdown of costs, of the $675,675 total, $166,790 is associated with the deck, $156,328 is associated with the bridge superstructure, $260,221 is associated with the bridge substructure, $60,453 is associated with other physical components with the structure, $1,883 is associated with non-elemental parts of the bridge (e.g. overhead costs, mobilization), and $30,000 is associated with "new-technology" activities, i.e., introducing and using the material for the first time.

The second function of the window is to act as a command center for starting important tasks and accessing other windows. The **Description...**, **Alternatives...**, and **Parameters...** buttons allow the user to edit the project objective, the list of alternatives that satisfy the objective, and the parameters that are common to all alternatives. Life-cycle costs can be recalculated by pressing the **Compute LCC** button, and Monte Carlo simulations can be performed (and a graph of their results shown) by pressing the **Monte Carlo** button.

To check-mark all of the **Level 1**, **Level 2**, and **Level 3** categories of cost, press the **All Costs** button; press **No Costs** to uncheck-mark all of the cost types. To have the other windows act upon only a subset of all costs types, check-mark only those **Level 1**, **Level 2**, and **Level 3** costs. When other windows are accessed, they will only show the costs that match the currently check-marked selection.

To see the life-cycle costs expressed in dollars per square foot (or per square meter), check-mark the **Per square foot** box. The dollar values that display are based on the values of bridge length and bridge width in the **Project Parameters** window (described in section 2.3.2). The box will read **Per square foot** or **Per square meter** depending on the units chosen by the **Use metric sizes** check box in the **Project Parameters** window.

To see the results expressed as the savings over the base case, check-mark the **Net savings** box. When the box is checked, alternatives' values that are positive indicate that the alternative provides net savings over the base case; if the values are negative, then the alternatives' costs are greater than the base case.

2.2.4 The LCC Steps Window

BridgeLCC uses the ASTM E 917 practice, in which, for example, the analyst defines the project, the alternatives, and the costs, and carries out sensitivity analysis. BridgeLCC provides a checklist of these framework items in the **LCC Steps** window, show in Figure 8. As the default, the window displays each time an analysis is started (this option can be turned off in the **Preferences** window).
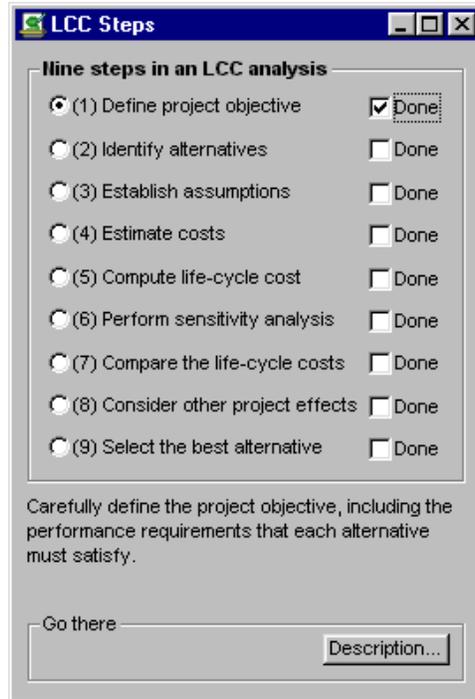
Figure 8. LCC Steps Window

Use the window to follow and complete the steps in the ASTM practice. When one of the step buttons is pressed, the bottom of the window displays a brief explanation of how to carry out the step and buttons to execute the step. Check-mark each step's **Done** button as the step is completed.

2.3 Inputting Project Data

The second functional task of an analysis is to input three types of project data:

> **1. project description and alternatives data:** descriptions of the project, the project objectives, the minimum performance criteria each alternative must meet, and the alternatives that meet these criteria.

> **2. project parameter data:** the parameters common to all project alternatives. These include the discount rate and the traffic parameters used to calculate user costs.

> **3. cost data:** the individual costs that make up each project alternative's life-cycle cost.

Each type of project data is described in turn.

2.3.1 Project Description and Alternatives

The project and its alternatives are input in the **Project Description** and **Project Alternatives** windows. The **Project Description** window, shown in Figure 9, is used to name the project, to describe its objective and the performance requirements that each alternative must meet, and, as an option, to archive photographs and drawings supporting the objective and alternatives.
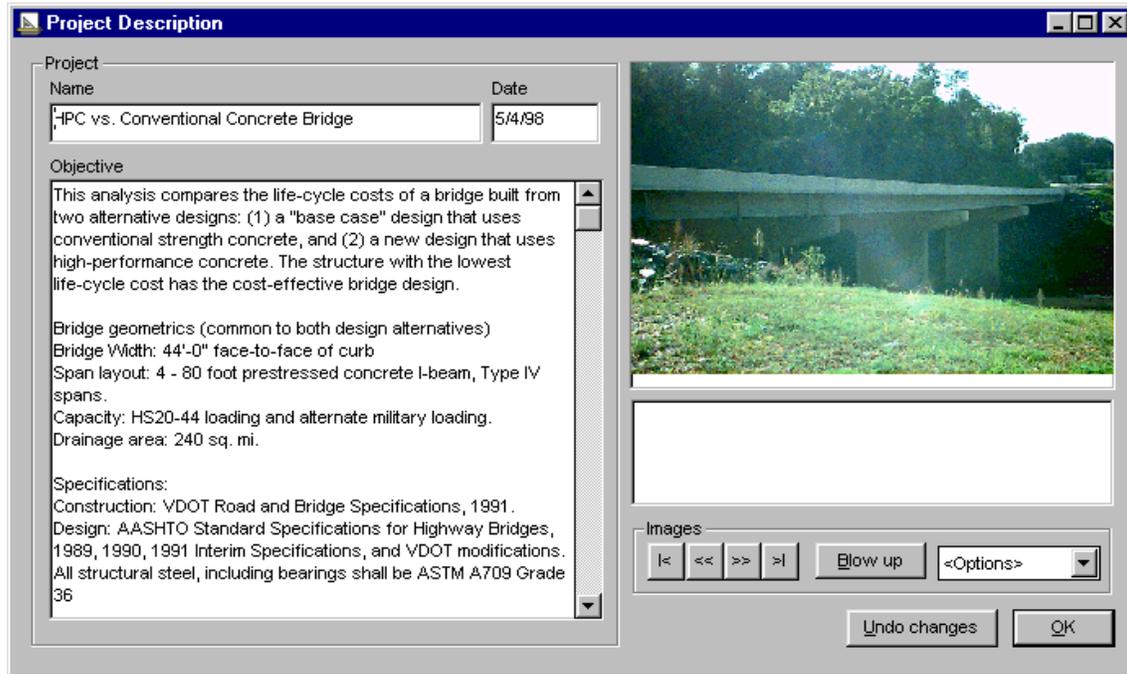
Figure 9. Project Description Window

Be sure to give an accurate description of the performance requirements each alternative must satisfy (e.g., HS-20 loads and a 75-year life). Project photos can be added or deleted, and comments can be given for each photo. BridgeLCC currently only accepts 256-color, Windows™ *.BMP bitmap files. Press the **Blow up** button to put the currently displayed image in its own window, where you can then edit the image, print it, or save it. Choose from the **Options** list box to add images, delete the currently displayed image, get more information about how to add images, and to make the currently displayed image the one that shows in the upper left of the **Cost Summary** window.

The names and descriptions of each project alternative are input in the **Project Alternatives** window (Figure 10).

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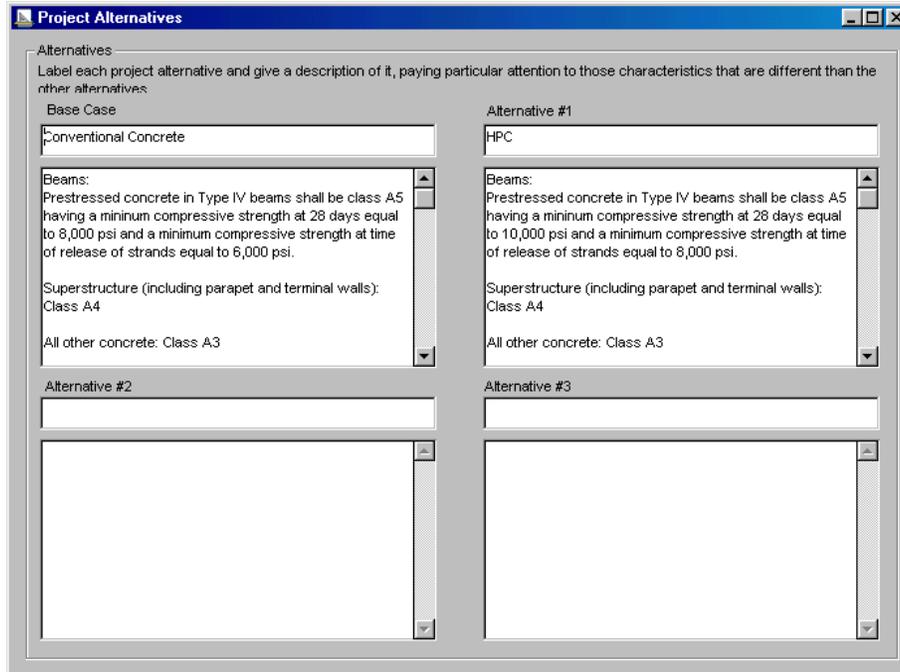
Figure 10. Project Alternatives Window

BridgeLCC can analyze up to four alternatives. Try to keep alternative names concise: the names inputted in the **Project Alternatives** window will appear on the alternatives' buttons on the **Cost Summary** window and on the title bars of the **Edit Cost** windows (this latter window is described in section 2.3.3).

2.3.2 Project Parameters

The project parameters are the variables common to all alternatives; they are divided into groups in the **Project Parameters** window, shown in Figure 11.

Figure 11. Project Parameters Window

Input the number of lanes of traffic and the size of the bridge deck in the **Size of Bridge** group. The information on lanes is used to document the type of structure; the bridge length and width values are used to calculate the life-cycle costs per square foot (square meter) of bridge deck. If you are expressing the bridge dimensions in meters, check mark the **Use metric sizes** box.

Input the base year and study period of the analysis in the **Study Period** group. The base year is the first year of life span and is the year to which all future costs are discounted. The study period is typically the "life cycle" of the structure, or the period over which the structure performs its intended task before being disposed.

Use the **Interest Rates** group to input the average rate of inflation over the study period and to input the real discount rate at which future costs are adjusted to account for the time value of money. *BridgeLCC in its current form requires the user to express all costs in base-year, constant dollars.* If the base year is 1999, then the user inputs what it costs *in 1999* to complete the task. BridgeLCC uses the **Inflation** rate to calculate what tasks performed in the future will cost in the future, and uses the **Real Discount** rate to discount future costs to the present. See the **Life-Cycle Costing Terminology** window (section 4.2) for definitions of the inflation and real discount rates.

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The **Traffic Set** group is the set of parameters used to calculate user costs, or the costs to drivers during bridge construction, repair, and other work. User costs are calculated as the sum of driver delay costs, vehicle operating costs, and increased accident costs. Using the equations in Appendix B, BridgeLCC computes the user cost per day of traffic delays; these daily costs are listed in the lower portion of the screen. BridgeLCC then multiplies the number of days in a user cost item in the **Edit Cost** window by the daily rate to compute the total user cost of that item.

A hypothetical example is useful. Suppose that traffic on the bridge has to be controlled for three days in the base year so that three-rail metal guardrails can be installed. Using the parameters in Figure 11 and the equations in Appendix B, the per-day user costs of this traffic control are $1,568. Multiplied by three days, the total user cost of installing the guardrails is 3 × $1,568 = $4,704.

Instead of inputting their own traffic parameters, the user can load a new set by pressing the **Import** button. This button will open the **Traffic Database** window, shown in Figure 12.

Figure 12. Traffic Database Window

The **Traffic Database** window shows a database of alternative traffic profiles. It allows the user to in effect move the structure to another location (e.g., from an urban highway with high volumes of traffic

to a rural highway with fewer cars). A new traffic set can be created by choosing the **New** button and then inputting user-specified values.

Once the set has been chosen, click the **Import this set** button; this will replace the set of traffic parameters in the **Project Parameters** window with the new set, and return to the **Project Parameters** window.

The set of traffic parameters currently displayed in the **Project Parameters** window can also be added to the traffic database by selecting the **Save this set** button. Make sure you assign a useful name to the new set in the database.

2.3.3 Project Costs

BridgeLCC provides two windows for inputting and editing of alternatives' costs: the **Edit Cost** and **Browse All Costs** windows. Figure 13 shows the **Edit Cost** window.
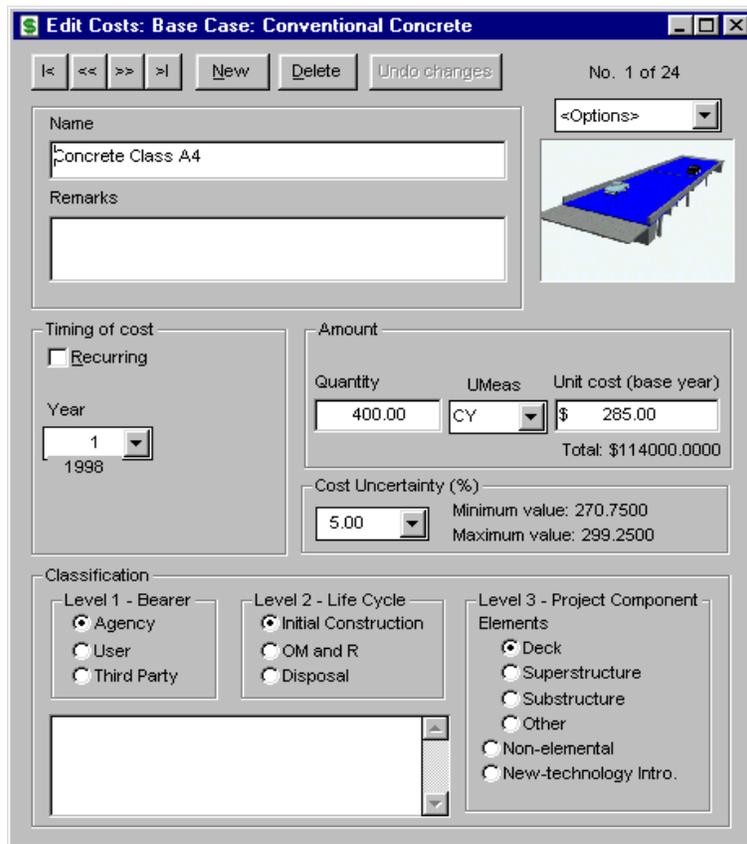
Figure 13. Edit Cost Window

Use this window to create, edit, classify, and delete costs. The information on each cost is divided into sections. The **Name** field is the name that appears on all reports listing individual costs; the **Remarks**

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field should list important supporting data such as the source of the cost (e.g., a previous analysis) or anything that limits use of the cost (e.g., cost does not apply to very large bridges).

The **Timing of cost** group is used to date the cost. If the cost occurs only once, uncheck-mark the **Recurring** box and select the year in the **Year** drop-down list. If the cost occurs more than once—such as every month for one year, or every other year for ten years—then check-mark the **Recurring** box (as shown here on the right), select the **First year** and **Last Year**, and input a frequency in the **Cost occurs every** ____ field, either by selecting a value from the list or inputting a user-defined value.

Following the convention of most engineers' estimates, costs amounts are recorded as the quantity, unit of measure, and unit cost of item. The exception is when inputting a user cost (by selecting the **User** button in the **Level 1 (Bearer)** group; in this case the **Amount** group will look something like that shown here on the right. BridgeLCC allows you to use either the default values of user costs—based on per-day driver delay, vehicle operating, and accident costs calculated using the traffic parameters specified in the **Project Parameters** window—or to input your own user costs. Looking at the figure on the right, check-mark **On bridge** and **Under bridge** boxes depending on where traffic is affected. To specify your own user costs, uncheck-mark the **Default user** box; the quantity, unit of measure, and unit cost fields will then appear as they normally do.

Technical Note	Input all costs in the **Unit Cost** field in *base-year* dollars, that is, what it costs to perform the task in the base year of the study period. Say the base year is 1999. If the agency pays $5 per square foot in 1999 to repair a deck, then $5 is the cost in base-year dollars. If in the Year 2000 it costs $6 per square foot for the same repair, then $6 is the cost in *current-year* dollars. The $6 cost would have to be converted to its value in the base year ($5) before input in the **Unit Cost** field.

If you plan to perform Monte Carlo simulations, use the **Cost Uncertainty (%)** field to assign a probability distribution to the cost item. In the case of all costs other than default user costs, the uncertainty value chosen will create a range of unit cost outcomes; this range is shown on the right of the **Cost Uncertainty (%)** field. In the example shown to the right, the unit cost is $100 and the cost uncertainty is 10%. While BridgeLCC will still use the $100 when calculating the "best guess" life-cycle cost of the alternative and displaying it in the **Cost Summary** window, in Monte Carlo simulations BridgeLCC will randomly select a cost from a range of potential costs. Either uniform or normal (Gaussian) distributions can be selected in the **Monte Carlo Simulations** window. To complete the example of a $100 cost and 10% uncertainty, if the user has chosen to use uniform distributions, BridgeLCC will randomly select a cost between $100*(1- 0.1) = $90 and $100*(1 + 0.1) = $110. To aid the user in understanding the order of magnitude of the currently displayed cost item, the range for a uniform distribution is used is shown in the **Minimum value** and **Maximum value** lines.

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When using default user costs, the uncertainty value is used to create a range of days over which traffic will be delayed. Following the example above, if the best guess of traffic delays is 10 days and uncertainty is 10%, then the range of traffic delays is between 9 and 11 days.

Use the **Classification** group and its **Level 1**, **Level 2**, and **Level 3** subgroups to classify the cost according to (1) who incurs the cost (e.g., **Agency**, **User**, or **Third Party**), (2) in what period of the life cycle the cost occurs (e.g., **Initial Construction**), and (3) in what part of the project the cost occurs (e.g., **Deck**). When the user clicks one of these cost types, the lower left-hand field gives a brief definition of the cost type so that the user is sure the cost is classified correctly.

Scroll through the alternative's costs by pressing the buttons in the upper left-hand corner. Create a new cost by pressing the **New** button; delete the currently displayed cost by pressing the **Delete** button. Use the **<Options>** list box to copy one or more costs to an alternative (including the currently displayed alternative), to delete all costs currently listed in this **Edit Cost** window, and to access the **Edit Cost** window of another alternative.

The user can view a subset of the alternative's costs by going to the **Cost Summary** window and check-marking the desired subset of **Level 1**, **Level 2**, and **Level 3** cost types. For example, to see only the engineer's estimate, check-mark only the **Agency**, **Initial Construction**, and the four **Elemental** check boxes, then return to the alternative's **Edit Cost** window.

The second window for viewing and editing alternatives' costs is the **Browse All Costs** window, shown in Figure 14.

Figure 14. Browse All Costs Window

To view a particular alternative, click the alternative in the upper left-hand **Select alternative** list. To change the types of information shown for each cost, check-mark the appropriate boxes in the **Show** group and then press the **Update view** button. Press the **Set as default** button to save the current set of check-marked boxes as the default set.

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Individual cost data can be edited by double-clicking the item in the spreadsheet view in the lower portion of the window and then typing in new text. Individual costs *cannot* be added or deleted in the **Browse All Costs** window; use the **Cost Edit** window to do this.

To get a printout of the inputted costs, select **File/Print...** from the menu. Figure 15 shows the **Printing** window that will appear.
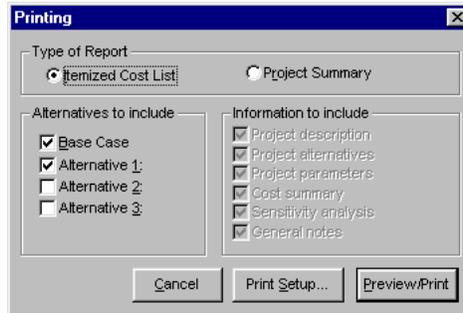
Figure 15. Printing Window

Press the **Itemized Cost List** button, check-mark the desired alternative(s), and press the **Preview/Print** button. BridgeLCC will then display a preview window of the cost list. If the preview looks OK, print the report by selecting **File/Print Report...** from the preview window's menu.

Figure 16. Itemized Report

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2.4 Reviewing Results

Once the costs for each alternative have been inputted and verified to be correct, BridgeLCC can display the life-cycle cost of each alternative in tables, graphs, and printed reports. If when viewing these tables, graphs, or reports you would like to see only a subset of all costs, check-mark the **Level 1**, **Level 2**, and **Level 3** classification types of the costs to be viewed, and then open the table, graph, or report.

2.4.1 Tables

The results of a cost analysis can be viewed in tabular form in the **Cost Summary** window (e.g., Figure 7). The window is accessed by selecting **Analysis/Cost Summary...** from the menu.

2.4.2 Graphs

BridgeLCC can graph the life-cycle costs of each alternative two ways. First, it can graph the life-cycle cost according the three cost levels (cost bearer, life cycle, and project component). To display a graph, select **Graphs** from the menu and then select either **Cost Bearer...**, **Life Cycle...,** or **Project Component...**. All three graphs can be displayed together by selecting **Graphs/All Three LCC Graphs...**, as shown in Figure 17.

Win 3.1	Note: BridgeLCC may cause general protection faults if graphs are created or updated repeatedly. The problem lies in how the Windows™ 3.x heap handles fonts. When a general protection fault may be imminent, a warning screen will display, suggesting that you save your analysis before proceeding.
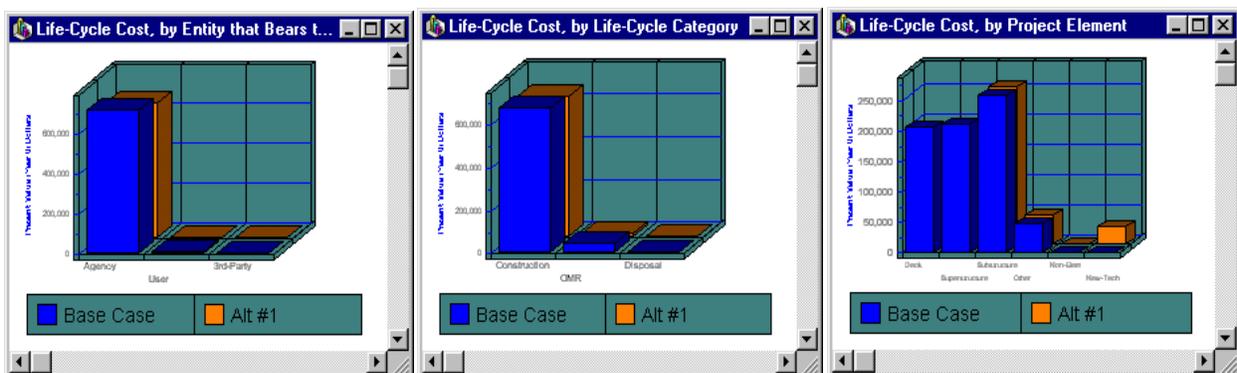
Figure 17. Graphs of Life-Cycle Costs, by Cost Types

BridgeLCC can also show four time lines of costs: annual costs in current-year dollars, annual costs in base-year dollars, cumulative costs in current-year dollars, and cumulative costs in base-year dollars. Figure 18 shows an example time line; it was created by selecting **Graphs/Annual Costs in Present-Value Dollars...** from the menu.
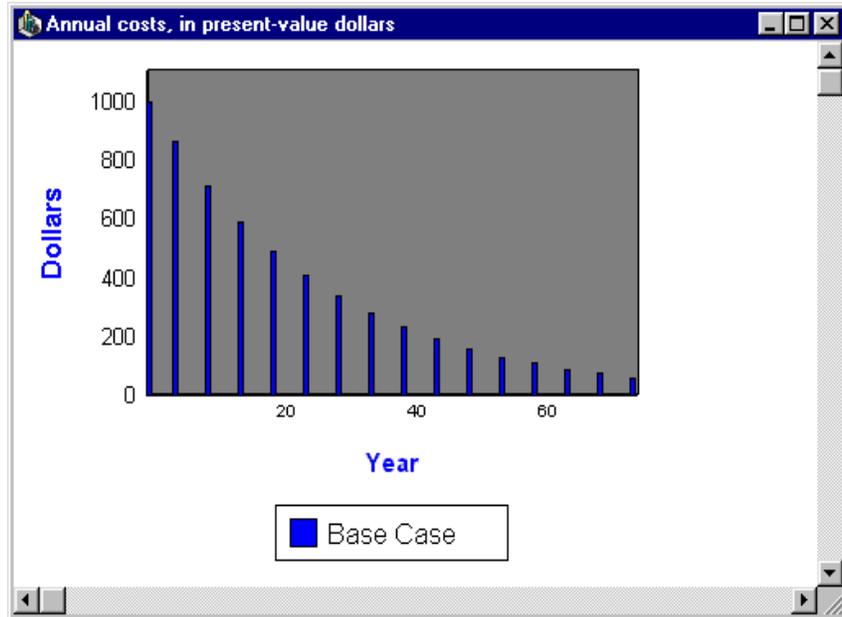
Figure 18. Annual Costs Window

The cumulative-costs graphs allow the user to see a "cumulative cash flow" for each alternative. Figure 19 shows an example graph, created by selecting **Graphs/Time Line of Cumulative Costs...** from the menu. All graphs can be printed by selecting either **File/Print Current Graph...** or **Graphs/Print Current Graph...** from the menu.
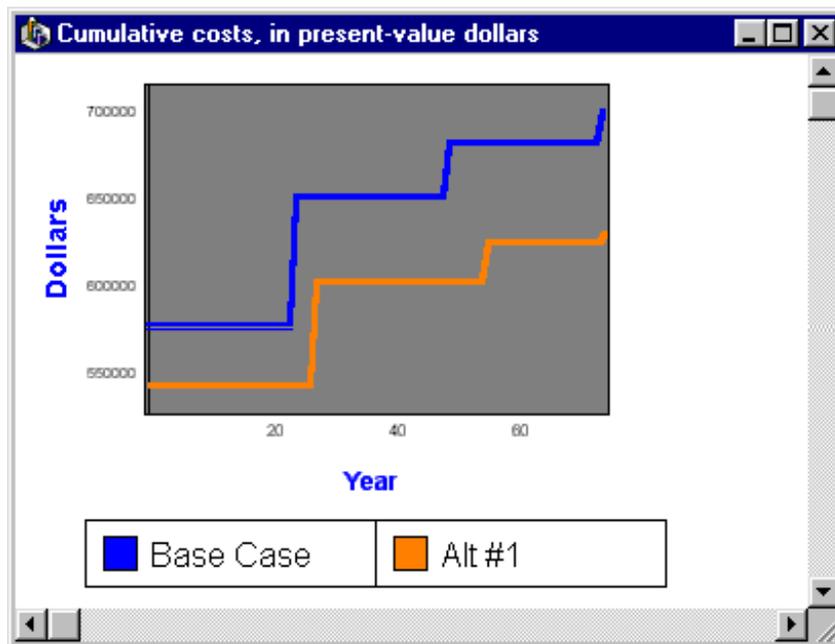
Figure 19. Cumulative Costs Window

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2.4.3 Reports

BridgeLCC prints two reports. The first report is a summary of all data used in the analysis and the summary figures for life-cycle costs shown in the **Cost Summary** window. The second report is an itemized list of each alternative's costs; this report is useful for verifying individual cost items. To print either report, select **File/Print...** from the menu (Figure 20 shows the **Printing** window), select the report to print from the **Type of Report** group, check-mark the alternatives to print, and then press the **Preview/Print** button.
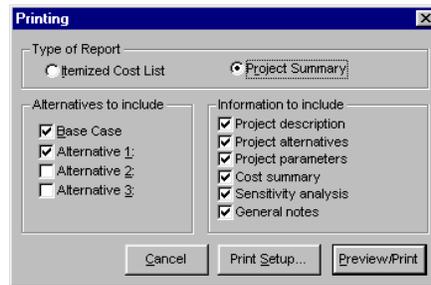
Figure 20. Printing Window

BridgeLCC will then display the **CA-RET Print Preview** window, shown in Figure 21 ("CA-RET" is the name of the printing program). If the preview of the report looks OK, then select **File/Print Report** from the preview window's menu.

Figure 21. CA-RET Print Preview Window

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3.0 Options

Chapter 2 describes the minimum BridgeLCC functions required to open an analysis, input costs, and display the results. This chapter and Chapter 4 describe additional BridgeLCC components that make life-cycle cost analyses more complete.

3.1 Preferences Window

The **Preferences** window allows the user to change options both for the current analysis and for all BridgeLCC analyses. The window, shown in Figure 22, is accessed by selecting **File/Edit Preferences** from the menu.
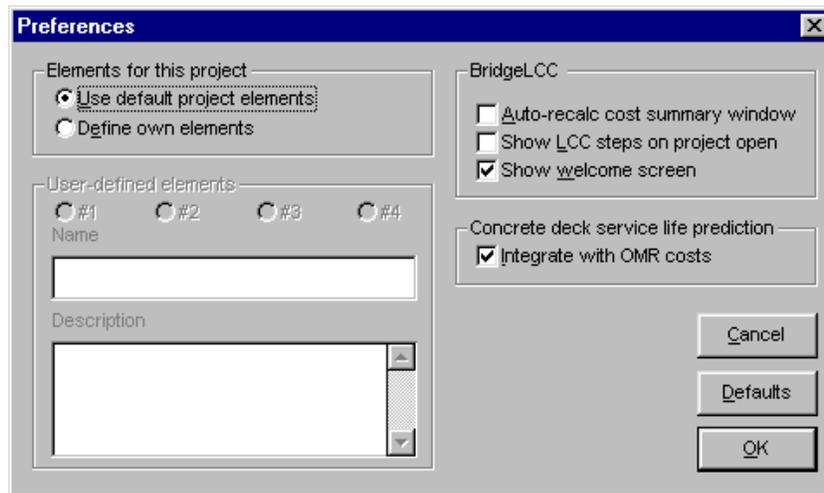
Figure 22. Preferences Window

Use the **Elements for this project** group box to select either default bridge elements (deck, superstructure, substructure, and other) or to define up to four elements. To define your own elements, select each radio button (e.g., **#1**) and input the element name and a brief description. The names chosen will appear in the **Cost Summary** and **Edit Cost** windows. The descriptions will appear in the lower-left corner of the **Edit Cost** window.

The **BridgeLCC** group contains settings that apply to all BridgeLCC analyses. When the **Auto-recalc cost summary window** box is check-marked, the **Cost Summary** window will recompute the life-cycle costs each time it is accessed and when the user check-marks/uncheck-marks one of the window's cost types (e.g., **Agency)**. When the **Show LCC Steps on project open** box is checked, the **LCC Steps** window will display every time an analysis is opened. When the **Show welcome screen** box is checked, the **Welcome** window will display when BridgeLCC is started.

Finally, the **Concrete Service Life Prediction Tool** can be integrated with the **Edit Cost** window by check-marking the **Integrate with OMR costs** check box. As shown in the figure on the right, when this box is marked, a **Service life...** button will appear in the **Timing** section of the **Edit Cost** window. When pressed, the button will take you to the **Concrete Service Life Prediction Tool** window where you can select a concrete mix. Once a mix has been selected and a predicted service life appears in the concrete window, press the **Use** button; the service-life years will then be used back in the **Edit Cost** window as the first year and frequency of the cost item.

3.2 Sensitivity Analysis

New-technology construction materials, such as high-performance concrete or FRP composites, bring new cost uncertainties to a bridge project. Because the materials have not been used often, few know their true costs with certainty. This uncertainty can apply to unit costs, quantities used in construction or repair of the structure, and the time required to perform project activities (which affects costs to drivers on the highway). BridgeLCC allows the user to first outline and then the analyze the sensitivity of the results to changes in the underlying parameters.

3.2.1 Sensitivity Analysis Window

BridgeLCC first assists the user in setting up a framework for uncertainty analysis. The **Sensitivity Analysis** window, shown in Figure 23, allows the user to document up to three different analyses of the affect on life-cycle cost of changes in the underlying parameters.
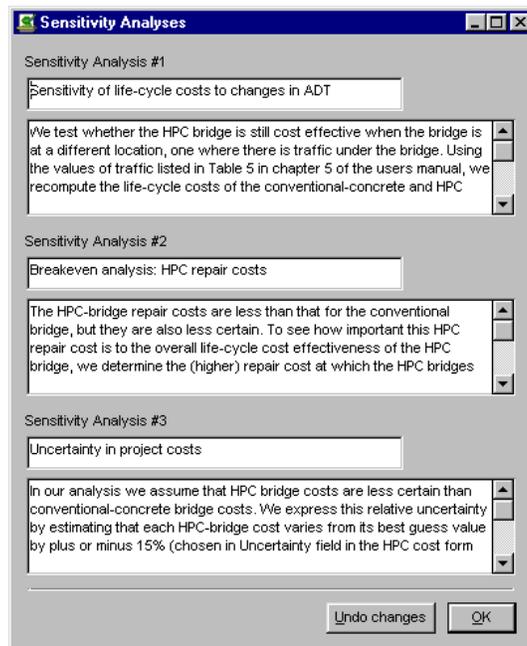
Figure 23. Sensitivity Analysis Window

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Two separate analyses are listed in the window in Figure 23. The **Sensitivity Analysis #1** section lists an analysis entitled "Discount Rate" and describes how the discount rate was changed and what effect that change had on the life-cycle cost of each alternative. The **Sensitivity Analysis #2** section lists an analysis entitled "Cost Uncertainty" and describes how allowing individual costs to vary in a probabilistic sense affects the life-cycle cost effectiveness of each alternative.

3.2.2 Monte Carlo Simulations

The dollar amounts inputted in the **Edit Cost** window are the considered to be the engineer's "best guess"of the true cost of the particular item. But these amounts may vary, affecting not only the cost of the individual item but also the life-cycle cost effectiveness of the bridge. Monte Carlo simulations allow the engineer to assign uncertainty to individual costs and then generate artificial data on life-cycle cost outcomes. The variability of these outcomes indicates the likelihood that one of the alternative bridges will be life-cycle cost effective in a probabilistic sense.
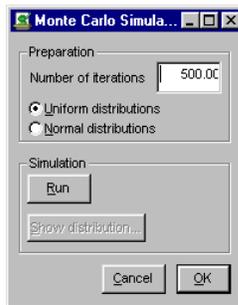
Figure 24. Monte Carlo Simulations Window

Using the **Monte Carlo Simulations** window (shown in Figure 24) BridgeLCC can perform simulations of possible life-cycle cost outcomes based on the uncertainty of individual costs. BridgeLCC models cost uncertainty two ways, depending on whether the engineer assumes that the costs have a uniform or a normal (Gaussian) distribution.

When a uniform distribution is assumed (by selecting **Uniform distributions** in the **Monte Carlo Simulations** window), each unit cost is modeled as a uniform cost distribution whose average value equals the "best-guess" value in the **Unit cost** field of the **Edit Cost** window and whose range is plus or minus X% of that value, where X is the value entered in the **Cost Uncertainty (%)** list box.

For example, if the **Unit cost** figure is $100 per square meter and the cost uncertainty is ±10%, the Monte Carlo simulation models the cost as having a probability distribution whose expected value is $100, lower bound is $100(1 - 0.10) = $90, and upper bound is $100(1 + 0.10) = $110, and as having an equal probability of achieving any unit cost in the range.

When a normal, or Gaussian, distribution is assumed (by selecting **Normal distribution** in the **Monte Carlo Simulations** window), each unit cost is modeled as a normal cost distribution whose average

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value equals the "best-guess" value in the **Unit cost** field of the **Edit Cost** window and the range of four standard deviations (two in each direction) is plus or minus X% of that value, where X is the value entered in the **Cost Uncertainty (%)** list box. Figure 25 summarizes these assumptions for the uniform and normal distributions when used in the $100 example above.
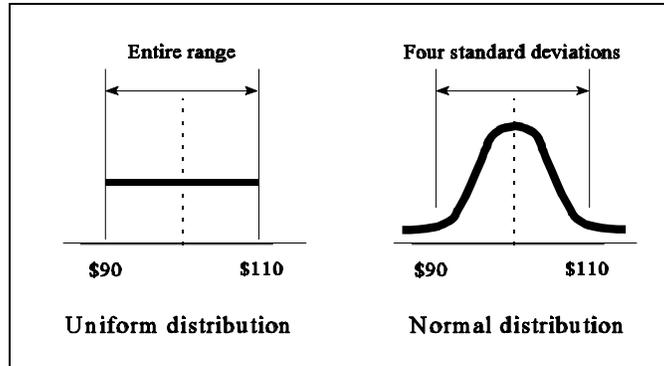
Figure 25. Assumptions about Uniform and Normal Distributions

Hint	Note: The **Cost Uncertainty (%)** list box can also be used to model uncertainty in cost *quantities* (the **Quantity** box in the **Edit Cost** window). Since cost = quantity × unit cost, uncertain unit cost has the same effect on cost as uncertain quantity. Said another way, the level of uncertainty chosen can be thought of as applying to either unit cost or quantity. However, BridgeLCC cannot model both quantity and cost uncertainties in the same cost item.

Once the uncertainties have been input, select the number of samples to use and then run the Monte Carlo simulations by pressing the **Run** button. Once the simulation is finished, press the **Display results** button to display a graph similar to Figure 26 (the graph will not have the arrows).
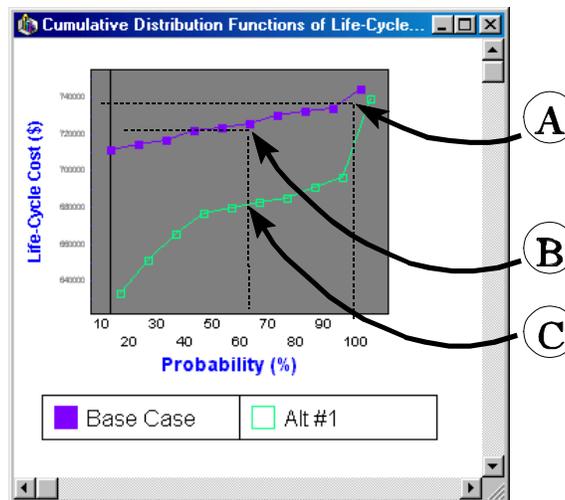
Figure 26. Cumulative Distribution Functions of Life-Cycle Cost

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Figure 26 shows the cumulative distribution of two competing alternative bridges (called "Base case" and "Alt #1"). Each line with square dots represents the distribution of possible life-cycle costs for the alternative and their cumulative probability of occurring. For example, point A indicates that there is a 100-percent probability that the life-cycle cost of the base case will be less than or equal to $740,000. Similarly, point B says that there is a 60% probability that the base case life-cycle cost will be less than or equal to $730,000. This is equivalent to saying that six times out of ten the base case life-cycle cost will be less than or equal to $730,000. Compare this with point C, where 60 percent of the time the Alt #1 life-cycle cost will be less than or equal to $680,000. Comparing the costs of the two alternatives over all probabilities, the graph shows that for 10% of the time (1 time out of 10), 20% of the time (2 times out of 10), and so on, the expected Alt #1 life-cycle cost will be less than the expected Base Case life-cycle cost.

By comparing the cumulative distributions of the alternatives, you can determine whether one of the alternatives is cost effective over the range of possible life-cycle cost outcomes. Chapter 5 gives a more complete description of how to interpret the Monte Carlo results.

3.3 Concrete Deck Service Life Prediction Tool

Part of calculating life-cycle costs is estimating the service life of one or more bridge components. BridgeLCC includes a concrete service life prediction tool developed by the Building and Fire Research Laboratory at NIST.[4] The tool allows the user to calculate and compare the estimated service life of different concrete designs. Figure 27 shows the **Concrete Deck Service Life Prediction** window, accessed by selecting **Tools/Concrete Service Life Prediction Tool...** from the menu.
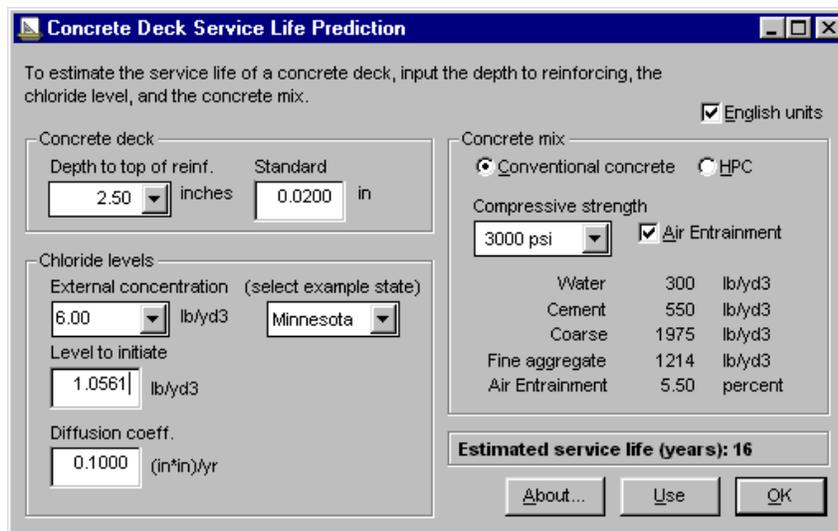
Figure 27. Concrete Deck Service Life Prediction Window

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[4] For a complete description of this service life prediction tool and the research upon which it is based, see Dale P. Bentz, James R. Clifton, and Kenneth A Snyder, "Predicting Service Life of Chloride-Exposed Steel-Reinforced Concrete," *Concrete International*, December 1996.

The service life of a concrete bridge deck is estimated in three steps. First, in the **Concrete Deck** section, input the depth to reinforcing and standard deviation of that depth (BridgeLCC will estimate a default standard deviation given a depth). In the **Chloride Levels** section, select a level of **External concentration** by either inputting a value directly or by selecting an example state to the right. If desired, change the value for **Level to initiate corrosion**. Finally, select a concrete mix in the **Concrete Mix** section. The service life prediction tool will then estimate the number of years before external chlorides will reach the reinforcing and initiate corrosion.

The service life tool can be integrated directly into the estimation of concrete deck repair costs. When the **Integrate with OMR Costs** box in the **Preferences** window is check-marked, and the **OM and R** button is pressed in the **Edit Cost** window, a **Service life...** button will be visible in the **Timing of costs** section of the **Edit Cost** window. This box and button are shown in Figure 28.

When the **Integrate with OMR costs** is check-marked...

... the **Service life** button will be visible when the **OM and R** button is pressed.
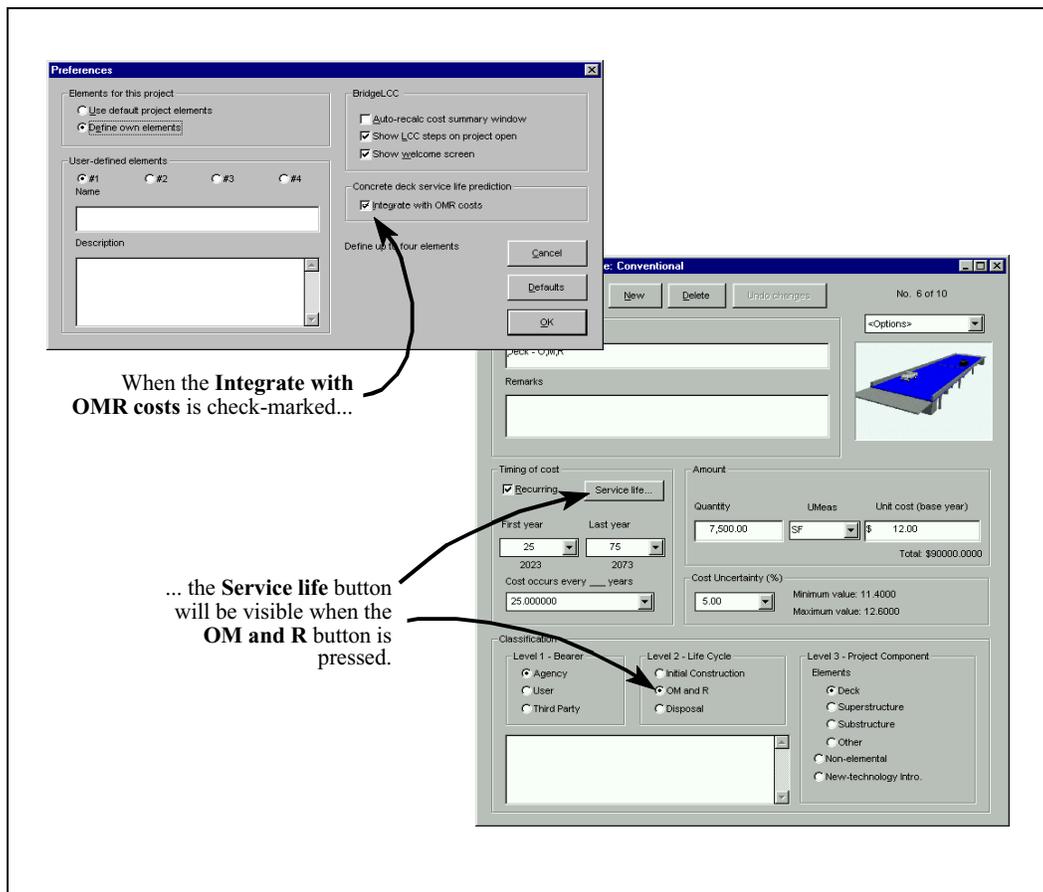
Figure 28. Integrating the Service Life Tool with the Estimation of OMR Costs

3.4 General Notes Window

The **General Notes** window, shown in Figure 29, allows the user to log notes about the analysis and the results. These notes are particularly useful when the analysis is about new-technology materials and techniques and will be read by other, potential users of these technologies. Use the upper, **Notes about the analysis** section to make an outline of the analysis you will perform and the lower, **Notes about the results** section to report the results.
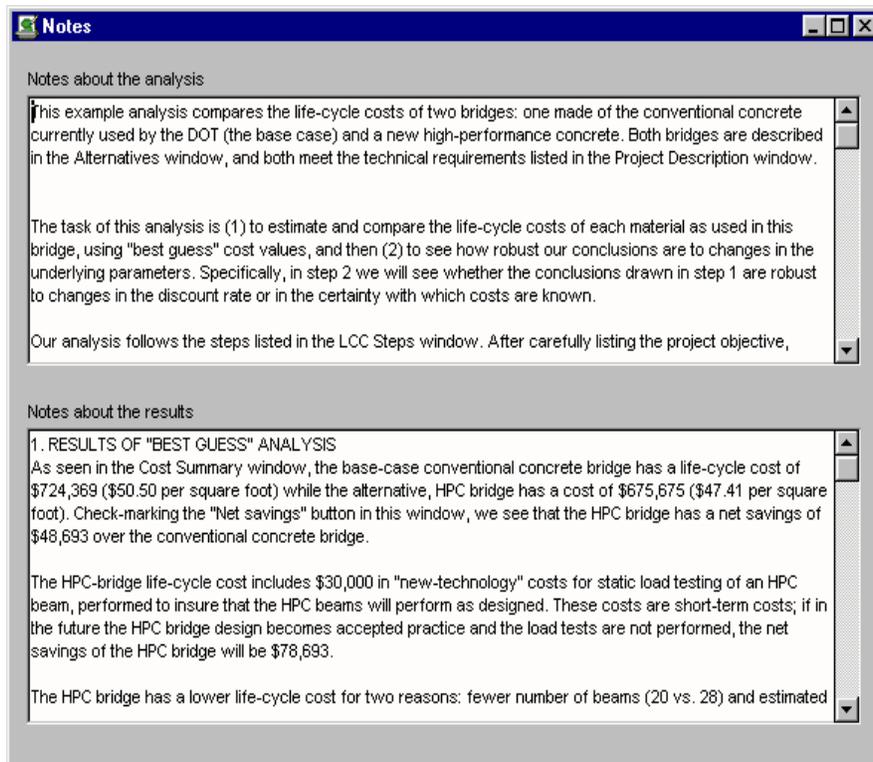
Figure 29. General Notes Window

3.5 Importing and Exporting Data

The **Import/Export Data** window (Figure 30) is provided so that the user can exchange data with spreadsheet programs such as Microsoft® Excel™, Corel® Quattro Pro™, and Lotus® 123™, as well as any program that can edit plain ASCII text. Engineers' estimates currently in spreadsheet form can be readily imported into BridgeLCC, and data created by BridgeLCC can be exported to spreadsheet programs to create graphs and to word processing programs to create tables. Use the **Import Data** section of the window to add new cost records to your analysis; use the **Export Data** section to export cost records and results of the project analysis.

BridgeLCC can only import cost data that is in the "ASCII, tab-delimited" format. In this format, each cost record is a single line, and the fields in this record are separated by tab characters (an example file, EXAMPLE.TXT, can be found in your BridgeLCC directory). The cost data you import must be in the same order as the fields that display in the spreadsheet-like form in the lower half of the window. Excel™, Quattro Pro™, and Lotus 123™ can save data in this tab-delimited format.

Hint	To make sure that the data you want to import has the correct field structure, use EXAMPLE.TXT (found in your BridgeLCC directory) to create your tab-delimited file. Open the file in your spreadsheet program and view the structure. Use this newly-created file to create cost records for input to BridgeLCC.

To import data, select the alternative to which you want to add records, press **Open**, and select a file from the open window. The records in the file should then display in the **Preview** section. If the structure of data looks correct (ignore the **FILTERSTR** and **STAMP** fields), press **Import**. Then access the alternative's **Edit Cost** window or the **Browse All Costs** window to see if the costs are correctly placed.
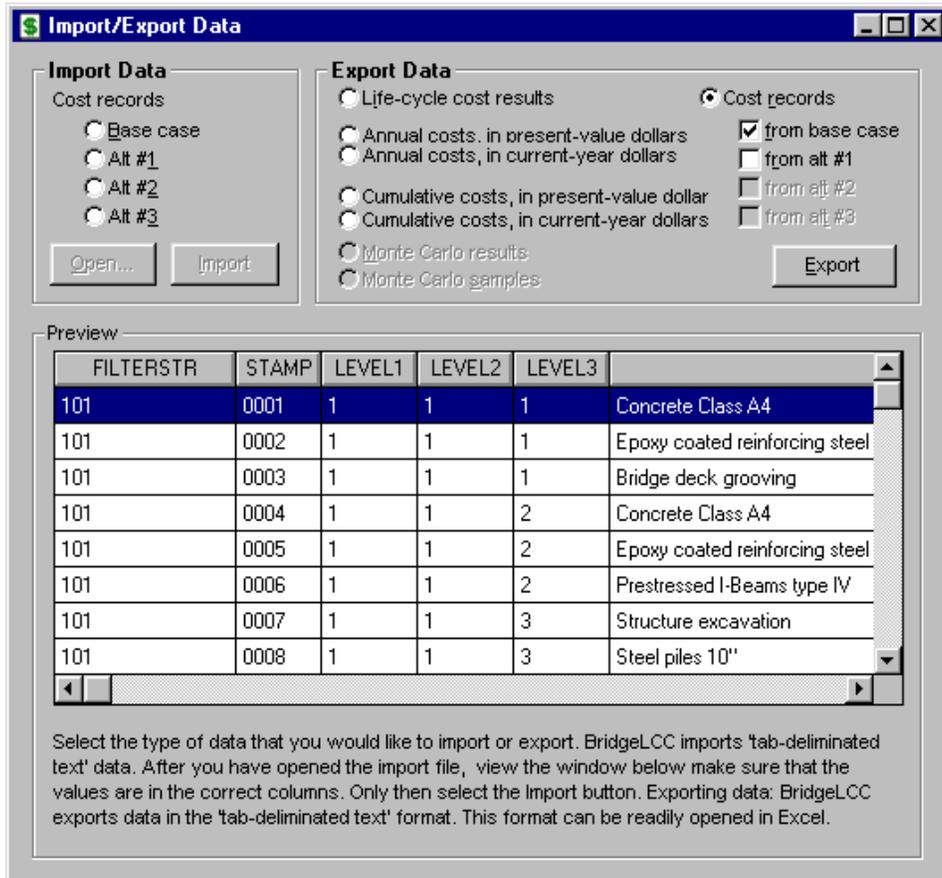
Figure 30. Import/Export Data Window

4.0 Help

To aid in the use of BridgeLCC and life-cycle costing in general, BridgeLCC provides a single **Help Topics** window containing three sections: (1) **BridgeLCC Windows**, (2) **Life-Cycle Costing Terminology,** and (3) **Cost Classification Scheme**. Each of these sections are accessed by selecting the associated button at the top of the window.

4.1 BridgeLCC Windows

The **BridgeLCC Windows** section is shown in Figure 31. First select a particular window on the left, and then select an item in the center panel. The right-hand panel will then give a description of the item and how to use it.
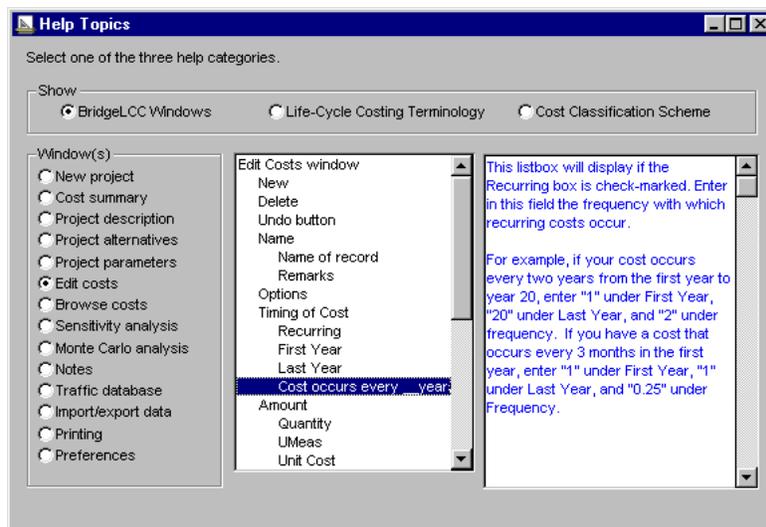
Figure 31. Help: BridgeLCC Windows

4.2 Life-Cycle Costing Terminology

The **Life-Cycle Costing Terminology** section, shown in Figure 32, provides definitions of the economic concepts most commonly used in building economics. The terms and their definitions are based in part on ASTM E 833, Building Economics Terminology.
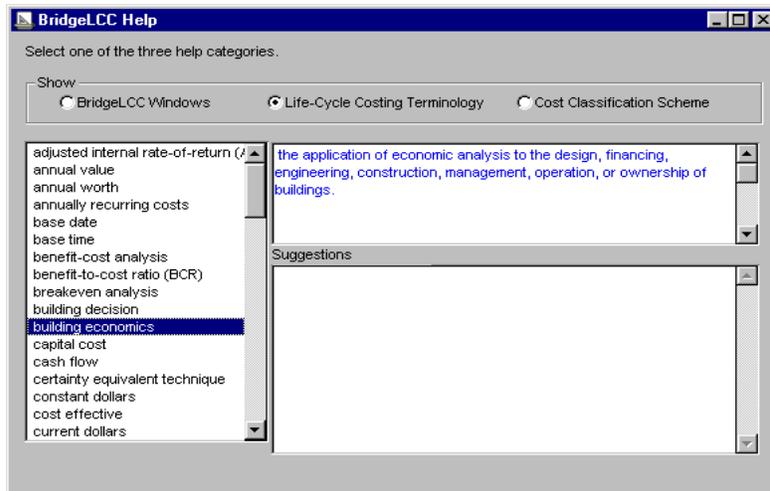
Figure 32. Help: Life-Cycle Costing Terminology Window

Select a term on the left to see its definition and a discussion of how it pertains to BridgeLCC and life-cycle cost analysis.

4.3 Cost Classification Scheme

BridgeLCC classifies each individual cost so that useful comparisons can be made between the alternative construction materials. The classification covers all potential costs to a project including costs to third parties not using the bridge but affected by bridge work, and costs associated with using a material for the first time. The **Cost Classification Scheme** section of the **Help** window is shown in Figure 33.
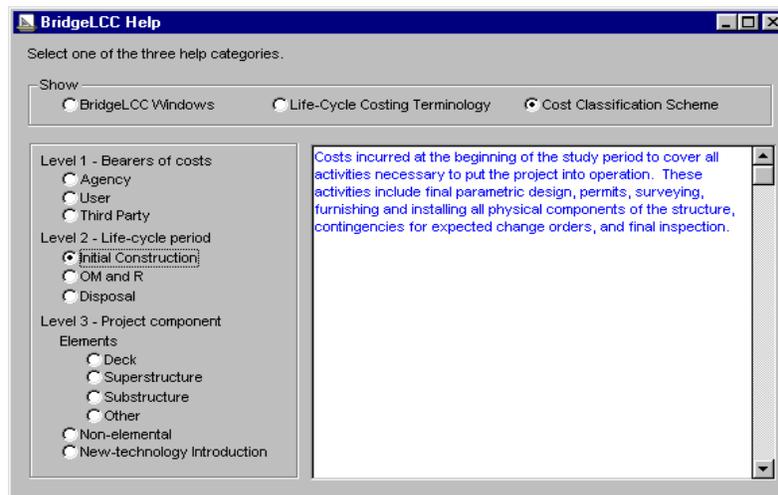
Figure 33. Help: Cost Classification Scheme

Press a cost's button to see its definition.

5.0 A Sample Analysis

This chapter provides an example life-cycle analysis to more completely illustrate how BridgeLCC is used to assess competing, alternative construction materials. The level of detail shown is meant to be typical. More or less detail can be used depending on the needs of the engineer and availability of data. This analysis can be found in the file CASE-1.LCC, located in your BridgeLCC directory.

In this example, an engineer is making a preliminary design of a highway bridge and is considering two alternative types of concrete. The "base case" concrete is the conventional mix currently used by the engineer. The alternative concrete mix is a high-performance concrete that the engineer has not used before, but which should produce stronger and more durable bridge members. The engineer wants to determine which of the two materials is life-cycle cost effective for this bridge.

The engineer follows the nine BridgeLCC steps, which are based on ASTM practice E 917 for measuring the life-cycle costs of buildings and building systems (see Appendix A for a description of the method). The **LCC Steps** window, shown in Figure 34, lists the nine explicit steps.
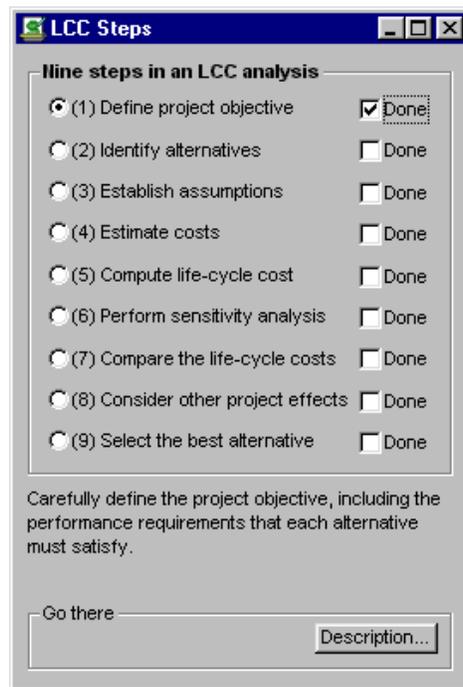
Figure 34. LCC Steps Window

This chapter is divided into three sections, each covering a logical division of this group of steps. Section 5.1 describes the project objective on which the life-cycle cost analysis is based, including the bridge performance requirements and the material alternatives that meet those requirements. Section 5.2 describes the project parameters which are independent of each alternative, such as the daily traffic volume on the bridge, the number of years the bridge is required to last, and the interest rate at which future costs are discounted to the present.

Next, the "best-guess" costs for the conventional concrete and the high-performance concrete are estimated, starting first with the costs incurred by the agency (the DOT). Following ASTM E 917, these costs are divided into initial construction costs; operation, maintenance, and repair (OM&R) costs; and disposal costs. Each of these three are further divided into groups based on the component of the structure to which the cost is tied. For example, the agency initial construction costs (i.e., the engineer's estimate) are divided into deck, superstructure, substructure, "other," non-elemental, and new-technology introduction costs.

Section 5.3 shows how to interpret the computed "best guess" life-cycle costs of each bridge design alternative. The life-cycle costs of each are compared using graphs which display breakdowns according to BridgeLCC's cost classification scheme. The engineer then revisits each alternative's "best guess" costs and determines to what extent uncertainty in these costs affects the overall life-cycle costs of each alternative bridge. The chapter ends with a summary of the sample analysis.

The following sections are written from the perspective of an engineer who is making a preliminary design of a bridge and, as part of that process, comparing the life-cycle costs of two competing, alternative materials: conventional-strength concrete and high-performance concrete.

5.1 Description of Project

Step 1:
Define the project objective and minimum performance requirements.

The project objective is to build maintain, and eventually dispose of a new highway bridge in a rural Virginia county. The engineer first makes a general description of the size of the bridge and the environment in which it will exist. The structure is shown in Figure 30. It is 100 meters (322 ft) long, 14.5 meters (47 feet) wide, and will carry two lanes of traffic over a stream. The bridge is part of a rural highway which has relatively low volumes of traffic. Winter precipitation and temperatures are mild, with only 5-10 days on average that require snow plowing and salting of roads.

Figure 35. Plan and Elevation Views of Bridge

The engineer next lists the minimum performance requirements of the structure. Both the conventional-concrete bridge and HPC bridge must satisfy these performance-based requirements.[5]

- The structure must be able to carry the loads prescribed in AASHTO's HS-20 specification.
- The spans between piers must not deflect more that *L/800* meters, where *L* is the distance between the piers.
- The bridge must last at least 75 years.

<table>
<tr><td>

Step 2:
Identify the alternatives for achieving the objective.

</td><td>

Table 1 lists the technical characteristics of the two alternative concretes that meet the above performance-based requirements. Sufficient detail is listed so that the differences in computed life-cycle costs can be understood in terms of these technical differences. For example, if it turns out that one bridge deck's repair bill is 50% less than the other, the engineer can ascertain that it is because the concrete is twice as durable.

</td></tr>
</table>

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[5] These requirements are intended to be representative of the types of requirements engineers must meet when designing bridges; states may have more or significantly different requirements.

Table 1. Technical Characteristics of the Base Case and Alternative Bridge Designs

Description	Base Case: Conventional Strength Concrete Normal Permeability Mix	Alternative #1: High-Strength Concrete New AASHTO Low Permeability Mix
Beams		
Type	Type III	Type IV
Concrete Class	A5	A5
Compressive cylinder strength (28 days)	6000 psi	8000 psi
Compressive Strength at time of release	4800 psi	6000 psi
Beams per span	7	5
Deck		
Concrete class	A3	A3 w/ low-permeability mix design
Piers		
Concrete class	A3	A3

To estimate costs, the engineer needs to itemize how the bridge will be built, maintained and repaired, and disposed of. The base-case, conventional-concrete bridge is built by first driving piles into the stream bed, pouring footings around the piles, forming and pouring the piers and bents, installing precast-prestressed beams, and then pouring the deck and approaches in place. Every 25 years the deck will be repaired for environmental corrosion and mechanical wearing; after 75 years the bridge will be demolished.

The alternative, HPC bridge uses high-strength concrete in the deck and beams. In addition, the deck uses a new AASHTO mix design which reduces the permeability of the concrete, thereby reducing the intrusion of road salt chlorides and ultimate corrosion of the reinforcing steel.[6] The high-performance concrete bridge is built, maintained, and disposed of the same way as the base case bridge but with two important exceptions. First, because of its higher-strength concrete beams, the alternative bridge has five beams between piers instead of seven. Second, because of the AASHTO low-permeability specification, the deck requires repair every 40 years instead of every 25.

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[6] For a description of this concrete specification, see Celik Ozyildirim, "Permeability Specification for High-Performance Concrete Decks," pending publication in *TRB Records*.

5.2 Data

5.2.1 Project Parameters

<table>
<tr><td>

Step 3:
Establish the basic assumptions for the analysis.

</td><td>

The project parameters quantify the conditions the bridge will experience regardless of the concrete used. The engineer starts by itemizing the factors that will affect the bridge over its life cycle. Three common factors are

</td></tr>
</table>

- traffic conditions,
- weather conditions, and
- economic conditions.

Traffic conditions, such as average daily traffic (ADT) and accident rates, determine the costs that bridge construction, repair, and disposal place on drivers who travel over the bridge (there is a stream under the bridge). Weather conditions determine how much road salt is placed on the road. Economic conditions, specifically the inflation rate and discount rate used by the life-cycle costing formulas, determine the relative importance of costs which occur later in the life of the structure.

Table 2 lists the traffic data the engineer compiled for the Virginia bridge. Departments of transportation often have records of the traffic levels a bridge is expected to experience in the future.

Table 2. Project Parameters

Project: VA bridge		Parameter Set:		Date:
Remarks:				
Item	**Traffic Over Bridge**		**Traffic Under Bridge**	
	Year 1	**Last Year**	**Year 1**	**Last Year**
Length of affected roadway (miles)	1.0	1.0	0	0
Average daily traffic (ADT) (#)	5,000	10,000	0	0
Normal driving speed (mph)	55	55	1.0	1.0
Roadwork driving speed (mph)	25	25	1.0	1.0
Normal accident rate (per mil veh miles)	1.9	1.9	1.9	1.9
Roadwork accident rate (per mil veh miles)	2.2	2.2	2.2	2.2
Hourly driver cost ($)	$5.00	$5.00	$5.00	$5.00
Hourly vehicle operating cost ($)	$8.00	$8.00	$8.00	$8.00
Cost per accident ($)	$100,000	$100,000	$100,000	$100,000

The "Length of affected roadway" is the length of road over which traffic is slowed or diverted. "Average daily traffic (ADT)" is the number of cars that drive over the bridge every day; the engineer estimates that this traffic volume will increase from 5,000 to 10,000 over the 75-year life of the bridge. "Normal driving speed" is the traffic speed when there is no bridge work that will affect traffic flow, while "Roadwork traffic speed" is the speed of traffic when it is diverted around roadwork.

The "Normal accident rate" and "Roadwork accident rate" are estimates of how often accidents occur outside of and during bridge work (the rates are in accidents per million vehicle-miles, where vehicle-miles the product of the number of vehicles and the average miles each car drives). The "Cost per accident" is the average total cost of an accident. "Hourly driver cost" is the value of drivers' time, and "Vehicle operating cost" is the value of commercial vehicles' time. If the engineer does not have one or more of the required values in-house, national values or values from other states can be used.

For the base case bridge, an engineer will likely know how often and how much the bridge will need repair in order to last 75 years (unless the engineer typically designs a bridge to last 40 years; in this case an explicit 75-year schedule may not be available). However, the engineer may not know how long the high-performance concrete bridge deck will last before repair is required. The level of road salt applied is the key parameter for determining how long the bridge deck will last. Table 3 lists some example values of road salt levels for different states.

Table 3. Salt Exposure in Various States

Salt Level	Level in kg/m^3	States using this level
Low	5.06	KS, CA
Medium	10.11	MN, FL
High	15.17	DE, IA
Severe	20.90	WI, NY

The engineer can use the **Concrete Service Life Prediction Tool** window to estimate and compare the service lives of the two alternatives and to generate repair schedules for them. The engineer can later change the repair schedules to see how sensitive the life-cycle cost of each alternative is to repair costs. If the costs are not sensitive to changes, then the engineer can conclude that the life-cycle costs are robust to changes in the repair schedules.

The last design-independent project parameters are the inflation rate and real discount rate. The inflation rate is the average rate at which prices will increase over a given year. The real discount rate is the rate at which future costs are discounted to base-year dollars. Federal infrastructure projects use a discount rate published in OMB Circular No. A-94.[7] Table 4, reprinted from the circular, shows what the real discount rate is for different time horizons.

Table 4. Real Discount Rate for Various Time Periods

Number of years	Discount Rate (%)
3 years	3.4%
5 years	3.5%
7 years	3.5%
10 years	3.6%
30 years	3.8%

Since the bridge has costs that occur as much as 75 years in the future, we use the maximum number of years in the table, 30, and the corresponding rate, 3.8%. Private-sector projects may use a different discount rate. The engineer inputs the traffic and economic parameters in the BridgeLCC **Project Parameters** window. When complete, the window will look something like Figure 36.

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[7] OMB Circular No. A-94, Appendix C, Revised January 1998.

Figure 36. Project Parameters Window

5.2.2 Project-Alternative Cost Data

Step 4: Identify, estimate, and determine the	The second type of data required by BridgeLCC is the set of costs for each bridge alternative. The engineer uses the **Cost Summary**, **Edit Cost**, and **Browse All Costs** windows and the cost classification scheme to systematically input the constituent costs. In this example the engineer first inputs the base-case costs and then the alternative costs. For each bridge, the engineer starts with the agency costs, and then inputs the user costs and third-party costs.

Base Case Material: Conventional-Strength Concrete

Agency Costs

The engineer organizes costs into initial construction costs; operation, maintenance, and repair (OM&R) costs; and disposal costs. Initial construction costs are a good place to start since many departments of transportation (DOTs) make an engineer's estimate of a bridge's construction cost before its drawings are sent out to bid. The engineer in this example uses the quantities of materials needed for the bridge and unit costs in a engineer's estimate from a previous structure to compile the initial construction costs. These costs are then input into BridgeLCC using the **Edit Cost** window.

| Project: **Route 40 in Virginia** | | | | Date: **May 12, 1998** | | | pg# 1 | of | 3 pgs |

Remarks: **Agency costs for the base case, conventional strength bridge. The HPC bridge will use the same costs, but reduce the number of beams and add new-material introduction costs.**

Name	Remarks	Cost Categories			Cost Quantities						
		Cost Bearer	Life-Cycle	Proj Comp	Qty	UMeas	Unit Cost	Range (±%)	Start Year	End Year	Freq
INITIAL CONSTRUCTION COSTS											
DECK											
Concrete Class A4	for the deck	agency	ic	deck	400	cy	$285.00	0	1	1	1
Epoxy coated reinforcing steel	for the deck	agency	ic	deck	77,000	lbs	$0.55	0	1	1	1
Bridge deck grooving		agency	ic	deck	1,564	SY	$3.10	0	1	1	1
SUPERSTRUCTURE											
Concrete Class A4	for diaphrams	agency	ic	super	45	cy	$285.00	0	1	1	1
Epoxy coated reinforcing steel	for diaphrams	agency	ic	super	6,000	#	$0.55	0	1	1	1
Prestressed I-Beam Type IV (80 ft.)		agency	ic	super	28	ea	$7,000.00	0	1	1	1
SUBSTRUCTURE											
Structure excavation		agency	ic	sub	702	cy	$28.50	0	1	1	1
Steel piles 10"		agency	ic	sub	1,190	lf	$17.60	0	1	1	1
Pile point for 10" steel pile		agency	ic	sub	40	ea	$63.03	0	1	1	1
Concrete Class A3		agency	ic	sub	716	cy	$219.90	0	1	1	1
Reinforcing steel		agency	ic	sub	50,570	#	$0.45	0	1	1	1
Epoxy coated reinf. steel		agency	ic	sub	25,230	#	$0.57	0	1	1	1

Remarks: **Agency costs for the base case, conventional strength bridge. The HPC bridge will use the same costs, but reduce the number of beams and add new-material introduction costs.**

Name	Remarks	Cost Categories			Cost Quantities						
		Cost Bearer	Life-Cycle	Proj Comp	Qty	UMeas	Unit Cost	Range (±%)	Start Year	End Year	Freq
Cofferdam		agency	ic	sub	2	ea	$9,536.88	0	1	1	1
OTHER CATEGORY											
Concrete class A4	for parapet	agency	ic	sub	20	cy	$285.21	0	1	1	1
Epoxy coated reinf. steel	for parapet	agency	ic	sub	2,760	#	$0.55	0	1	1	1
Preformed Elastomeric Joint Sealer		agency	ic	sub	252	lf	$19.35	0	1	1	1
Dry riprap		agency	ic	sub	2,054	tn	$17.49	0	1	1	1
OM&R											
Overlay concrete to repair deck		agency	omr	deck	44	cy	$1,200.00	0	25	50	25
NBI inspection every two years		agency	omr	non-el	1	ls	$150	0	2	74	2
DISPOSAL											
Dispose of deck	based on cy concrete	agency	disp	deck	0.33	ls	$80,000	0	75	75	1
Dispose of superstructure	based on cy concrete	agency	disp	super	0.04	ls	$80,000	0	75	75	1
Dispose of substructure	based on cy concrete	agency	disp	sub	0.61	ls	$80,000	0	75	75	1

Remarks: **Agency costs for the base case, conventional strength bridge. The HPC bridge will use the same costs, but reduce the number of beams and add new-material introduction costs.**

Name	Remarks	Cost Categories			Cost Quantities						
		Cost Bearer	Life-Cycle	Proj Comp	Qty	UMeas	Unit Cost	Range (±%)	Start Year	End Year	Freq
Dispose of other	based on cy concrete	agency	disp	other	0.02	ls	$80,000	0	75	75	1

Following the cost classification, the engineer enters "agency" in the Level 1 (Cost Bearer) column, "ic" in the Level 2 (Life-Cycle) column, and the appropriate component in the Level 3 (Project Component) column.

The Start Year, End Year, and Frequency columns are used to enter the first year that the cost occurs, the last year the cost occurs, and the frequency with which the cost occurs. A frequency of "1" means that the cost occurs once a year, a frequency of "0.5" means the cost occurs twice a year, a frequency of "5" means the cost occurs every five years, and so on. Since all of the initial construction costs for this bridge occur in the first year and only once, a "1" is input into the Start Year, End Year, and Frequency columns. All of costs in the worksheet are input into BridgeLCC using the **Edit Cost** window.

Following the cost classification scheme, the engineer then generates a worksheet of all OM&R costs. Since the engineer estimates that there are no operation or maintenance expenses for the bridge, this is essentially a repair schedule for the structure. The engineer estimates that the base case bridge deck will require repair every 25 years. Each repair involves grinding off a thin layer of the bridge deck road surface and then applying a skim coat of new concrete. The engineer estimates this will take 40 cubic yards of concrete at a cost of $1,200 per cubic yard (which includes the cost of grinding off the old layer). No other maintenance or repair is required.

The final life-cycle category of cost is bridge disposal, which occurs in year 75. Since the cost is borne by the agency and occurs during disposal, the Level 1 entry is "agency" and the Level 2 entry is "disp." The cost is broken down into disposal components based on the volume of concrete in each component. Since all costs occur in the last year of the life cycle and only occur once, the Start Year is "75," the End Year is "75," and the Frequency is "1."

All initial construction, OM&R, and disposal costs are now entered. The engineer can view and edit these costs the **Browse All Costs** window. To view, for example, just the initial construction costs for the deck, the engineer can access the **Cost Summary** window, check-mark only the **Agency**, **Initial Construction**, and **Deck** check boxes, and then access the **Browse All Costs** window. The engineer can edit individual cost items by double-clicking the entry.

User Costs

Traffic can be affected during construction, repair, and eventual disposal of the bridge. The user costs of these activities are estimated by creating new cost items in the **Edit Cost** window and then inputting the number of days that each activity affects traffic. This data is used in conjunction with the traffic data in the **Project Parameters** window to compute project user costs. The following page shows the worksheet of user costs compiled for the two bridges.

Project: **Route 40 in Virginia**					Date:				pg#	of	pgs

Remarks: User costs for base case and alternative structure

Name	Remarks	Cost Categories			Cost Quantities						
		Cost Bearer	Life-Cycle	Proj Comp	Qty	UMeas	Unit Cost	Range (±%)	Start Year	End Year	Freq
Base Case Bridge											
Redirect traffic during deck repair	year 25 and 50	user	omr	deck	7	days			25	50	25
Alternative Bridge (HPC)											
Redirect traffic during deck repair	year 40	user	omr	deck	7	days			40	40	1

Third-Party Costs

These costs could include revenues lost by adjacent businesses due to bridge construction, repair, and disposal, or environmental damage such as pollution of the stream under the bridge. For this particular project the engineer can find no third-party costs.

Alternative #1: High-Performance Concrete

The engineer estimates that the costs of the alternative, high-performance concrete bridge are the same as the base case bridge, but with three important differences. First, the high-performance concrete allows the engineer to use 5 beams in each span instead of the 7 beams in the base case. This reduces the total cost of bridge beams. Secondly, even though the number of beams is reduced, the engineer requests that the beam fabricator perform some static load tests on one of the high-performance concrete beams to verify its load carrying capacity. This costs the DOT an additional $30,000. Finally, the new low-permeability AASHTO specification for concrete extends the period between deck repairs from 25 years to 40 years. This reduces the number of repairs from 2 (in years 25 and 50) to 1 (in year 40).

These costs that differ from the base case bridge are show on the following page.

Project: **Route 40 in Virginia**				Date:				pg#	of	pgs

Remarks: **Costs in the HPC bridge design that differ from the base case design. The beam cost and repair costs below modify the values that were in the base case design. The static testing cost is a new cost item.**

Name	Remarks	Cost Categories			Cost Quantities						
		Cost Bearer	Life-Cycle	Proj Comp	Qty	UMeas	Unit Cost	Range (±%)	Start Year	End Year	Freq
Prestressed I-Beam Type IV (80 ft.)		agency	ic	super	20	ea	$7,000.00	0	1	1	1
Overlay concrete to repair deck		agency	omr	deck	44	cy	$1,200.00	0	40	40	1
Redirect traffic during deck repair	year 40	user	omr	deck	7	days			40	40	1
Static load testing of a beam	to insure capacity	agency	ic	new	1	ls	$5,000.00	0	1	1	1

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Once inputted, the engineer uses the **Cost Summary** window to compute the life-cycle costs and to assess the life-cycle cost effectiveness of each concrete mix.

5.3 Results

5.3.1 Best Guess Values

Step 5: Compute the life-cycle cost of each alternative

Once all costs have been input for each alternative and the life-cycle costs have been computed (via the **Compute LCC** button in the **Cost Summary** window), the results can be displayed three ways:

- in the **Cost Summary** window,
- in graphs (e.g., selecting **Graphs/All Three...** from the menu), or
- by printing reports (selecting **File/Print...** from the menu).

The **Cost Summary** window, shown in Figure 37, indicates that HPC is the cost-effective bridge material: its total life-cycle cost is $675,675 while the conventional-concrete bridge cost is $724,369.
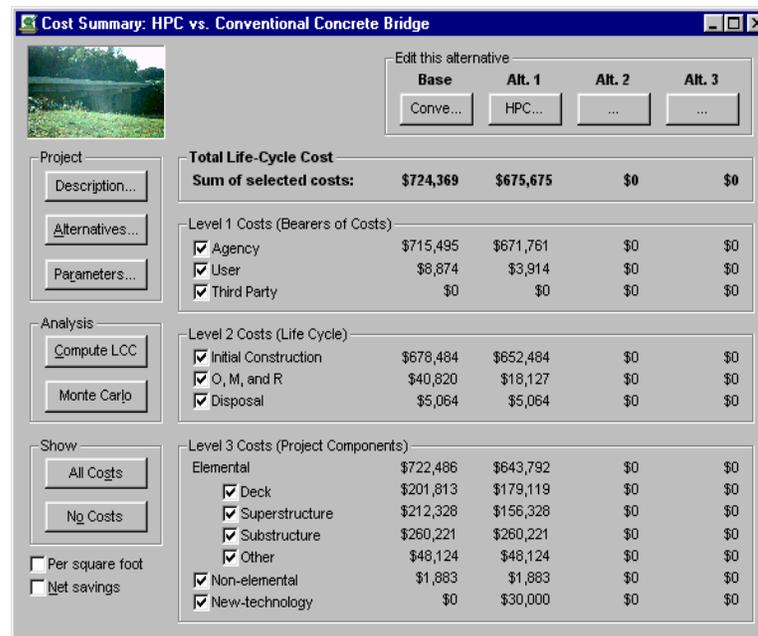
Figure 37. Cost Summary Window

By check-marking the **Net savings** box the Cost Summary window in Figure 38 shows that the HPC bridge has a net savings of $48,694 over the base case bridge, and that $43,734 of these savings are in agency costs.
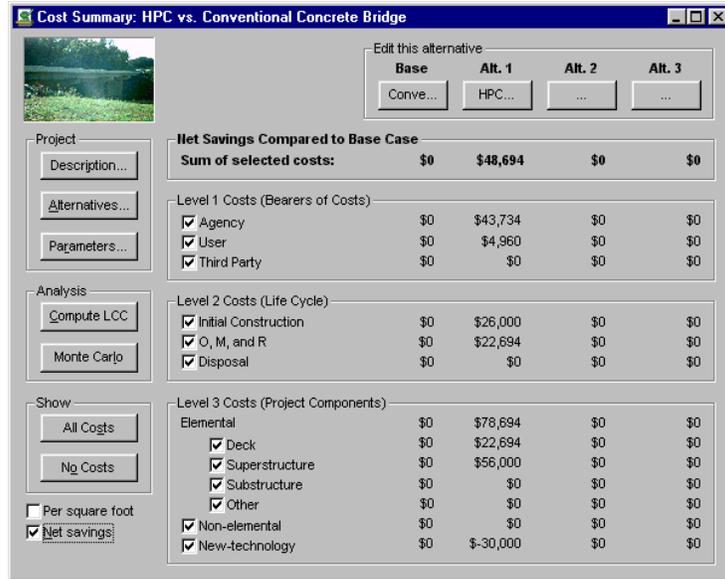
Figure 38. Cost Summary Window of Total Life-Cycle Costs

The initial-construction savings that the HPC bridge generates to the agency can be seen by check-marking the **Agency**, **Initial Construction**, and all **Level 3 Costs** check boxes (and keeping the **Net savings** box check-marked). Figure 39 shows these savings.
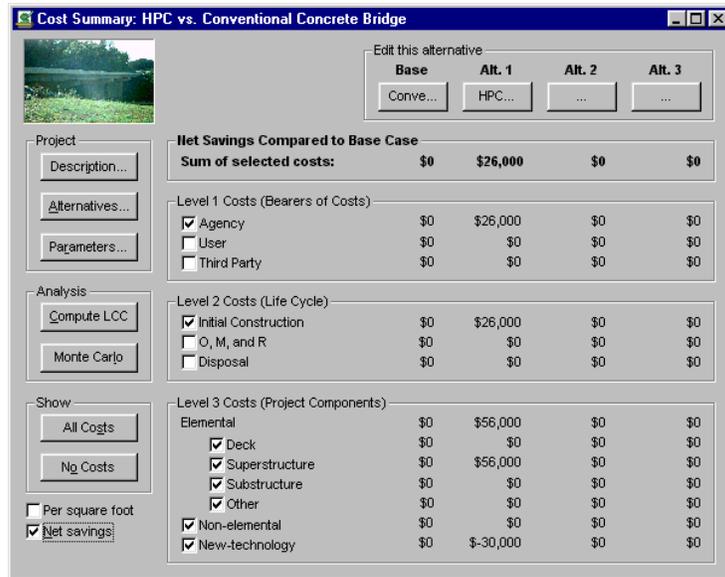
Figure 39. Cost Summary Window of Net Savings in Agency Initial Construction Costs

Comparing these savings with the technical differences listed in Table 1, the figure illustrates how the use of five HPC beams (instead of seven for the conventional-concrete bridge) saves the agency $56,000 in superstructure costs, but generates an additional $30,000 in new-technology costs. Similarly, Figure 40, listing the net savings in OM&R costs to the agency, shows how the HPC low permeability mix design decreases repair costs by $17,734.
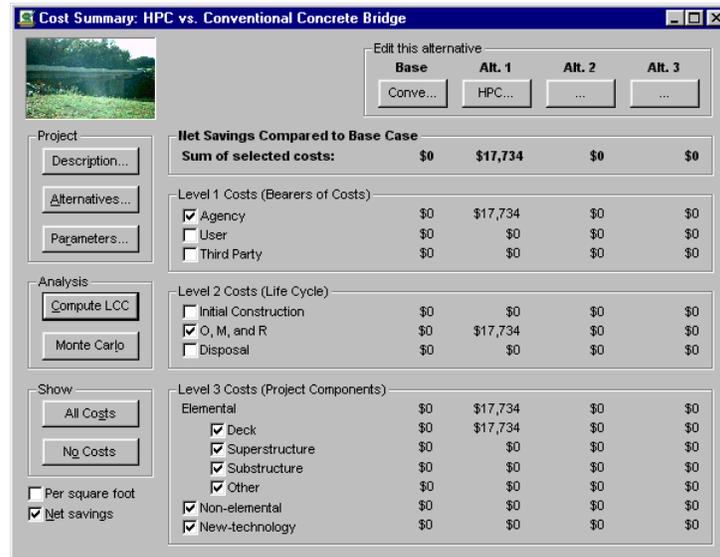
Figure 40. Cost Summary Window of Net Savings in Agency OM&R Costs

If in the long term the engineer accepts the high-performance concrete into normal practice, he will not need to perform the static-load HPC beam test and the agency will not have to incur this new-technology cost. The long-term savings to the agency can be seen by uncheck-marking only the **New-technology** project-component cost (and uncheck-marking the **User** and **Third Party** boxes). Figure 41 shows that, if the HPC becomes accepted practice, the long-term net savings to the agency of HPC are $73,734.

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Cost Summary: HPC vs. Conventional Concrete Bridge

Edit this alternative

	Base	Alt. 1	Alt. 2	Alt. 3
	Conve...	HPC...	...	...

Net Savings Compared to Base Case

Sum of selected costs:	$0	$73,734	$0	$0

Project
- Description...
- Alternatives...
- Parameters...

Analysis
- Compute LCC
- Monte Carlo

Show
- All Costs
- No Costs

☐ Per square foot
☑ Net savings

Level 1 Costs (Bearers of Costs)

	Base	Alt. 1	Alt. 2	Alt. 3
☑ Agency	$0	$73,734	$0	$0
☐ User	$0	$0	$0	$0
☐ Third Party	$0	$0	$0	$0

Level 2 Costs (Life Cycle)

☑ Initial Construction	$0	$56,000	$0	$0
☑ O, M, and R	$0	$17,734	$0	$0
☑ Disposal	$0	$0	$0	$0

Level 3 Costs (Project Components)

Elemental	$0	$73,734	$0	$0
☑ Deck	$0	$17,734	$0	$0
☑ Superstructure	$0	$56,000	$0	$0
☑ Substructure	$0	$0	$0	$0
☑ Other	$0	$0	$0	$0
☑ Non-elemental	$0	$0	$0	$0
☐ New-technology	$0	$0	$0	$0

Figure 41. Cost Summary Window of Long-Term Net Savings in Agency Costs

Figures 42 and 43 show the summary report and cost graphs of the total life-cycle cost of each alternative.

Preview for SUMMARY.RET

BridgeLCC Summary Report
5/3/99

Project Description

HPC vs. Conventional Concrete Bridge (date: 5/4/98)
This analysis compares the life-cycle costs of a bridge built from two alternative designs: (1) a "base case" design that uses conventional strength concrete, and (2) a new design that uses high-performance concrete. The structure with the lowest life-cycle cost has the cost-effective bridge design.

Bridge geometrics (common to both design alternatives)
Bridge Width: 44'-0" face-to-face of curb
Span layout: 4 - 80 foot prestressed concrete I-beam, Type IV spans.
Capacity: HS20-44 loading and alternate military loading.
Drainage area: 240 sq. mi.

Specifications:
Construction: VDOT Road and Bridge Specifications, 1991.
Design: AASHTO Standard Specifications for Highway Bridges, 1989, 1990, 1991 Interim Specifications, and VDOT modifications.
All structural steel, including bearings shall be ASTM A709 Grade 36

User costs:
The bridge is on a rural highway and built over a stream. The old bridge is used until the new one is built, preventing traffic interruptions. Maintenance resurfacing after 25 or so years requires the closing of one lane. ADT levels are so low that the user costs of maintenance are small. There are no disposal user costs since cars will cross this bridge until its successor is finished.

The enclosed photographs represent what the key shape and design characteristics are for the prototypical structure.

Project Alternatives

BASE CASE: Conventional Concrete

Figure 42. Project Summary Window

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Figure 43. Graphs of Life-Cycle Costs, by Cost Types

5.3.2 Sensitivity Analysis

> **Step 6: Perform sensitivity analysis**

The engineer next uses BridgeLCC to determine whether the cost effectiveness of HPC is robust to changes in some of the underlying parameters. BridgeLCC allows the engineer to perform several types of sensitivity analysis, including sensitivity of the life-cycle costs to changes in project parameters, breakeven analysis, and cost uncertainty analysis. Project-parameter analysis can determine, for example, whether the HPC bridge is still cost effective in an area with higher levels of average daily traffic. Breakeven analysis can determine by how much HPC repair costs can increase before the HPC bridge is no longer cost effective. Cost uncertainty analysis can apply probability distributions to individual costs to see if HPC is still cost effective when its constituent costs are not known with certainty.

Sensitivity Analysis #1: Sensitivity of Life-Cycle Costs to Changes in ADT

The engineer first tests whether the HPC bridge would still be cost effective in areas with different levels of on-bridge traffic. The first-year and final-year ADT values in the **Project Parameters** window are changed and life-cycle costs re-computed. Table 5 lists the alternative sets of ADT used by the engineer and the re-computed life-cycle costs.

Table 5. Sensitivity Analysis: Effect of Different ADT Sets on Life-Cycle Cost

Set	On-Bridge ADT		Life-Cycle Cost	
---	First-Year	Last-Year	Base Case	Alternative #1
1	0	0	$715,495	$671,761
2	0	2,500	$716,807	$672,436
3	2,500	5,000	$719,932	$673,718
4	5,000	20,000	$729,616	$678,377
5	20,000	50,000	$756,237	$690,120

Table 5 indicates that Alternative 1, the high-performance concrete bridge, is cost effective regardless of the particular traffic levels experienced over the life cycle of the structure.

Sensitivity Analysis #2: Breakeven Analysis: HPC Repair Cost

The HPC bridge has a lower life-cycle cost than the base case because it has both a lower initial construction cost and a lower repair cost. However, the engineer may have some uncertainty regarding what the HPC repairs will be. Suppose the engineer determines that the deck will be repaired in year 40, as planned, but there is uncertainty about how much repair will be required. The engineer asks, "what is the maximum amount of repair the HPC bridge can realize before it is no longer cost-effective?" We determine this breakeven level of repair by iteratively changing the repair cost in year 40 until we find the cost that makes the life-cycle cost of alternative 1 equal that of the base case. This cost is found to be $262,000.The HPC bridge, therefor, can sustain a total of $262,000 in repair costs in Year 40 and still be life-cycle cost effective.

Sensitivity Analysis #3: Uncertainty in Project Costs

Our final sensitivity test determines whether relative uncertainty in the HPC bridge's costs prevent it from always being the life-cycle cost-effective bridge material. For example, suppose that there is a small probability that the HPC-bridge costs are all much higher than the base-case bridge costs; in this case there is a small probability that the HPC bridge will not be life-cycle cost effective.

The engineer tests a specific example. Suppose he or she believes that the costs for the base case bridge can vary as much as 5% from the best-guess values, while the HPC bridge unit costs can vary as much as 15% from their best-guess values.

For each of the base case costs, the engineer puts "5%" in the **Cost Uncertainty** field of the **Edit Cost** window or in the **Percent** column in the **Browse All Costs** window. The engineer also puts "15%" in the same fields for the HPC bridge.

Once input, the engineer runs a Monte Carlo simulation by pressing the **Monte Carlo** button on the **Cost Summary** window or by selecting **Analysis/Monte Carlo Simulation...** from the menu. In the **Monte Carlo Simulation** window, the engineer selects the number of samples to make, selects either uniform or normal distributions for the costs, and presses the **Run** button. The simulation will produce a graph in similar to Figure 44.
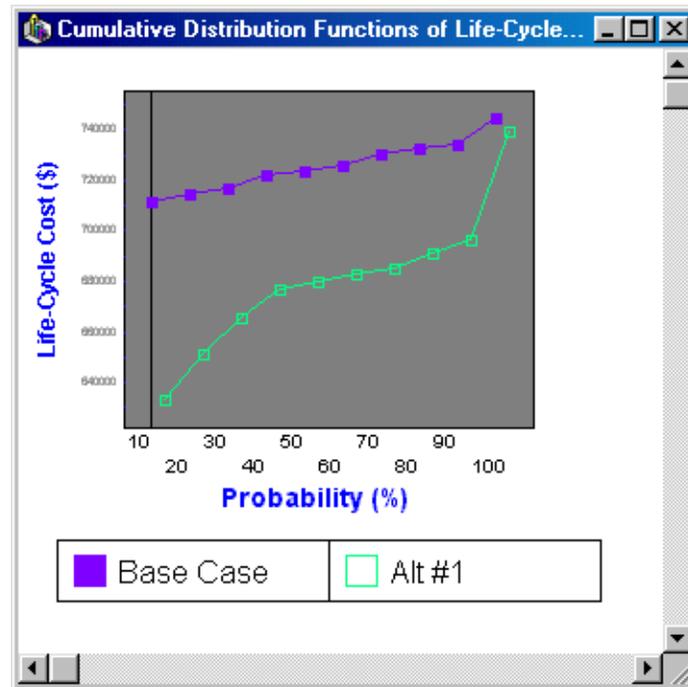
Figure 44. Graph of Monte Carlo Results

The graph shows the range of possible life-cycle costs for each alternative. Moving from left to right across the graph, we see that, for each probability level, Alt #1 (the HPC bridge) has a lower expected life-cycle cost than the Base Case (conventional-concrete bridge). For example, 10% of the time (ten times out of 100) the HPC-bridge life-cycle cost is less than or equal to $630,000, while 10% of the time the base-case bridge life-cycle cost is less than or equal to $710,000. Said another way, the cost of the HPC bridge will be at least as low as $630,000, while the cost of the base-case bridge will at least as low as $710,000. The HPC bridge has a lower possible life-cycle cost.

Since for every probability level the HPC bridge has a lower expected life-cycle cost than the base-case bridge, the HPC bridge is cost effective in a probabilistic sense. In a statistical sense, the HPC bridge cost distribution *strictly dominates* the conventional-concrete bridge cost distribution.

If one alternative's distribution does not strictly dominate all other alternatives distributions, none of the material alternatives would be cost effective in a probabilistic sense. Some additional procedures for including risk attitude in project evaluation would be required to establish the preferred bridge.[8]

Step 7: Compare the alternatives' life-cycle costs	The engineer now compares the alternatives based on their "best guess" life-cycle costs in the **Cost Summary** window and on the three sensitivity tests. The HPC bridge is cost-effective based on best guess values: $675,675 versus $724,369. The sensitivity analysis allows the engineer to conclude that the HPC bridge is life-cycle cost effective (1) for all traffic conditions (at least when the bridge has no under-bridge traffic), (2) when HPC repair cost is $262,000 or less, or (3) when the base case and HPC bridges' costs vary by 5% and 15%.
Step 8: Consider other project effects	Factors other than cost can affect an engineer's design about what material to use. These non-cost factors could include architectural considerations, material restrictions, or politics. An engineer can use additional procedures such as the multi-attribute decision analysis (MADA) to weigh cost and non-cost factors simultaneously.[9] In this example analysis, only cost affects the final material decision.
Step 9: Choose the life-cycle cost-effective alternative	Given that all cost and non-cost factors have been considered, the engineer can conclude that the HPC bridge is life-cycle cost-effective when compared with his base-case, conventional-concrete bridge. Its life-cycle cost is lower than the other alternatives, and sensitivity analysis indicates that this conclusion is robust to the selected changes in underlying parameters and assumptions about cost uncertainty.

This completes the example analysis. To summarize, two alternative bridge materials (and their associated designs) were considered: conventional-strength concrete and high-performance concrete. BridgeLCC was used to

- compile all of the relevant project data and bridge costs,
- compute the "best guess" estimates of life-cycle cost of each alternative bridge,
- compare cost breakdowns using the included cost classification scheme,
- test how sensitive the life-cycle costs of each are to changes in project parameters,
- determine how high some of the HPC bridge's constituent costs can be before it is no longer cost effective, and
- determine whether higher uncertainty in individual costs makes the HPC bridge no longer cost effective.

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[8] For more discussion about risk attitudes and uncertainty, see Rosalie T. Ruegg and Harold E. Marshall, *Building Economics: Theory and Practice* (New York, New York: Chapman and Hall, August 1990).

[9] For a detailed description of MADA techniques, see Gregory Norris and Harold E. Marshall, *Multi-attribute Decision Analysis Method for Evaluating Buildings and Systems,* 1995.

Under the particular set of sensitivity values, HPC is the cost-effective bridge material. HPC allows the designer to use fewer beams and to have a smaller repair schedule over the life of the structure. This saves the agency construction and repair costs, and saves drivers on the highway both time and cost.

Appendix A. The Life-Cycle Costing Methodology and Cost Classification Scheme

BridgeLCC uses a life-cycle costing methodology based on the ASTM practice E 917 for measuring the life-cycle costs of buildings and building systems, and a cost classification scheme developed by Ehlen and Marshall (1996) [10] The classification scheme in particular allows the user to capture all project-related costs and compare alternatives' life-cycle costs in useful ways. BridgeLCC's **Cost Classification** and **Edit Cost** windows give short definitions of each cost type.

This appendix gives an abridged description of the methodology and classification used in BridgeLCC.

A.1 The Life-Cycle Costing Methodology

A.1.1 Steps in Life-Cycle Cost Analysis

The recommended steps for calculating the life-cycle cost of a new-technology material vis-a-vis a conventional material are as follows:

1. **Define the project objective and minimum performance requirements**. The performance requirements of a project should be expressed in terms that do not preclude the use of a new-technology material.

2. **Identify the alternatives for achieving the objective**. Each alternative must satisfy the minimum performance requirements of the project.

3. **Establish the basic assumptions for the analysis**. These assumptions include specification of the base year for the analysis, the life-cycle study period, and the real discount rate.

4. **Identify, estimate, and determine the timing of all relevant costs**. Relevant costs are those costs that will be different among alternatives. Use the classification to be sure all costs are screened for inclusion. Be sure to consider all costs to direct users of the project, and any spillover costs associated with the project.

5. **Compute the life-cycle cost of each alternative** using the common data assumptions identified in step 3.

6. **Perform sensitivity analysis by re-computing the life-cycle cost for each alternative using different assumptions** about data inputs that are both relatively uncertain and significant in their impact on life-cycle cost. Sensitivity analysis

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[10] Mark A. Ehlen and Harold E. Marshall, *The Economics of New-Technology Materials: A Case Study of FRP Bridge Decking.* NISTIR 5864, Gaithersburg, MD: National Institute of Standards and Technology, 1996.

shows how sensitive a technology's costs are to uncertain data used in the economic analysis.

7. **Compare the alternatives' life-cycle costs** for each set of assumptions.

8. **Consider other project effects**—quantifiable and non-quantifiable—that are not included in the life-cycle cost calculus. If other effects are not equal and are considered significant, then turn to techniques such as multi-attribute decision analysis to account for all types of benefits and costs.

9. **Select the best alternative.** Where other things are equal (e.g., performance and non-quantifiable impacts) select the economically efficient alternative with the minimum life-cycle cost, i.e., the greatest net savings compared to the base-case alternative.

A.1.2   Requirements for an LCC Analysis

When using the LCC method, you must compute the life-cycle cost of two or more alternatives to measure cost effectiveness. The alternative with the minimum life-cycle cost is the most cost-effective option. If you make one of the alternatives a base case (usually the one with the lowest initial cost), you can compare the life-cycle cost of every other alternative against it to see which has the greatest net savings. The LCC and net savings approaches will both indicate the same best alternative.

Because we express future costs in our case study in constant or real dollars, we use a real discount rate. This means that you do not have to worry about inflation or deflation in arriving at your streams of future costs, because you are expressing costs in dollars of constant purchasing power, fixed on a calendar reference date, that exclude inflation or deflation (*if your costs include inflation, however, you need to remove this inflation prior to using them in BridgeLCC*). The real discount rate adjusts costs for the real earning opportunities of money over time. Government agencies tend to use real discount rates and constant dollars in their analyses.

Use the same fixed discount rate for all alternatives in a life-cycle cost comparison. Public projects typically are mandated to use a specific rate. Note that the economic viability of projects that save benefits or costs over time are very sensitive to the value of the discount rate. Figure A1 shows two significant effects that the discount rate has on present values of costs spread over time.

First, the present value of a given future cost amount decreases as the discount rate increases. For example, the present value of $1,000 ten years into the future drops from $613.91 at a discount rate of 5% (Point A) to $161.51 at a discount rate of 20% (Point B). Thus projects with cost savings spread into the future will generate larger present value net savings when evaluated with low rather than high discount rates.

Second, at any given discount rate, the farther into the future that any given amount occurs, the smaller its present value will be. Looking at the 5% discount rate line in Figure A1, $1,000 ten years out, worth $619.91 in present value (Point A), drops to a present value of $482.02 by year 15 (Point C).

Use the same study period for each alternative. The study period is the time over which the alternatives are compared. Using different study periods for different alternatives distorts the life-cycle cost measure. If project alternatives have different lives, include replacements in short-lived projects and consider the salvage value of long-lived projects to arrive at a common study period.

Implicit in any life-cycle cost analysis is the assumption that every proposed alternative will satisfy the minimum performance requirements of the project. These requirements include structural, safety, reliability, environmental, and specific building code requirements. Exclude from life-cycle cost analysis any alternatives that fail to meet the performance specifications of the project. If an alternative satisfies performance requirements and has additional positive features that are not explicitly accounted for in the life-cycle cost analysis, then consider an alternative economic measure such as net benefits.[11]
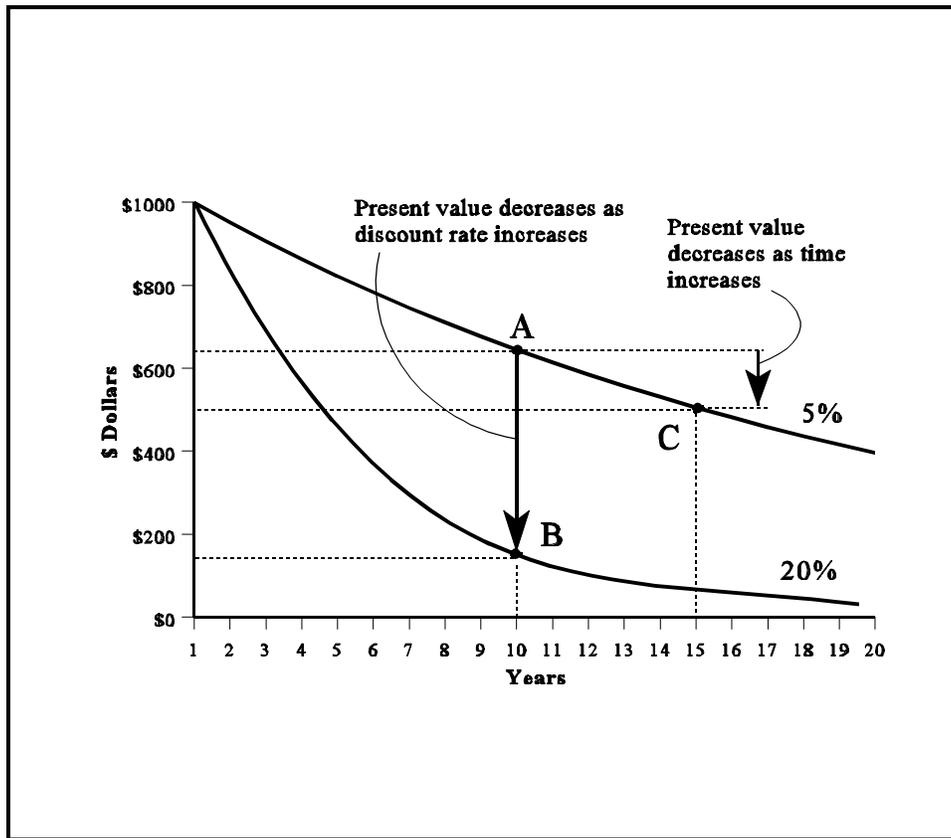
Figure A1. Present Value of Future Costs, by Discount Rate

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[11]For a comprehensive treatment of requirements for performing economic analyses of building and construction projects and of methods in addition to life-cycle cost, see Ruegg and Marshall, *Building Economics: Theory and Practice.*

A.1.3 Applications of LCC

The LCC method has multiple applications in project evaluation. We look at each in turn as it applies to construction.

A.1.3.1 Accept/Reject Decision

Choosing whether or not to do a project is an accept/reject decision. One example is deciding whether to coat an existing concrete bridge deck with polymer concrete asphalt or leave the deck "as is." The decision rule is to choose the alternative with minimum life-cycle cost.

A.1.3.2 Material/Design Decision

This application occurs when you must choose the most cost-effective of multiple material/design alternatives to satisfy an objective. The decision rule is to choose the material/design with minimum life-cycle cost. For example, given a particular material, what fabrication and construction method minimizes life-cycle cost? In this application, the decision has already been made to replace the deck with a particular material; the life-cycle cost analysis is needed to decide which design is most cost effective.

A.1.3.3 Efficiency Level or Size Decision

Choosing how much of something to invest in is the efficiency level or size decision. An example is choosing the thickness of polymer-concrete asphalt to apply to a bridge deck. The decision rule is to choose the thickness of the coating that minimizes the life-cycle cost of the polymer-concrete road surface (where all thicknesses considered meet minimum performance requirements).

A.2 The Cost Classification Scheme

There are two primary reasons for establishing a life-cycle cost classification or taxonomy when evaluating new-technology materials. First, the classification insures that all costs associated with the project are taken into account, and that these costs are accounted for in each alternative. This includes costs incurred by the owner/operator (agency costs),[12] by direct users of the structure (user costs), and by organizations or individuals indirectly affected by the structure (spillover or third-party costs). Included are costs relating to the introduction of new materials (new-technology introduction [NTI] costs).[13]

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[12]We use the word *agency* here to refer to public or private agency. In the case illustration, the bridge structure is built by government agencies. For privately contracted facilities, the agency is the private firm incurring the costs.

[13]New-technology introduction (NTI) costs are those costs associated with activities that bring the new material from the research laboratory to full acceptance by the construction industry. Examples include full-scale testing and non-destructive evaluation.

Second, the classification scheme allows for a detailed, consistent breakdown of the life-cycle cost and net savings estimates at several levels so that a clear picture can be had of the respective cost differences between material/design alternatives.

The classification scheme produces additional benefits such as providing a format for defining, collecting, and analyzing historical data for future projects, ensuring consistency in the data for economic evaluation of projects over time and from project to project, providing a check list for value engineering procedures, and providing a database format for computer-automated cost estimating.

The specifications of our classification scheme (Figure A2) are general enough to cover the spectrum from privately owned and operated projects to publicly owned and operated projects.
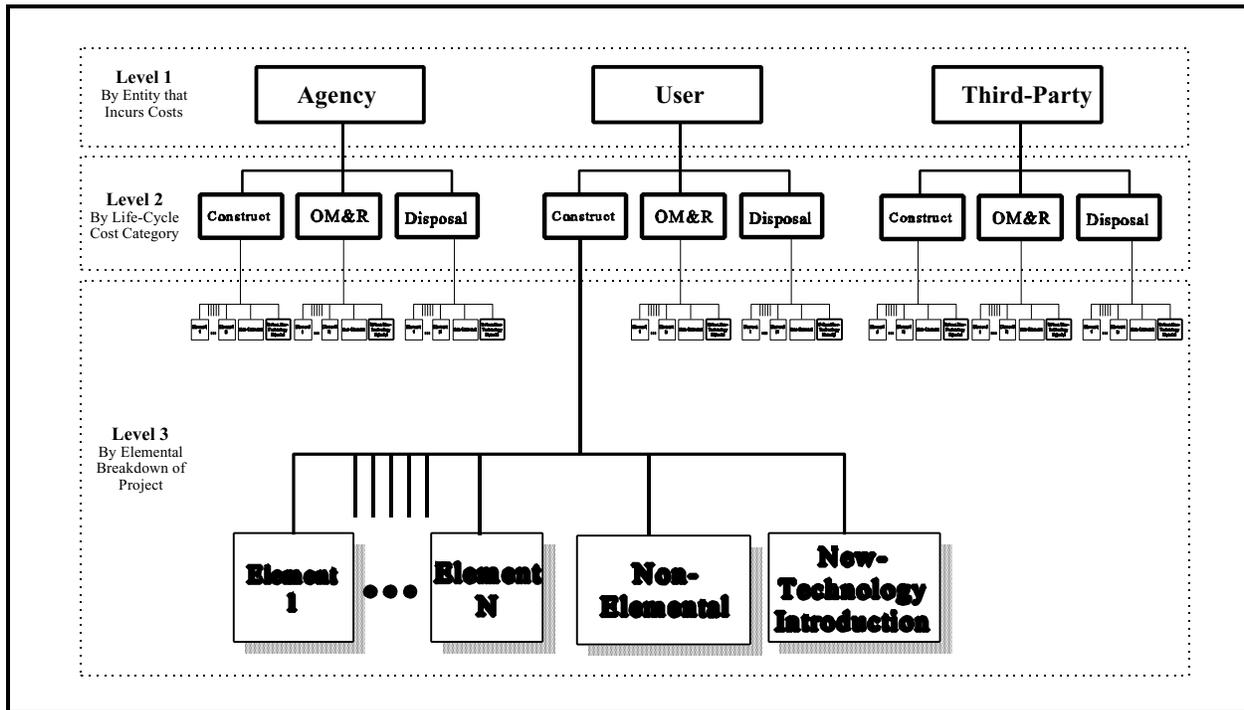
Figure A2. LCC Cost Classification

The owners of some privately owned and operated structures might not include in their life-cycle cost analysis all of the user costs and spillovers that result from their projects; public agencies do not always incorporate such costs either. But environmental laws, for example, have forced private firms to internalize many spillover costs. And public agencies are beginning to treat user costs and other spillover costs as integral parts of their economic evaluations. Since new-technology materials are expected to have a significant impact on user costs, and public agencies are paying increasing attention to user costs in economic evaluations, it is important to include these costs in any life-cycle cost comparison of alternative materials.

A.2.1 Costs by the Entity that Bears the Cost (Level 1)

Agency Costs

Agency costs are all costs incurred by the project's owner or agent over the study period. These include but are not limited to design costs, capital costs, insurance, utilities, and servicing and repair of the facility. Agency costs are relatively easy to estimate for conventional material/designs since historical data on similar projects reveal these costs.

User Costs

User costs accrue to the direct users of the project. For example, highway construction often causes congestion and long delays for private and commercial traffic. New bridge construction impacts traffic on the highway over which it passes. Maintenance and repair of an existing bridge, along with the rerouting of traffic, can impact drivers' personal time, as well as the operating cost of vehicles sitting in traffic. Accidents, involving harm to both vehicles and human life, tend to increase in road work areas. These traffic delay costs, vehicle operating costs, and accident costs can be computed using simple formulas and tabulated traffic statistics from state departments of transportation. Similar types of user costs can be computed for projects where changes to buildings or other structures directly impact occupants.

Third-Party Costs

Third-party or spillover costs are all costs incurred by entities who are neither the agency/owners themselves nor direct users of the project. One example is the lost sales for a business establishment whose customer access has been impeded by construction of the project, or whose business property has been lost through the exercise of eminent domain. A second example is cost to humans and the environment from a construction process that pollutes the water, land, or atmosphere.

A.2.2   Costs by LCC Category (Level 2)

Level 2 groups costs according to the life-cycle categories typically used in the LCC formula: construction; operation, maintenance, and repair (OM&R); and disposal.

A.2.3 Costs by Elemental Breakdown (Level 3)

The third level of classification organizes costs (1) by specific functional element of the structure or facility, (2) by activities not assignable to functional elements (e.g., overhead), and (3) by any activities associated with the introduction of a new-technology material. Parts (1) and (2) are the traditional "elements" in an elemental cost estimate. We add part (3) on new-technology introduction costs to measure the unique costs of using a new material. We call these three groups an elemental classification.

Elemental Costs

Elements are major components of the project's structure, and are sometimes referred to as component systems or assemblies. Major elements that are common to most buildings, for example, are the foundation, superstructure, exterior closure, roofing, and interior. Elements common to bridges are superstructure, substructure, and approach. Each element performs a given function regardless of the materials used, design specified, or method of construction employed.

Individual cost estimates at the elemental level (e.g., $/square meter to furnish and install a concrete deck) are most useful in the pre-design stage when a variety of material/design combinations are being considered. This is the stage at which large net savings can be achieved by making economically optimal material/design choices. Detailed cost estimates of each alternative at the pre-design stage may not be economically feasible; elemental-based estimates, on the other hand, can be done quickly and are generally accurate enough to guide material/design decisions. Note, however, that for new-technology material/designs, there will not always be sufficient data to do element-based estimates; detailed products-based estimates and crew studies may be necessary.[14]

BridgeLCC includes the PONTIS 2.0 element structure, which divides a bridge into four elements. Table A1 lists the elements and the bridge components assigned to each element. Use Table A1 to assign your individual costs to the correct element

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[14]The following concrete slab estimate illustrates a products-based estimate with crew study. First, tabulate and price all materials to be used for constructing the slab, including materials for formwork. Next, determine the labor hours, equipment requirements, and associated costs for excavation, forming, pouring, finishing, and then removing formwork. Sum your product costs for the final estimate. An elemental estimate for the same slab, on the other hand, is simply the cost per square meter to furnish and install the slab, including all material, labor, and equipment costs. But you must first know this cost per square meter to do the elemental estimate.

Table A1. Bridge Elements

Element	Includes	
Deck	Concrete (Bare)	Steel - Open Grid
	Concrete Unprotected with AC Overlay	Steel - Concrete Filled Grid
	Concrete Protected with AC Overlay	Steel - Corrugated/Orthotropic/Etc.
	Concrete Protected with Thin Overlay	Timber (Bare)
	Concrete Protected with Rigid Overlay	Timber Protected with AC Overlay
	Concrete Protected with Coated Bars	
	Concrete Protected with Cathodic System	
Superstructure	Closed Web/Box Girder	Timber Truss/Arch
	Open Girder/Beam	Arch
	Stringer (stringer-floor beam system)	Cable (not embedded in concrete)
	Thru Truss (Bottom Chord)	Floor Beam
	Thru Truss (Excluding Bottom Chord)	Pin & Hanger Assembly
	Deck Truss	
Substructure	Column or Pile Extension	Submerged Pile Cap/Footing
	Pier Wall	Submerged Pile
	Abutment	Cap
		Culver
Other	Strip Seal Expansion Joint	Elastomeric Bearing
	Pourable Joint Seal	Movable Bearing (roller, sliding, etc.)
	Compression Joint Seal	Enclosed/Concealed Bearing
	Assembly Joint/Seal (Modular)	Fixed Bearing
	Open Expansion Joint	Pot Bearing
	Approach Slab w/ or wo/AC Overlay	Disk Bearing
	Bridge Railing	

Non-Elemental Costs

Non-elemental costs are all costs that cannot be attributed to specific functional elements of the project. A common example of a non-elemental agency cost is overhead and profit;[15] a non-elemental third-party cost could be spillover costs. Because elemental cost categories are useful for generating and updating historical unit cost measures, all project costs that are not truly elemental must be excluded from these historical statistics and put in the non-elemental group.

New-Technology Introduction (NTI) Costs

The final category contains costs directly associated with using a new material. The costs are generated from activities that insure that the designer is satisfied with the material's performance and predicted service life. Said another way, the NTI costs cover the activities that bring the material from the research

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[15]In making an estimate to bid on a project, a private company will have overhead and profit included as a cost element. Profit for the contractor comprises a part of costs to the agency that contracts out the project.
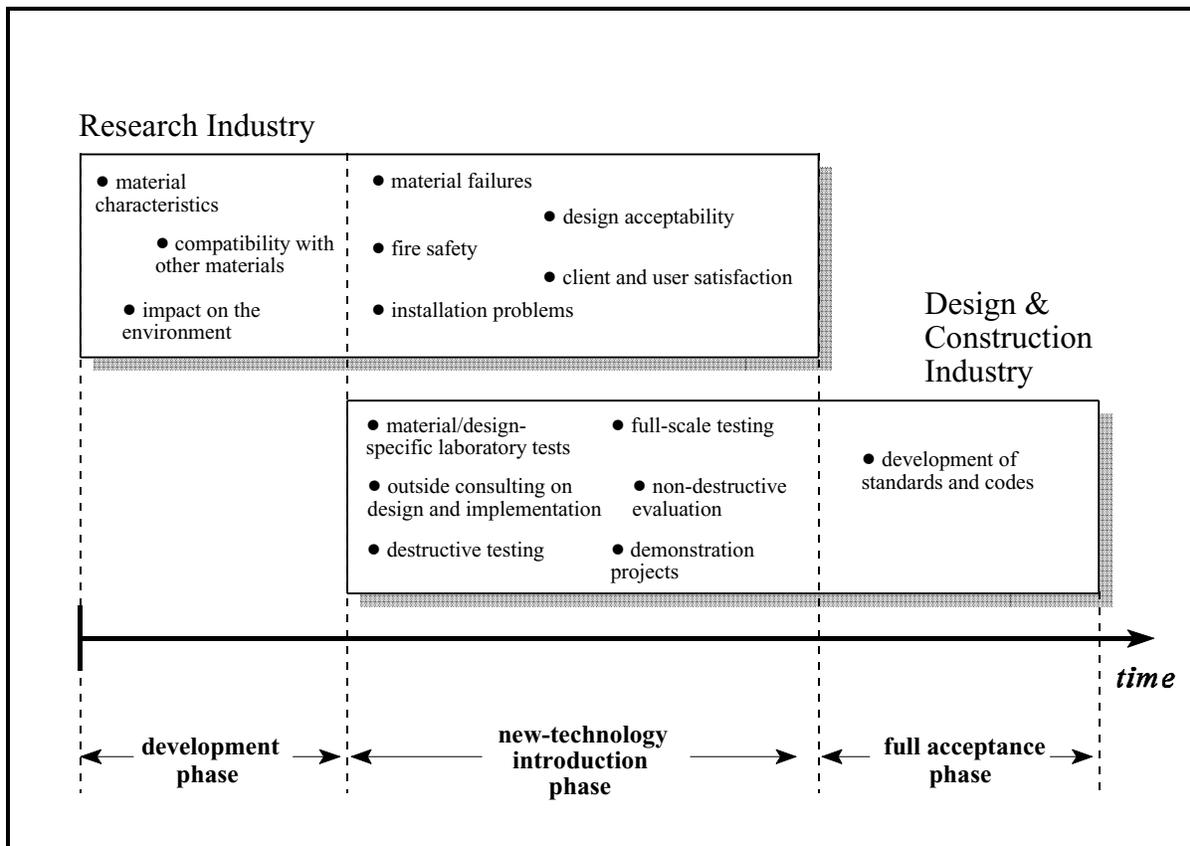
Figure A3. Evolution of New-Technology Materials

laboratory to full field implementation. Figure A3 illustrates typical activities that occur in the new-technology introduction phase.[16]

In the development phase of a new material, laboratory researchers develop an understanding of the material's properties such as its structural and corrosive behavior and corrosion resistance, and how well it performs in conjunction with other materials. If promising applications are identified, both the research and construction industries will conduct activities which introduce and integrate the new-technology material to mainstream construction. These activities will include investigating material failures and installation problems and carrying out demonstration projects and non-destructive evaluation. If the material reaches full acceptance, these activities tend to diminish or stop.

New-technology introduction costs are all project-assignable costs. They include the extra time and labor to design, test, monitor, and use the new technology. These activities and costs disappear once the designer is satisfied with the technology's performance and service life, the technology enters full

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[16]The list of NTI-phase activities is from H. J. Rosen and P. M. Bennett, *Construction Materials Evaluation and Selection: A Systematic Approach* (New York, NY: Wiley, 1979).

implementation, and its application has become routine. Examples of activities which help insure acceptability of a new-technology material and design include[17]

- Full-scale testing and other laboratory tests;
- Demonstration projects;
- Hiring consultants and/or research institutions to assist in the evaluation process;
- The training of inspection, maintenance, and repair crews in the use of the new material;
- Non-destructive monitoring and evaluation of the new structure; and
- Additional material testing for government acceptance.

The costs of these activities can be directly estimated, as we do in the case study in Chapter 5.

A.2.4   An Example of the Cost Classification Scheme

As an example of how the cost classification is used to organize a life-cycle cost estimate, Figure A3 shows a schematic of a typical engineer's estimate.

Prior to public bidding of a highway overpass project, a state engineer estimates new construction costs by making a detailed quantity take-off of materials, and then assigning unit costs which reflect the labor, material, and equipment necessary to put the sub-component materials in place. These quantity take-offs are often structured by bridge component (level 3 project elements): bridge deck (element 1), substructure (element 2), and approach roadways (element 3). Non-elemental costs and new-technology introduction costs are then estimated and grouped as separate categories of level 3 costs. Next, because these level 3 elemental costs occur during initial construction, they are classified as level 2 initial construction costs. Finally, these are level 1 agency costs.

There are at least three benefits to this life-cycle cost classification of an engineer's estimate. First, it requires little to no restructuring of how current estimates are organized. Second, it insures proper identification and placement of costs due to its top-down and bottom-up functionality. The classification insures proper identification of all construction costs by allowing the estimator to start at the top of the classification (level 1) and work his or her way down each level. The classification's bottom-up ability is equally important: any estimate of a cost can be placed properly in the life-cycle cost classification by noting which entity bears the cost (level 1), which period in the life cycle the cost occurs (level 2), and what component of the project generates the cost (level 3).

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[17]A new material also has some costs which may be difficult to compute. For example, a designer may not be as familiar with the new-technology material as with conventional materials, including properties such as tensile and compressive strength, modulus, fracture toughness, and maximum bearing pressure. This lack of knowledge could impact total project costs through higher factors of safety in design.
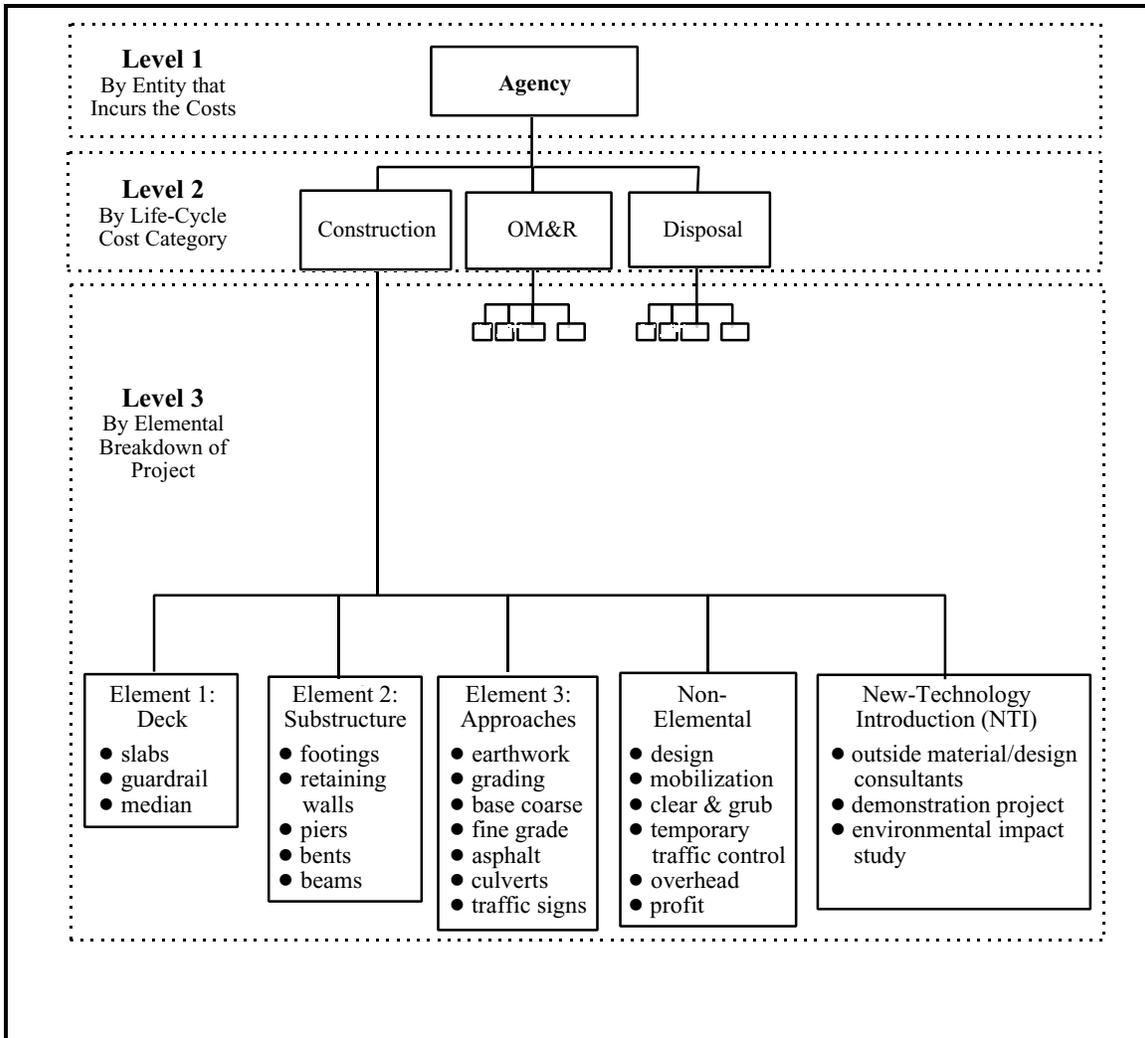
**Figure A4. An Example of the Cost Classification for an Engineer's Estimate
of New Bridge Construction (with NTI Costs)**

The third benefit of this life-cycle cost classification is that actual construction costs classified by the same structural elements can be used to compile historical unit cost data on level 3 bridge element costs to be used in future life-cycle cost analyses.

Appendix B. Life-Cycle Costing Formulas

B.1 Basic Formula

Equation B1 shows the formula used in BridgeLCC to future costs to present value and sum them into a single life-cycle cost number.

$$PVLCC = \sum_{t=0}^{T} \frac{C_t}{(1 + d)^t},$$
(B1)

where

C_t = the sum of all costs incurred at time t, valued in base-year dollars

d = the real discount rate for converting time t costs to time 0, and

T = the number of time periods in the study period.

The unit of time used is typically the year; thus C_t is the sum of all costs that occur in year t, and T is the number of years in the study period.

B.2 User Costs

User costs accrue to the direct users of the project. For example, highway construction often causes congestion and long delays for private and commercial traffic. New bridge construction impacts traffic on the highway over which it passes. Maintenance and repair of an existing bridge, along with the rerouting of traffic, can impact drivers' personal time and the operating cost of vehicles sitting in traffic. Accidents, involving harm to both vehicles and human life, tend to increase in road work areas.

These traffic delay costs, idle-capital costs, and accident costs can be computed using simple formulas and tabulated traffic statistics from state DOTs. BridgeLCC computes three types of user cost are typically computed:

- *driver delay costs* - the personal cost to drivers delayed by roadwork;
- *vehicle operating costs* - the capital costs of vehicles delayed by roadwork; and
- *accident costs* - the cost of damage to vehicles and humans due to roadwork.

Equation B2 can be used to compute the cost to drivers of roadwork-related traffic delays.

$$\text{Driver Delay Costs} = \left(\frac{L}{S_a} - \frac{L}{S_n} \right) \times ADT \times N \times w,$$
(B2)

where

L is the length of affected roadway or which cars drive,

S_a is the traffic speed during bridge work activity,

S_n is the normal traffic speed,

ADT as the average daily traffic, measured in number of cars per day,

N as the number of days of road work, and

w as the hourly time value of drivers.

The hourly value w is a weighted average of commercial vehicle drivers' and personal automobile drivers' time. Vehicle operating costs can be calculated using eq (B3).

$$\text{Vehicle Operating Costs} = \left(\frac{L}{S_a} - \frac{L}{S_n} \right) \times ADT \times N \times r, \qquad \text{(B3)}$$

where r is a weighted-average vehicle cost similar to the weighted cost in equation (B2), and the remaining parameters are the same as those in eq (B2). Accident costs can be calculated using eq (B4).

$$\text{Accident Costs} = L \times ADT \times N \times (A_a - A_n) \times c_a, \qquad \text{(B4)}$$

where c_a is the cost per accident, A_a and A_n are the during-construction and normal accident rates per vehicle-kilometer, and the remaining parameters are the same as those listed in eqs (B2) and (B3).

Appendix C. Worksheets

The following set of worksheets can be used to itemize technical data, project parameters, and individual cost items prior to inputting them into BridgeLCC.

Technical Characteristics of the Alternative Bridge Designs

Description	Base Case:	Alternative #1:	Alternative #2:	Alternative #3:

Project Parameters

Project:	Parameter Set:		Date:
Remarks:			

Item	Traffic Over Bridge		Traffic Under Bridge	
	Year 1	Last Year	Year 1	Last Year
Length of Affected Roadway (miles)				
Average Daily Traffic (#)				
Normal Driving Speed (mph)				
Roadwork Driving Speed (mph)				
Normal Accident Rate (per mil veh miles)				
Roadwork Accident Rate (per mil veh miles)				
Hourly Driver Cost ($)				
Hourly Vehicle Operating Cost ($)				
Cost Per Accident ($)				

Project:					Date:			pg#	of	pgs
Remarks:										

Name	Remarks	Cost Categories			Cost Quantities						
		Cost Bearer	Life-Cycle	Proj Comp	Qty	UMeas	Unit Cost	Range (±%)	Start Year	End Year	Freq

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