A FRAMEWORK FOR ASSESSING SUSTAINABILITY IN THE DESIGN OF MICHIGAN BRIDGES AND LIFE CYCLE COST ANALYSIS

By

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ABSTRACT

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The bridge construction industry in US is increasingly becoming aware of sustainability and its importance in the future. The existing research and literature mainly focus on how sustainability can be integrated in bridges, but till now, there is no research specifically related to the development of a rating system for measuring the sustainability of green bridges. This thesis presents a rating system for green bridges. It is presented in two parts; the first part presents the framework for implementing sustainability in design, construction and maintenance for bridges and the Delphi approach with the focus being on design, while the second part deals with guidelines for conducting the Life Cycle Cost Analysis (LCCA) of bridges. The first part, the framework, is divided into three categories i.e. design, construction and maintenance. There are fourteen criteria in the design category, six criteria in the construction category and eight criteria in the maintenance category. The second part, LCCA, summarizes a thorough research that establishes guidelines for conducting LCCA on bridges in Michigan and discusses the case studies on the application of LCCA in deciding low cost and best performance alternatives for bridge project. This thesis provides guidelines for bridge construction industry professionals in gauging sustainability and carrying out advance studies on various topics related to the LCCA of green bridges.

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CHAPTER 1 INTRODUCTION

1.1 OVERVIEW

In recent years, the notion of sustainability has gained a great deal of recognition and is growing rapidly throughout the world. The World Commission on Environment and Development, in their report on our common future (1987), defines sustainability as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN, 1987). The idea behind this concept is to protect the natural resources which are depleting rapidly and provide future generations with a natural environment by making communities healthier, economically stronger and socially diverse.

In an effort to achieve sustainability in buildings, the United States Green Building Council (USGBC) developed the Leadership in Energy and Environmental Design (LEED®) rating system with the intention of significantly eliminating harmful environmental impacts through high-performance, water and energy efficient design, construction, and operations practices. The LEED® rating system is designed for rating all types of buildings including new and existing commercial, institutional and residential buildings. The rating system is structured into five main environmental categories: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality and each category entail various credits. It is reported that from 2005 to 2008, green building construction increased dramatically from 2% to 20% of the overall construction (Siemens, 2009).

Bridges comprise a huge investment of capital, materials and energy and are associated with the significant economic, social and environmental costs. “According to the U.S. Department of Transportation, of the 600,905 bridges across the country as of December 2008, 72,868 (12.1%) were categorized as structurally deficient and 89,024 (14.8%) were categorized as functionally obsolete” (AASHTO, 2008). It is therefore, imperative to integrate sustainable practices in bridge design, construction and maintenance, which will result in building a healthier environment and efficient use of resources and investment. Until now bridge construction industry and professional bridge engineers have been unable to develop any type of rating system for the sustainable bridges and there was a dire need to describe explicit ways and procedures to define and measure sustainability in bridges.

In an effort to define sustainability in bridges, the Michigan Department of Transportation (MDOT) took a step forward to develop a sustainable bridge rating system, which can be utilized to categorize green bridges. MDOT funded Michigan State University (MSU) research project to develop a framework for assessing the sustainability in bridge design, construction and maintenance and provide a set of sustainable guidelines.

This thesis is a part of an MDOT research project and more details about the project can be found in MDOT Final Report RC-1586 entitled ‘Implementation of Sustainable and Green Design and Construction Practices for Bridges’ (MDOT, 2012).

1.2 NEED STATEMENT

The need for this research is twofold. Firstly, there is a need to develop a sustainable assessment system for bridge design, construction and maintenance to improve the quality of the transportation system by application of sustainable construction practices and efficient use of material and resources. The focus of this thesis is to deal with the implementation of sustainable practices in bridges. Secondly, it is also important to elucidate total life cycle cost associated with the design, construction and maintenance of bridges in order to decide the best performance and lowest long-term maintenance cost alternative.

1.2.1 Need for a Sustainability Rating System for Bridges

The need for sustainable bridges is obvious, as they offer benefits such as, being built rapidly, long service life with an optimal use of resources, lowest maintenance cost and minimal disruption to the environment. In addition, the implementation of sustainable strategies has improved the economic and environmental performance of bridges. Due to the numerous benefits of implementing sustainable practices, transportation agencies in the US are enthusiastic to adopt sustainable techniques in bridge design, construction and maintenance. According to the Secretary of the US Department of Transportation, the Department's priorities are safety, economic recovery and establishment of sustainable highway programs (CTRE, 2004).

In the United States, there is currently no national standard for guiding and/or measuring sustainability practices for bridges. There is a limited amount of research done in this area and presently, there is no official rating system to gauge the sustainability in bridges. Furthermore, the design and construction professionals in the bridge industry are mostly unaware of the sustainable practices that can be used in bridge design, construction and maintenance.

This research study will guide transportation agencies and bridge professionals in measuring sustainability in green bridges.

1.2.2 Life Cycle Cost Analysis (LCCA) of Bridges

LCCA is used to evaluate the costs and benefits of a bridge construction project. It is presently the most common tool used to make a sensible decision in selecting a low cost and best performance alternative. It enables a total cost comparison of various design alternatives, and brings to a logical decision, whichever is suitable for the execution of a project. All the pertinent costs that occur throughout the service life of bridge are included. The precise application of LCCA to a bridge construction project offers a great deal of choices in making a logical decision on the specific type of design, construction and maintenance. Currently, there are several tools available to evaluate benefits-cost for planning of a highway project, such as Cal-B/C, NET-BC, the NCDOT Benefits Matrix Model, and the Redbook Wizard. (NCHRP, 2003)

It is pertinent to understand that green bridges may incur high initial construction cost as compared to conventional bridges. However, the overall agency cost of green bridges is at a lower end owing to less maintenance and long service life. This research study will provide a consistent methodology for efficiently evaluating agency costs for sustainable bridge construction projects and a cost comparison of High Performance Concrete (HPC) and Conventional Concrete (CC).

1.3 RESEARCH GOALS AND OBJECTIVES

The general intent of this research is to assist the bridge construction industry and professional bridge engineers in integrating sustainability in bridge design, construction, and maintenance. The specific objectives to be accomplished are to:

a. Summarize existing sustainability rating systems related specifically to green buildings, highways and bridges.

b. Develop a generic framework for green and sustainable bridge design, construction and maintenance.

c. Conduct surveys and interviews, and assign points/weights to all criteria of suggested framework using the Delphi Method.

d. Conduct LCCA of green bridges.

1.4 RESEARCH METHODOLOGY

The research study consists of four major objectives 1) Literature review, 2) development of sustainable framework, 3) conduct surveys using Delphi method and 4) life cycle cost analysis of green bridges. The methodology adopted to achieve these objectives is organized in the Figure 1-1. The text box on the right side describes the details and steps involved in each objective.

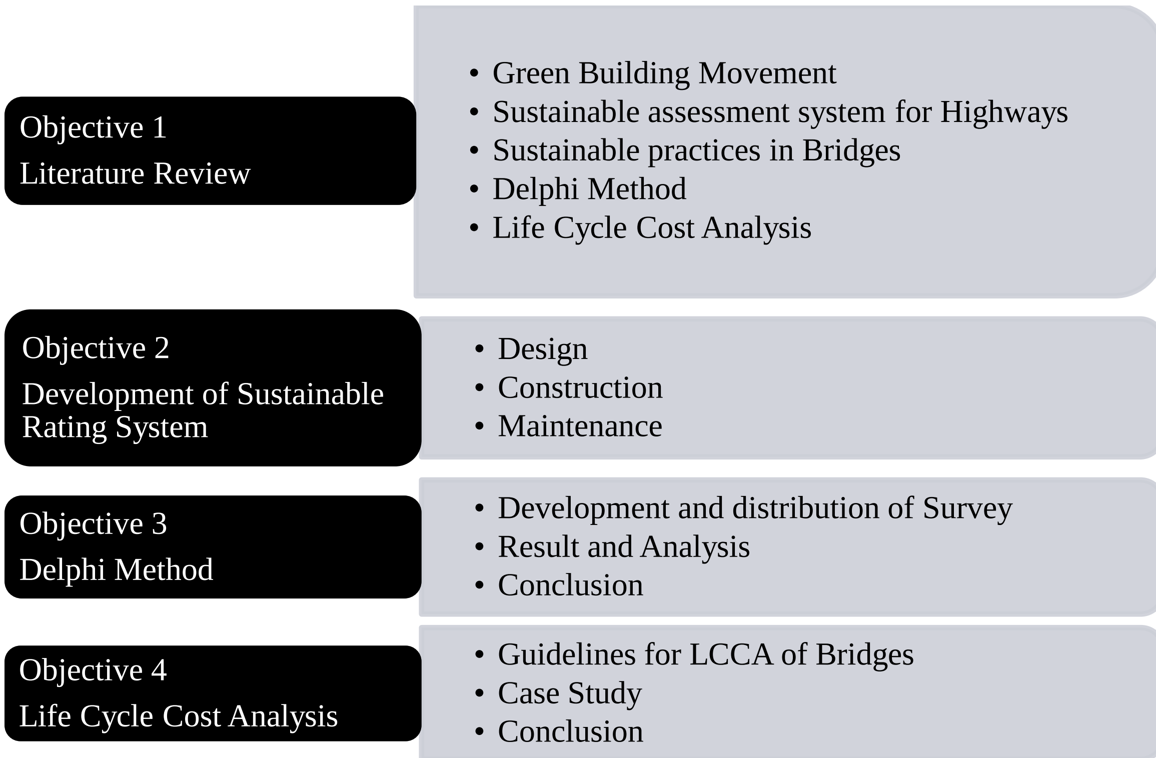

Figure 1-1 Flow Chart of Research Methodology

Objective – 1: Summarize existing sustainability rating systems related specifically to green buildings, highways and bridges.

To achieve this objective, first the U.S. Department of Transportation and Federal Highway Authority's (FHWA) sustainable construction practices and approaches were reviewed. The literature review includes analysis of USGBC's Leadership in Energy and Environmental Design (LEED®), New York State Department of Transportation's (NYSDOT) Leadership in Transportation and Environmental Sustainability (GreenLITES) Project Design Certification Program and US Department of Transportation's Sustainable Highways Self-Evaluation Tool. Finally, sustainable construction practices adopted by different transportation agencies are compiled.

Objective – 2: Develop a generic framework for green and sustainable bridge design, construction, and maintenance.

This objective mainly deals with the development of a framework for gauging sustainability in green bridges. The framework is divided into three parts; Design, Construction and Maintenance, as shown in Figure 1-2:

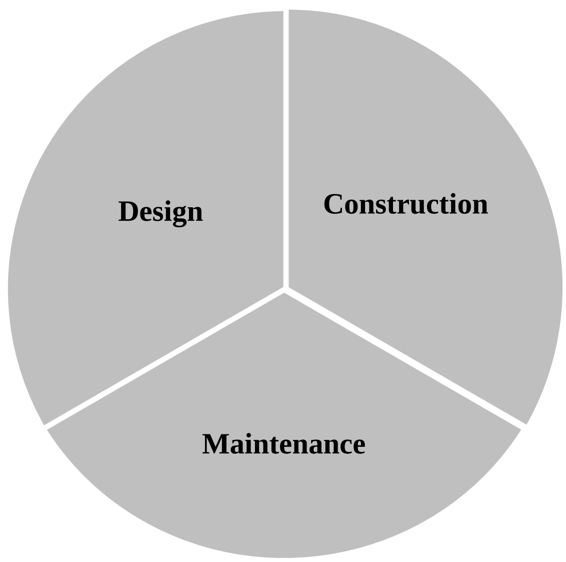

Figure 1-2 Main Categories in the Sustainability Framework

These three main categories are sub-divided into different criteria. The design category entails three sections, i.e. site, material, and other. Overall it contains a total number of 14 criteria. While, the construction category has 6 criteria and the maintenance category include 8 criteria. Figure 1-3 below lists the categories and criteria considered in the sustainable framework.

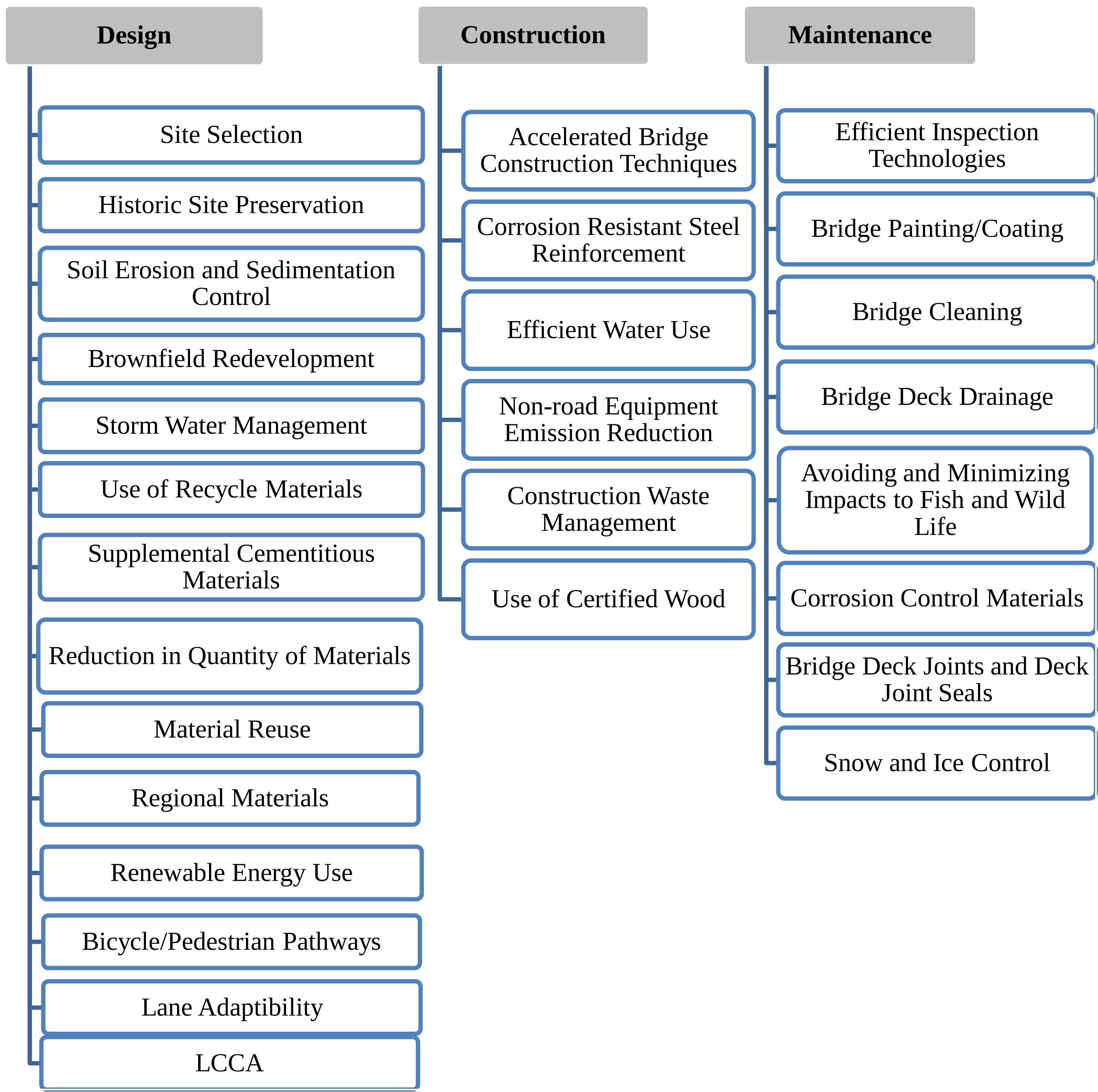

Figure 1-3 Layout of Sustainability Framework for Bridges "For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this dissertation."

Objective – 3: Conduct surveys and interviews, and assign points/weights to all criteria of suggested framework using Delphi Method

Here, literature related to Delphi was reviewed. The method is employed to collect responses of MDOT officials by means of designed surveys and interviews. The survey was developed and distributed among the participants from MDOT's design, construction, maintenance and environmental professionals and experts. It ran for two rounds and took approximately six weeks to develop consensus.

The result from the Delphi Method was used to assign weights to all categories and criteria developed in objective 2. Figure 1-4 explains the phase cycle in Delphi method.

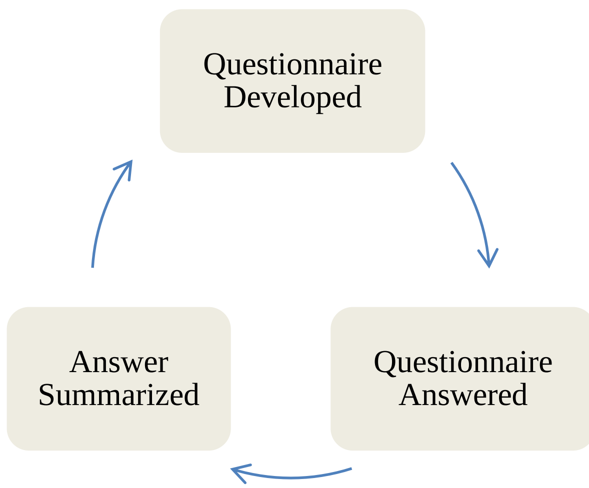

Figure 1-4 Phases in Delphi Method

Objective – 4: Conduct a life cycle cost analysis (LCCA) of green bridges

This objective focuses on conducting life cycle cost analysis (LCCA), a method for assessing the total life cycle cost of a bridge project. The purpose of LCCA is to estimate the overall costs of project alternatives and to help in suggesting the lowest cost and best performance alternative. This objective includes defining the LCCA for bridges, selection of accurate inputs, and the detailed method for conducting LCCA. Overall, this section discusses a consistent methodology for efficiently evaluating agency costs for sustainable bridge construction projects and a cost comparison of High Performance Concrete (HPC) and Conventional Concrete (CC).

This research concludes after assigning suitable weights to all criteria and will facilitate the bridge industry in building sustainable bridges.

1.5 RESEARCH LIMITATIONS

This section describes the research limitations considered in developing the thesis. It includes limitations involved in sustainability framework and LCCA of bridges. The following is the list of research limitations:

1. The research mainly focuses on the compilation of standards related to the design, construction and maintenance phase.
2. The terms “sustainable bridge” and “green bridge” are used interchangeably.
3. The sustainable bridge rating system is mainly developed only for the bridges in Michigan.
4. This study highlights environmental sustainability issues and mainly focuses on site, material, construction and maintenance related problems.
5. In Delphi survey, the overall response rate is 60% owing to limited numbers of bridge experts and professionals in MDOT.
6. In LCCA of green bridges, the research compares only the agency cost of two superstructures: one using Conventional Concrete Mix and the other using High

Performance Concrete mix in superstructure. The agency cost includes initial construction cost, repair, maintenance and disposal costs.

1.6 CHAPTER SUMMARY

This chapter outlines the research need, goals and objectives, methodology, limitations, and research contribution. LEED® is a standard rating system used for measuring sustainability in buildings, but the bridge construction industry lacks such specifications and standards. This research study is an effort to develop a rating system which can be used as a constructive tool to define and measure sustainable bridges. The research will also assist bridge engineers to build long lasting and cost effective bridges with a minimum impact on the environment.

CHAPTER 2 LITERATURE REVIEW

2.1 CHAPTER OVERVIEW

This Chapter deals with the literature review, which encompasses three main categories: sustainability concept, Delphi method and LCCA of bridges. Figure 2-1 illustrates the overall composition of the literature review.

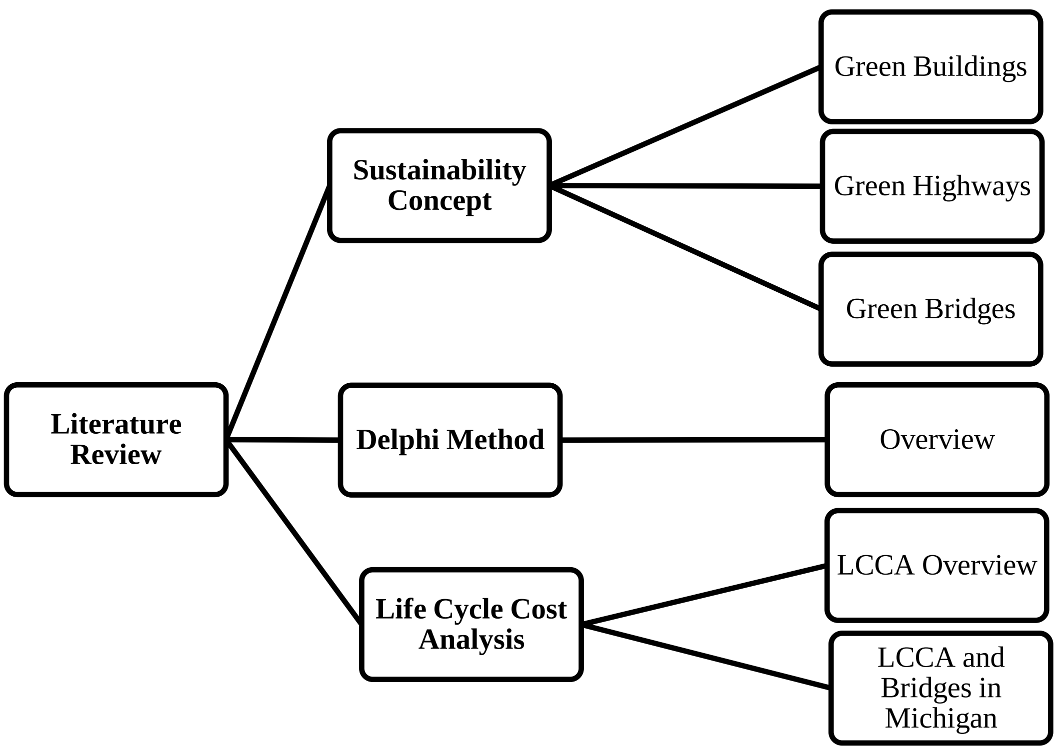

Figure 2-1 Systematic Diagram of Literature Review

The first category, sustainability concept, primarily comprise of study of sustainable buildings, highways and bridges. In Green Buildings, US Green Building Council's LEED® 2009 was thoroughly studied and credits related to bridges were analyzed. (USGBC, 2009) Green roads include the study of New York State Department of Transportation's (NYSDOT)

Green Leadership in Transportation, Environmental Sustainability (GreenLITES, 2008) Project Design Certification Program, Federal Highway Administration (FHWA), US Department of Transportation's Sustainable Highways Self-Evaluation Tool and different standards outlined by Centre for Environmental Excellence by American Association of State Highway and Transportation Officials (AASHTO, 2009). In addition, "Development of rating system for Sustainable bridges", various research papers, articles and journals on design, construction and maintenance of sustainable bridges, mentioned lately in the Chapter, were reviewed under Green Bridges.

The second category, Delphi method, presents an overview of application of Delphi technique to the research study, establishing minimum requirements for the participants and interpretation of response rate and analysis of data. The third category of review, LCCA of bridges, provides an overview of LCCA and bridges in Michigan. Several journal articles and publications on LCCA of pavements and bridges (mentioned in section 2.4) were reviewed.

2.2 SUSTAINABILITY CONCEPT

2.2.1 GREEN BUILDINGS AND LEED® 2009

Leadership in Energy and Environmental Design (LEED®, 2009) is a rating system for design, construction and operation of sustainable buildings. It was developed by US Green Building Council (USGBC) in 1998. This rating system was mainly developed to define and measure Green Buildings. USGBC developed five versions i.e. Version 1.0 in 1998, Version 2.0 in 2000, Version 2.1 in 2002, Version 2.2 in 2005 and Version 3.0 in 2009. LEED® version 3.0 is currently used for existing and new commercial, residential and institutional buildings. Since its inception in 1998, the USGBC has grown to encompass more than 24,662 projects in the United States and 30 countries covering over 1.627 billion square feet of development area

(USGBC, 2009) which shows the impact and wide recognition for LEED® in US and around the globe. At present, LEED® is the most adapting system in the United States that addresses all kind of the buildings and project types. More than 400 U.S. buildings have received LEED® ratings and more than 3400 buildings are registered and therefore potentially seeking certification. (Fowler, 2006)

The rating system is divided into six main categories with additional points awarded for innovation. These categories are based on energy consumption, location, environmental principles and material used. They are: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Indoor Environmental Quality, Material and Resources, and Innovation in design. These categories are further divided into various credits. Each credit has certain requirements, listing strategies to fulfill those requirements. The rating system has a total of 100 base points and four certification levels i.e., certified, silver, gold and platinum. It is important to mention here that this is the most updated version of LEED®, credit weights are calculated based on a life cycle analysis tool (TRACI), and additional regional priority points are taken into account. Certification levels defined under LEED® 2009, Version 3 are:

a) Certified 40 – 49 points;

b) Silver 50 – 59 points;

c) Gold 60 – 79 points;

d) Platinum 80 points and above.

Certain credits can be adopted from LEED® 2009 rating system to develop the rating system for bridges. The factors considered in analyzing the sustainability of buildings are materials, water, energy, location and indoor air quality while the critical factors that apply to bridges are location, materials, water and traffic impacts. Whittemore (2010) explained the equivalent goals for sustainable bridges by comparing them with the sustainable goals for buildings. The given analysis explained the useful metrics from LEED® 2009 that can be taken to define and measure sustainability in bridges. From these, some useful metrics can be extracted to define and measure sustainable bridges.

For example, when crediting for water use and quality, how the hydraulic openings will affect the upstream and downstream floodplains and what systems are in place, ensures that the consumption of the potable water is the least and the runoff from the structure is of the highest quality. Therefore, such requirements are to be established after reviewing the standards which ensures the optimum use of water and its quality (Whittemore, 2010). Likewise, certain other credits and prerequisites from LEED®, 2009 can also be adopted in the rating system for bridges. These are:

a) Construction activity pollution prevention
b) Site selection
c) Brownfield Redevelopment
d) Storm-water Management-Quantity Control
e) Storm-water Management-Quality Control
f) Recycled Content
g) Material Reuse
h) On-Site Renewable Energy
i) Regional Materials
j) Innovation in Design.

2.2.2 GREEN HIGHWAYS

NYSDOT GreenLITES Project Design Certification Program;

Green Leadership in Transportation and Environmental Sustainability (GreenLITES, 2008) is a rating system for transportation projects, developed by NYSDOT in September 2008. It basically measures project performance, identify sustainable practices and an appropriate certification level is awarded. The program focuses on improving safety and mobility, transportation sustainability, conserving energy and natural resources and preserving historic and scenic sites.

The main five categories in NYSDOT approach are based on the principles of energy consumption, location, environmental principles and material used. The categories are: Sustainable Sites, Water Quality, Material and Resources, Energy and Atmosphere, and Innovation/Unlisted.

The GreenLITES rating system awards points, shown in Table 2-1, on the basis of project design details and the project is rated according to its impact and contribution to the sustainable practices. After summing the score by incorporating sustainable practices into the project design, the following certification levels may be awarded:

a. Certified
b. Silver
c. Gold
d. Evergreen.

Table 2-1 - Distribution of points for the certification levels (GreenLITES, 2008)

Name	Point Range	Percentile Range	Approximate Std Dev Range	% of Dept Projects
Non-certified	0 – 14	< 33%	< -0.5σ	33%
Certified	15 – 29	33 – 67%	-0.5σ – 0.5σ	34%
Silver	30 – 44	67 – 90%	0.5σ – 1.5σ	23%
Gold	45 – 59	90 – 98%	1.5σ – 2.5σ	8%
Evergreen	60 & up	> 98%	> 2.5σ	2%

Currently, there is no certification program for the transportation project nationwide. This is the first step, taken by NYSDOT, to encourage sustainable practices in a project. The program is intended to provide guidelines for other Department of Transportation in integrating sustainability initiatives.

US Department of Transportation's Sustainable Highways Self-Evaluation Tool;

This sustainability evaluation tool is jointly developed by University of Washington and construction company CH2M HILL in October 2011. It has only one version i.e. Pilot test version. It includes three main categories, system planning and process criteria, project development criteria and operations and maintenance criteria. The pilot version contains a total number of 61 criteria: 16 criteria in system planning and process category, while 30 criteria in project development category and operation and maintenance category entails 15 criteria.

The vital goal of developing this tool is to assist transportation agencies in incorporating sustainability techniques into highway projects. In addition, it offers an approach to evaluate different kind of transportation projects. The tool has two scorecards for evaluation of a project: basic scorecard and extended scorecard. The basic scorecard gauges sustainability in small reconstruction/bridge replacement, preservation and restoration projects. It offers 20 sustainability practice criteria for consideration in a project. On the other hand, extended scorecard mainly focuses on new construction and major reconstruction projects. It has a total of 30 sustainability practice criteria, 20 same criteria as the basic scorecard with an additional 10 sustainability practice criteria.

Several sustainability criteria for transportation projects can also be related to bridge projects like storm water, LCCA, recycle and reuse material, construction waste management. These formerly mentioned criteria are almost similar in all sustainable rating systems except the criteria snow and ice control, which adds uniqueness to this assessment systems. This self evaluation tool can also be referred as a sustainability standard to develop a rating system specifically for green bridges.

Center for Environmental Excellence by AASHTO;

The main focus of Center for Environmental Excellence is to promote responsible planning in construction projects, efficient management of resources and encourage innovative ways to simplify the transportation delivery process. It was developed with the assistance of Federal Highway Administration (FHWA). The Center is classified into four sections: Environmental topics, the centre, research and resources. The environmental topics provides information on air quality, environmental considerations in Planning, Environmental Enhancements, Environmental Management Systems, Historic Preservation/Cultural Resources, Sustainability, Waste Management/Recycling/Brownfields and Water Quality. The Center has developed a manual on environmental issues and construction maintenance practices involved in transportation projects. The manual includes ten chapters and an appendix.

The second chapter (Organizational Environmental Stewardship Practices) discusses DOT environmental policies, mission statement, standards and performance measures. It also highlights special practices and approaches through which sustainability can be integrated in transportation projects.

The seventh chapter, Bridge Maintenance, focuses on bridge maintenance activities like repairing bent or damaged steel beams, cracked or spalled concrete, damaged expansion joints, and bent or damaged railings. The other useful sections related to the bridge operations in this chapter are preventative bridge maintenance practices, life cycle decision making and accounting for ecological risks, maintaining drainage from bridge decks and bridge cleaning. The chapter identifies best practices in bridge preventative maintenance, highlighting:

1. Penn DOT's program,
2. Over 40 State DOTs using the Bridge Rating and Analysis of Structural Systems (BRASS) software suite,
3. Connecticut DOT using electronic monitoring systems to check the condition of the bridges. The sensors provide information on structural integrity and wear, and contribute to bridge life and stress assessment data.

The environmental section of manual, as discussed earlier, provided guiding principles in developing criteria in maintenance category like bridge cleaning, bridge painting and coating and bridge deck drainage.

2.2.3 GREEN BRIDGES

The following research papers, articles and journals provided significant literature on green bridges. These are Hunt (2005), Ralls (2007), Whittemore (2010), Environmental Protection Agency (EPA, 2007), Lob (2010), Lwin (2010) and Horsley (2009). These research articles and papers will be referred repeatedly in the next chapter i.e. Framework for achieving sustainability in bridge design, construction and maintenance.

2.3 DELPHI METHOD

This section presents an overview of Delphi method, its application to current research study and a brief methodology. Also, discussed are some of the publications related to the Delphi.

2.3.1 Overview

The idea of Delphi method was originally conceived by Professor Kaplan, an associate professor at University of California, Los Angeles, working for the RAND Corporation. The method based on structured surveys conducted from the participants, which are mainly professionals and experts. The process is repeated over several rounds, till the time consensus is established. After the culmination of each round, feedback is provided to the participants. The participants in the next round with the results of the previous round can either revise the original assessments or they can stick to their previous opinion. The survey is done anonymously using a questionnaire.

Figure 2-2 shows the overview of the Delphi method employed for this research study.

Figure 2-2 Delphi Process

Overall, the author considered various Delphi studies either published in journals or available online. These are Miller (2006), Mary K (2000), Hallowell (2010), Skulmoski (2007), Gohdes (2004), and McGeary (2009). Hallowell (2010) elucidates use of Delphi technique in construction engineering and management and set several guidelines for implementation of such research method. It also talks about the selection of participants and minimum requirements desirable for the participants and experts to undertake the survey. This method is particularly used in construction engineering and management to obtain experts opinion, particularly when experimental research is unrealistic or there is a lack of empirical evidence (Hallowell, 2010). All other the studies used Delphi approach to obtain quantitative results. Chapter 4 of the thesis will further highlight the methodology adopted for this research study.

2.4 LCCA OF BRIDGES

This section entails an overview of life cycle cost analysis and a brief discussion on bridges in Michigan.

2.4.1 LCCA Overview

LCCA is "an engineering economic analysis tool useful in comparing the relative merit of competing project implementation alternatives" (FHWA, 2002). It helps the transportation agencies to consider the different alternative's cost incurred during the service life of a project and opt for the best performance option with the lowest cost. For example, LCCA will help finding out whether the use of high-performance concrete in a bridge project, which may add to the initial cost but result in reduced maintenance cost, is cost-effective or not.

These guidelines for conducting LCCA of sustainable bridges will emphasize the importance of consider not only the initial costs in planning, design and construction of a bridge but also long-term costs, including operation, repair and maintenance etc. This thesis includes defining LCCA for bridges, estimating the accurate input parameters, generic approach for conducting LCCA. A review of the available and significant LCCA models is presented as well. Towards the end, the report discusses the case studies on the application of LCCA in deciding the best alternative for a project.

2.4.2 LCCA and Bridges in Michigan

Michigan Department of Transportation (MDOT) has dynamically been involved in pursuing sustainable techniques in most of its projects and has an impressive record of designing and constructing sustainable bridges. In Michigan, the state enacted PA 79, a bill that mandates the MDOT to use LCCA for all pavements projects greater than $1 million (MDOT, 2000). Furthermore, to improve the cost-effectiveness of its new/ rehabilitation/ replacement projects, MDOT needs to invest in the lowest cost alternative and the sustainable bridge design with extended service life. Chapter 5 summarizes a thorough research that establishes guidelines for conducting LCCA on bridges in Michigan.

2.5 CHAPTER SUMMARY

The chapter summarizes the research in three main categories i.e. sustainability concept, Delphi method and LCCA of bridges. After successful development of a rating system for green buildings i.e. LEED® 2009, transportation agencies are also making their ways in integrating sustainability in roadway and bridge design projects. The bridge industry is making a significant advancement in this area and until now, various DOTs have already included sustainable practices in their design, construction and maintenance phases.

CHAPTER 3 FRAMEWORK FOR ASSESSING SUSTAINABILITY IN BRIDGE DESIGN, CONSTRUCTION AND MAINTENANCE

3.1 FRAMEWORK OVERVIEW

Based on the detailed content analysis discussed in the previous chapters, the framework is divided into three sections: 1) Design, 2) Construction, and 3) Maintenance. The design section entails site, materials and others while construction section is based on construction techniques, water use, renewable energy, construction waste, and fuel efficiency. The maintenance section highlights sustainability issues in bridge painting, cleaning, drainage and impacts on aquatic and wildlife. This thesis discusses the design section in depth while more details on the construction and maintenance sections are given by Gangwal (2012), which describes the complementary components of the MDOT research project entitled 'Implementation of Sustainable and Green Design and Construction Practices for Bridges' (MDOT, 2012).

The description, intent, requirements and standards have been established for each criterion by consulting various references such as American Association of State Highway and Transportation Officials (AASHTO), American Standard for Testing Materials (ASTM), Environmental Protection Agency (EPA), LEED®, 2009 and MDOT's 2012 Standard Specification for Construction.

Table 3-1 summarizes the overall sustainability framework and shows the intent of each credit. In order to be comprehensive, all credits are listed.

Table 3-1– Overall Framework for Assessing Sustainability in Bridge

DESIGN		
Criteria	**Criteria Name**	**Intent**
Criteria 1.1.1	Site Selection	To select sites that does not have impacts on the environment due to the location.
Criteria 1.1.2	Historic Site Preservation	To avoid development of historic sites and reduce the socio-cultural environmental impact from the location of a bridge on a site.
Criteria 1.1.3	Soil Erosion & Sedimentation Control	To reduce pollution such as soil erosion that may be due to wind or water, sedimentation and dust and particulate matter generation during construction activities.
Criteria 1.1.4	Brownfield Redevelopment	To rehabilitate contaminated sites and reduce pressure on undeveloped land.
Criteria 1.1.5	Storm-Water Management	To reduce the quantity of pollution and run-off from storm-water that is discharged into surface waterways or storm-sewers.
Criteria 1.2.1	Use of Recycle Materials	To increase the demand for materials that incorporate recycled materials, thereby reducing environmental impacts resulting from extraction and processing of virgin materials.
Criteria 1.2.2	Supplemental Cementitious Materials	To replace a certain percentage of Portland cement used in concrete mixes.
Criteria 1.2.3	Reduction in Quantity of Materials	To reduce the amount of material, used in the construction of bridges by using innovative civil engineering techniques.
Criteria 1.2.4	Material Reuse	To reuse bridge materials and attachments to reduce demand for virgin materials and reduce waste
Criteria 1.2.5	Regional Materials	To increase demands for materials and products that are extracted and manufactured within the region.
Criteria 1.3.1	Renewable Energy Use	To reduce the electrical consumption and promote the use of renewable energy technologies.
Criteria 1.3.2	Bicycle/ Pedestrian Pathways	To promote the use of alternative transportation through bicycling and walking and thus minimize pollution and energy demand.
Criteria 1.3.3	Lane Adaptability	To provide a framework for additional lanes for any unforeseen conditions.
Criteria 1.3.4	Life Cycle Cost Analysis	To estimate the overall cost of the project alternatives.

Table 3-1 (Cont'd)

	CONSTRUCTION	
Criteria 2.1	Accelerated Bridge Construction Techniques	To open a cost-effective, long-lasting bridge to traffic with increased safety and reduced traffic disruption in a shortened construction period
Criteria 2.2	Corrosion resistant steel reinforcement	To prevent bridge reinforcement from corrosion by penetration of chloride thus preventing the bridge from early deterioration and extending the service life of the bridge.
Criteria 2.3	Efficient Water Use	To conserve water through efficient use during bridge construction.
Criteria 2.4	Non-road equipment emission reduction	To use fuel-efficient vehicles throughout the construction process, thus reducing the energy demands and carbon emission.
Criteria 2.5	Construction Waste Management	To divert waste generated in construction and demolition from disposal and in landfills and incineration
Criteria 2.6	Use of Certified Wood	To encourage best forest management practices
	MAINTENANCE	
Criteria 3.1	Efficient Inspection Technologies	To use efficient inspection technologies and processes for proper maintenance action decision thus enhancing the service life and reducing life cycle cost of the bridges.
Criteria 3.2	Bridge Painting/Coating	To prevent bridge components from deterioration due to corrosion thus increasing the age of bridges.
Criteria 3.3	Bridge Cleaning	To clean components of bridges vulnerable to dirt, bird drop accumulation etc. thus increasing efficiency of the bridge components and lessen maintenance requirements.
Criteria 3.4	Bridge Deck Drainage	To avoid impacts on the deck structure and reinforcing bars due to inefficient drainage.
Criteria 3.5	Avoiding and Minimizing Impacts to Fish and Wild Life	To avoid impacts on fish and wild life due to maintenance activities.
Criteria 3.6	Corrosion Control Materials	To prevent or minimize the corrosion of bridge elements due to the penetration of sodium chloride.
Criteria 3.7	Bridge Deck Joints and Deck Joint Seals	To eliminate bridge deck joints, when possible.
Criteria 3.8	Snow and Ice Control	To implement snow and ice control techniques and to reduce the environmental impacts

3.2 FRAMEWORK

An extensive content analysis of MDOT's current practices as well as existing sustainability and bridge related sources was carried out to develop the framework. After going through a significant research session by consulting different journals, articles, books and websites, MDOT's design and construction manuals, New York State Department of Transportation (NYSDOT) Leadership In Transportation and Environmental Sustainability Project Design Certification Program (NYSDOT, 2008), LEED®, 2009, Sustainable Highways Self-Evaluation Tool (FHWA, 2012) and a master's thesis on "development of a rating system for sustainable bridges" provided significant guidance in selecting and defining categories and credits for the sustainability framework.

3.3 DESIGN SECTION

The design category focuses on measures that can be taken during the design of bridges. Creating plans and employing methods in the design that result in achieving sustainability will be the intent of this category. The design principles will be consistent with MDOT policy and standards. MDOT has already been practicing several sustainable techniques and has incorporated these criteria in their design strategies, which are environmentally responsible.

The design section is divided into sites, materials and other which are further subdivided into various criteria. Guidance is given under each criteria for assigning points to the particular category. The Table 3-2 summarizes design categories in sustainability framework and shows intent, standards and references of each credit.

Table 3-2 - Categories in Design Section

Criteria	Title	Standards	Reference
		Site	
1.1.1	Site Selection	Appendix M of Construction General Permit of US department of Environmental Protection Agency (EPA). Appendix D of EPA's Construction general permit.	EPA, 2011, "Environmental Protection Agency" Hunt, L.R. (2005), "Development of Rating System for Sustainable Bridges" MS Thesis, Massachusetts Institute of Technology, MA. LEED®, 2009, "Leadership in Energy and Environmental Design" LEED® pp. 17, Washington DC.
1.1.2	Historic Site Preservation	Section 106 of the National Historic Preservation Act. State Historic Preservation Office (SHPO). 2311 Cultural Resources Survey, P/PMS Task Manual MDOT.	Hunt, L.R. (2005), "Development of Rating System for Sustainable Bridges" MS Thesis, pp.16, Massachusetts Institute of Technology, MA. MDOT, 2012, 2311, Cultural Resources Survey, P/PMS task manual pp. 70
1.1.3	Soil Erosion and Sedimentati on Control	Principles of Runoff Control for Roads, Highways, and Bridges; Erosion, Sediment and Runoff Control for Roads and Highways, Environmental Protection Agency (EPA); Part 1.1.2: Soil Erosion and Sedimentation Control, Chapter 9, Storm-water Best Management Practices (BMP's). Michigan Department of Environmental Quality (MDEQ).	LEED®, 2009, "Leadership in Energy and Environmental Design" LEED® Reference Guide for Green Building Design and Construction, 2009 Edition, Washington DC. World Health Organization (WHO), 1999. "Hazard Prevention and Control in the Work Environment: Airborne Dust". EPA, 2011, "Environmental Protection Agency"

Table 3-2 (Cont'd)

1.1.4	Brownfield Redevelopment	Section 2.4, Contamination Investigation (2800 Series), P/PMS Task Manual, MDOT. EPA 2011, Environmental Protection Agency, Brownfield Sites, Region 4: Land Revitalization and Reuse.	MDOT, 2012. Contamination Investigation (2800 Series), P/PMS Task Manual, pp. 129, MDOT. EPA 2011, Environmental Protection Agency, Brownfield Sites, Region 4: Land Revitalization and Reuse.
1.1.5	Storm-Water Management	Soil Erosion and Sedimentation Control Manual, MDOT. Part 1.1.2: Soil Erosion and Sedimentation Control, Chapter 9, Storm-water Best Management Practices (BMP's). Michigan Department of Environmental Quality (MDEQ).	EPA 2007, U.S. Environmental Protection Agency. Reducing Storm-water Costs through Low Impact Development (LID) Strategies and Practices. 2007. MDOT, Michigan Department of Transportation, 2006. "Chapter 9-Storm-water best management practices", pp. 3-13, MDOT drainage manual
		Material	
1.2.1	Use of Recycled Materials	Section 3.12.3 "General Recommendations for DOTs with Regard to Recycling and Waste Management" of Chapter 3 "Designing for Environmental Stewardship in Construction & Maintenance" 3.12.3	Center for Environmental Excellence by the American Association of State Highway and Transportation Officials. http://environment.transportation.org/environmental_issues/construct_maint_prac/compendium/manual/3_12.aspx. Recycled Materials Resource Center, "Summary of FHWA International Technology Scanning Program for Recycled Materials Use in Highway Environments. http://ntl.bts.gov/DOCS/handbook.html.

Table 3-2 (Cont'd)

1.2.2	Supplemental Cementitious Materials	Section 3.12.3 "General recommendation for DOT with regard to recycling and waste management" of chapter 3 "Designing for environmental stewardship in construction and maintenance" 3.12.3. See fly ash section 7.01	MDOT, 2003, "Standard Specification for Construction", http://mdotwas1.mdot.state.mi.us/public/specbook/ accessed on Jun 22, 2012. Balogh, 2012, "High Reactivity Metakaolin (HRM)", http://www2.basf.us/functional_polymers/kaolin/pdfs/1high_reactivity_Metakaolin.pdf, pp. 1-2, accessed on June 22, 2012.
1.2.3	Reduction in Quantity of Materials	Hunt, L.R. (2005), "Development of Rating System for Sustainable Bridges" MS Thesis, Massachusetts Institute of Technology, MA.	Hunt, L.R. (2005), "Development of Rating System for Sustainable Bridges" MS Thesis,pp.21, Massachusetts Institute of Technology, MA.
1.2.4	Material Reuse	Section 5.7.14 "Aluminum Sign Recycling and Chromate Coating Elimination" and Section 5.7.3 Recycled Concrete Material/Aggregate (RCM/RCA) of Chapter 5 "Pavement, Materials, and Recycling".	Center for Environmental Excellence by the American Association of State Highway and Transportation Officials (AASHTO) 2009.
1.2.5	Regional Materials	Material and Resource Credit 5 of LEED® 2009.	LEED®, 2009, "Leadership in Energy and Environmental Design" LEED® Reference Guide for Green Building Design and Construction, 2009 Edition, pp. 380-385, Washington DC.

Table 3-2 (Cont'd)

		Others	
1.3.1	Renewable Energy Use	ANSI/ ASHRAE/ IESNA Standard 90.1-2007 (Exterior Lighting).	Green Leadership In Transportation and Environmental Sustainability. (GreenLITES) Project Design Certification Program September 2008.
1.3.2	Bicycle/ Pedestrian Pathways	Bicycle and Pedestrian Legislation in Title 23 United states Code (U.S.C), Office of Planning, Environment and Reality (HEP), FHWA.	FHWA, Federal Highway Administration, Bicycle and Pedestrian Provisions of the Federal-aid Program, http://www.fhwa.dot.gov/environment/bikeped/bp-broch.htm, accessed on Jan 05, 2012. LEED®, 2009, "Leadership in Energy and Environmental Design" LEED® Reference Guide for Green Building Design and Construction, 2009 Edition, Washington DC. FHWA, Federal Highway Administration, 2012. "Bicycle and Pedestrian Legislation in Title 23 United States Code (U.S.C.)", Bicycle and Pedestrian Program, www.fhwa.dot.gov/environment/bicycle_pedestrian/legislation/sec217.cfm
1.3.3	Lane Adaptability	High-Performance Materials for Substructures, Foundations, and Earth Retaining Systems Workshop, Bridge and Structures Research and Development (R&D), Federal Highway Administration Research and Technology, FHWA, Publication Number: FHWA-HRT-08-058, February 2009.	Hunt, L.R. (2005), "Development of Rating System for Sustainable Bridges" MS Thesis, pp.17, Massachusetts Institute of technology, MA.

Table 3-2 (Cont'd)

1.3.4	Life Cycle Cost Analysis	NCHRP, National Cooperative Highway Research Program, 2003. "Bridge Life Cycle Cost Analysis Report 483".	NCHRP, National Cooperative Highway Research Program, 2003. "Bridge Life Cycle Cost Analysis Report 483", Washington DC. Fuller S., 2010. "Life Cycle Cost Analysis", Whole Building Design Guide, National Institute of Standards and Technology (NIST).

Category 1.1 - Site

Criteria 1.1.1 Site Selection (6 points)

Description:

Site selection plays a vital role towards sustainability. Preference should be given to already develop sites, as further environmental damage is limited due to lesser construction activities. Selecting the site wisely preserve natural habitats; avoids encroachment of sites on water bodies and agricultural lands.

Intent:

The objective of this criterion is to select sites that do not have impacts on the environment due to the location.

Requirements:

a) Try to avoid sites, which are identified as habitats of any species on federal or state threatened endangered lists. The criteria can be found in Appendix D of EPA's construction general permit (USGBC, 2009).

b) Try to avoid placing footings and piers in water bodies to minimize environmental impacts. Consider choosing sites where crossing distance is minimum (Hunt, 2004).

c) In case of bridges over the road, try to avoid placing footings within 50 feet of any water body such as seas, lakes, rivers and streams which could support aquatic life, recreational or industrial use, consistent with the terminology of the clean water act (USGBC, 2009). Also, avoid constructing or developing sites within 100 feet of the wetlands as defined in

Appendix M of construction general permit of Environmental Protection Agency (EPA) (EPA, 2011).

d) Reconstructing a bridge at the same location of the bridge being replaced, rather than relocating it and having more environmental impacts at a new location might be a consideration for points.

Points Criteria:

- 3 points for meeting any two requirements.
- 6 points for meeting all the requirements.

Standard/Resource:

- Appendix M of Construction General Permit of Environmental Protection Agency (EPA)
- Appendix D of EPA's Construction general permit.

Criteria 1.1.2: Historic Site Preservation (3 Points)

Description:

Historic sites and/or structures give a sense of pride and are significant for a nation. This section encourages preserving and conserving sites, structures of any historical significance. The main purpose is to avoid any potential harm or damages to historic sites and/or structures.

Intent:

The objective of this credit is to avoid development of historic sites and reduce the socio-cultural environmental impact from the location of a bridge on a site.

Requirements:

a) Show in documents the project team does not demolish any historical bridge as defined by section 106 of the National Historic Preservation Act.

b) The identification of cultural resources is required for compliance with the National Environmental Policy Act (NEPA), Section 106 of the National Historic Preservation Act (Section 106), and Section 4(f) of the 1966 Department of Transportation Act (Section 4(f)) (MDOT, 2012).

c) Section 106 of the National Historic Preservation Act primarily describes about the four steps which are Initiation of the Section, Identification of Historic properties, Assess Adverse Effects and Resolving Adverse Effects and Implementation. If the bridge structure is being built on a historic site or spans over a historic site, improvements should be made to the facilities and/ or access to the site (Hunt, 2004).

Points Criteria:

- 3 points for meeting the above requirement.

Standard/Resource:

- Section 106 of the National Historic Preservation Act
- State Historic Preservation Office (SHPO)
- 2311 Cultural Resources Survey, P/PMS task manual, MDOT

Criteria 1.1.3: Soil Erosion and Sedimentation Control (6 Points)

Description:

"Erosion of soil due to wind or water is one of the major sources of environmental problems. Erosion is a process or combination of processes in which the earth materials are loosened or transported by natural agents such as wind or water. Soil is a valuable resource for the plant growth and it maintains biodiversity. Loss of soil may lead to water quality issues and inhibits biodiversity. Sedimentation is the deposits of soil particles or other pollutants in storm-sewers or adjacent water resources. If affects the flow capacity of the stream channels and increase turbidity levels. Turbidity reduces sunlight penetration in water, which reduces photosynthesis, which in turn affects aquatic vegetation and decrease oxygen levels" (USGBC, 2009). Air-borne dust generation is another major environmental problem, which may lead to many human health problems. Construction activities may result in air-borne contaminants, which may be in gaseous forms, which includes, dust, mists, smoke and fumes. It may lead to widespread lung diseases such as pneumoconiosis (WHO, 2011).

Intent:

The objective of this credit is to reduce pollution such as soil erosion which may be due to wind or water, sedimentation and dust and particulate matter generation during construction activities.

Requirements:

a) Develop a comprehensive erosion and sedimentation control (ESC) plan prior to earth activities. Show ESC requirements in specifications, drawings and cost estimates for bridge projects.

b) Apply ESC practices to prevent excessive on-site damage.

c) Develop a schedule and implement inspection and maintenance program.

d) Follow the Best Management Practices (BMP's) mentioned in Principles of Runoff Control for Roads, Highways, and Bridges; Erosion, Sediment and Runoff Control for Roads and Highways, Environmental Protection Agency (EPA)to control the addition of pollutants to coastal waters and erosion and runoff control for bridges.

Points Criteria:

- 6 points for meeting all of the above requirements.

Standards/Resources:

- Principles of Runoff Control for Roads, Highways, and Bridges; Erosion, Sediment and Runoff Control for Roads and Highways, Environmental Protection Agency;
- Part 1.1.2: Soil Erosion and Sedimentation Control, Chapter 9, Storm-water Best Management Practices (BMP's)
- Michigan Department of Environmental Quality (MDEQ)

Criteria 1.1.4: Brownfield Redevelopment (2 points)

Description:

The sites, which have been abandoned due to contamination from previous activities, are called as brownfield sites. They can be redeveloped or reused once cleaned up. Redeveloping brownfield sites may avoid environmental and health problems and reduce pressure on undeveloped lands. It is estimated that there are more than 450,000 brownfield sites in the United States (EPA, 2011).

Intent:

The objective of this credit is to rehabilitate contaminated sites and to reduce pressure on undeveloped land.

Requirements:

a) Conduct project area contamination survey to identify and analyze environmental contamination information and take appropriate action accordingly to protect workers health, safety and rehabilitate damaged sites thus reducing pressure on undeveloped land. "This task is performed for all jobs entailing sub-grade work or work outside of existing shoulders (any earth work/disturbance). This also applies to work on or near asbestos covered utilities; bridges having lead based paint, demolition projects, and includes all classes of projects that require subsurface, environmental or soils testing" (MDOT, 2009).

b) Conduct preliminary site investigations (PMI) according to part 2820 of section 2.4, Contamination Investigation, P/PMS task manual, MDOT.

Points Criteria:

- 2 points for meeting all of the above requirements.

Standard/Resource:

- Section 2.4, Contamination Investigation (2800 Series), P/PMS task manual, MDOT
- EPA 2011, Environmental Protection Agency, Brownfield Sites, Region 4: Land Revitalization and Reuse

Criteria 1.1.5: Storm-Water Management (5 Points)

Description:

Storm-water originates during precipitation. It is important to control the quantity of runoff water to reduce burden on municipal streams. Storm-water is also a major source of pollution for all types of water bodies in United States (EPA, 2007). The pollution may include sediments, pesticides, oil and grease, metals, other chemicals etc. The water from precipitation, if does not infiltrate into the ground take the form of surface runoff and then, it includes contaminants from the surface and finally mixes into storm-sewers or adjacent water resources. Storm-water may not be able to infiltrate to the ground due to greater imperviousness of the site or unavailable water retention and treatment techniques. Effective on-site management practices let storm-water infiltrate the ground, thereby reducing the volume and intensity of storm-water flows. Additionally, reducing storm-water runoff helps maintain the natural aquifer recharge cycle and restore depleted stream base flows. Managing Storm-water on site may help in lowering the storm-water fees. It is important to consider storm-water management plans early in the design phase for minimizing economic costs.

Intent:

The objective of this credit is to reduce the quantity of pollution and run-off from storm-water that is discharged into surface waterways or storm-sewers.

Requirements:

a) Implement a Storm-water Management Plan (SWMP), which will include a description of plans to accomplish illicit discharge elimination, public education, and storm-water pollution prevention to meet the requirements of National Pollutant Discharge Elimination System (NPDES) issued by Michigan Department of Environmental Quality (MDEQ) (MDOT, 2012).

b) Follow the MDOT-Approved Best Management Practices (BMP's) which can be used on MDOT projects. These BMPs can be taken from the Soil Erosion and Sedimentation Control (SESC) Manual and the MDOT Storm-Water Management Plan (SWMP). Table 9-1 of chapter 9 of MDOT drainage manual provides a list of MDOT-Approved BMP practices and section 9.4.2.2 gives the description of MDOT-Approved BMP practices.

Points Criteria:

- 2 points for meeting the minimum requirements.

Standard/Resource:

- Michigan Department of Environmental Quality (MDEQ)
- Chapter 9, Storm-water Best Management Practices, MDOT Drainage Manual
- MDOT Soil Erosion and Sedimentation Control Manual

Category 1.2- Materials

Description:

The environmental impact of materials brought into the bridge project and disposal of materials that leave the bridge project are the two main concerning issues. Using recycled materials, regional materials, reducing the quantity of materials and reusing materials will help in minimizing environmental impacts associated with material use. Therefore, following measures are suggested to minimize environmental impacts associated with materials selection, waste disposal and waste generation:

a) Selecting sustainable materials;

b) Practicing waste reduction;

c) Reusing and Recycling.

Material Criteria Characteristics

The Table 3-3 shows metrics for materials and can be used to decide the compliance with each credit, based on weight, volume or cost, and materials that should be included and excluded in the calculations. Materials that are blacked out in the table are excluded from the corresponding credit calculations. The divisions in the left most column of the below table shows materials concrete, metal, deck and deck systems, foundations etc. These are associated with material used in the bridges. The materials column AASHTO LRFD bridge design specifications are used to determine the divisions of materials, which are shown in the first column. The format of the table is extracted from LEED 2009.

Table 3-3 - Matrix for Calculating Material Requirements for Achieving Sustainability

(USGBC, 2009)

Material	**Use of Recycle Materials**	**Material Reuse**	**Regional Material**	**Reduction in Quantity of Material**	**Construction Waste management**
	Based on cost of qualifying materials as % of overall material cost	Based on replacement value($)	Based on cost of qualifying materials as % of overall material cost	Based on weight or volume	Based on weight or volume
Concrete					
Metal Deck and Deck System					
Foundations Abutments, Piers and Walls					
Railings					
Joints and Bearings					

Credit 1.2.1: Use of Recycled Materials (5 Points)

Description:

Recycling means reuse of waste material into the production process. The use of recycled materials saves resources and primary raw material, reduces air and water pollution, and extends limited landfill life. Recycled materials can also save financial resources through lower material costs and lower disposal costs or tipping fees. In some cases, using recycled products can improve material performance as well. Consequently, using recycled materials is a key aspect of more efficient and environmentally sensitive highway design and construction (AASHTO, 2009).

Intent:

The objective is to increase the demand for the materials that incorporate recycled content, thereby reducing impacts resulting from extraction and processing of virgin materials.

Requirements:

a) Include a recycling strategy in the sustainability aspect of strategic plans and long range research priorities;
b) Create a framework to consider the use of recycled materials in project planning, alternatives analysis, and mitigation analysis;
c) Encourage long term materials supply plans and recycled materials availability plans;
d) Develop clear engineering and environmental guidelines at the State and Federal level that are available for suppliers and decision-makers;
e) Develop courses on recycling;

f) Evaluate contractors with respect to use of recycled materials or environmental protection during contract performance reviews;

g) Develop and implement the use of warranty and performance based specifications.

Steel is the most recycled material in the world. At the end of their useful life, about 88% of all steel products and nearly 100% of structural steel beams and plates used in construction are recycled into new products (AISC, 2009).

There are several recyclable materials such as fly ash, slag cement and silica fume that can partially be substituted for Portland cement. See criteria 1.2.2 for a list of usable materials.

Points Criteria:

Points will be awarded based on the percentage of recycled materials used on the project. The percentage of recycled materials used on the project is calculated based on cost.

% recycled materials = (Total cost of recycled materials/Total cost of all materials) X 100

The points will be awarded based on the below criteria:

Table 3-4 - Points Distribution Table for Recycled Material Percentages

% Recycled Materials Used	Points
10	2
20	5

Standard/Resource:

- Section 3.12.3 "General Recommendations for DOTs with Regard to Recycling and Waste Management" of Chapter 3 "Designing for Environmental Stewardship in Construction & Maintenance" 3.12.3.

Criteria 1.2.2: Supplemental Cementitious Materials (3 Points)

Description:

There are several supplemental cementitious materials (SCM) that can be used to replace a percentage of the Portland cement used in concrete mixes.

Using a supplemental material such as fly ash or silica fume will result in an overall reduction of materials used. Fly ash is finely divided residue resulting from the combustion of ground or powdered coal. Use of fly ash in concrete started in the United States in the early 1930's. Currently, MDOT only allows a maximum substitution of 15 percent. Slag cement is a cementitious material and can be substituted for cement on a 1:1 basis. Section 701.3 of MDOT's 2003 Standard Specifications for Construction indicates that substitution rates of up to 40 percent are acceptable for concretes exposed to deicing chemicals. If fly ash and slag cement are used in the same mix, up to 40% of the Portland cement can be substituted but the fly ash portion cannot exceed 15% (MDOT, 2003).

Silica fume can be used to make a turnery cementitious blend High Reactivity Metakaolin (HRM) (Balogh, 1995) is a refined form of ASTM C618 Class N pozollan that enhances the performance characteristics of many cement-based mortars, concretes and related products.

Intent:

To reduce the embodied energy associated with the cement by replacing a part of it with supplemental cementitious materials.

Requirements:

a) Replace a portion of the Portland cement with fly ash, silica fume, slag cement, or HRM up to the set maximum.

b) An alternative material may be used if testing is submitted that shows the proposed mix design complies with ASTM 1077 and will reach the required compressive strength for the project.

Points Criteria:

Calculate the quantity of supplemental cementitious materials (which will be used to replace a portion of the cement) as a percentage of total quantity of cement. Points will be awarded if minimum specified percentage of SCM is used.

The points will be awarded only if below criteria is met.

Table 3-5 - Point Distribution for SCMs with Percentages

% SCM	Points
5	1
10	2
15	3

Standards/Resources:

- Section 3.12.3 "General Recommendations for DOTs with Regard to Recycling and Waste Management" of Chapter 3 "Designing for Environmental Stewardship in Construction & Maintenance" 3.12.3. See Fly Ash Section 701

Criteria 1.2.3: Reduction in Quantity of Materials (3 Points)

Description:

Materials like aggregate, cement or steel-reinforcement are the major contributor in the construction of bridges. Incorporating latest engineering techniques like pre-stressed/ pre-tension or post-tension, high strength concrete will significantly reduce the amount of material. Consequently, the reduction in the amount of material will result in lowering the overall life cycle cost of the project.

Intent:

The objective is to reduce the amount of material, used in the construction of bridges by using innovative civil engineering techniques.

Requirements:

This credit can be achieved by either employing structural techniques like supplementing the cement, recycling good quality steel members, or high strength materials. It may also incorporate materials that can be replaced by recycled content (Hunt, 2004).

Calculations can be done by weight or volume but must be consistent throughout.

% Reduction in material = (Total reduction in quantity of material)/ (Total quantity of all material used without employing strategies) X 100

Points Criteria:

Calculate the total quantity of materials when high strength, high performance materials were used on the project. Calculate the quantity if ordinary materials have used. Calculation can be done by weight or volume. Calculate the percentage of material reduced by the use of high performance materials.

- 3 points will be awarded, if at least 25% of the total materials are reduced.

Example 1:

Table 3-6 - Detailed Calculations for Calculating Reduction in Material

Material	**Unit**	**Total material required**	**Techniques / Strategies**	**Amount of material after employing strategies**	**Reduction in Quantity of Material**	**Comments**
Concrete	Tons		High Strength			Overall reduction in the quantity
Steel	Tons		Recycled Steel			Reducing the amount of new steel
Wood	Tons		Reuse			Reducing the amount of virgin wood
Total reduction in quantity of material						tons
Total quantity of all material used without employing any strategy						tons
% Reduction in Material					**%**	

Example 2:

Use of slag cement, other supplementary cementitious materials like fly ash and silica fume can reduce the quantity of Portland cement in a concrete mixture.

Table below highlights using slag cement in a mixture can not only substitute for a portion of Portland cement, but also can reduce total cementitious materials content (Portland + slag). In this example, cementitious contents can be reduced because slag cement typically increases 28-day strength of concrete mixtures.

Table 3-7 - Reducing Total Cementitious Materials Content with Slag Cement (SCA, 2012)

Case	% Slag Cement	Cementitious Materials (lb/cu yd)			28 Day	Reduction Due to Slag Cement Utilization		
Case 1: 5000 psi (St. Marys, 2002)		Cement	Slag Cement	Total Cementitious		Δ Cementitious (lb/cu yd)	Δ Cement (lb/cu yd)	Δ % Cement
	0%	470	0	470	5470	25	235	50%
	47%	235	210	445	6210			

Standard/ Resource:

- Hunt, L.R. (2005), "Development of rating system for sustainable bridges" MS thesis, Massachusetts Institute of Technology

Credit 1.2.4: Material Reuse (2 Points)

Description:

Re-use of demolished or salvaged materials should be encouraged. Reuse of material refers to the materials, which can be reused after deconstruction or demolition of the bridge. This will reduce the quantity of raw materials needed and will reduce the amount of economic and environmental impact due to mining and transportation. These materials can potentially be used in a number of pavement-related applications (e.g., concrete or HMA surface course, cement or asphalt stabilized base course and fill).

Intent:

The objective is to reuse the demolished bridge materials in road construction to reduce demand for virgin materials and reduce waste; thereby lessening impacts associated with the extraction and processing of virgin resources.

Requirement:

Integrate salvaged or demolished material in the construction of roadways. Layout comprehensive plans and strategies to make use of demolished material in base, sub-base, sub-grade, embankment fills and foundations stabilization. The major sources of Recycled Concrete Material (RCM) are demolition of existing concrete pavement, bridge structures, curb and gutter (AAHSTO, 2009). Also, consider the reuse of salvaged materials like girders, beams, traffic signs and posts, safety railings, lighting fixtures and sensors.

Points Criteria:

Percentage of reused materials is calculated based on cost.

The points are awarded based on the minimum percentage of reused materials used in the project.

Table 3-8 - Points distribution for Material Reuse

% Reused materials	Points
5	1
10	2

Table 3-9 - Example Calculations for Material Reuse

Material	Amount of total material	Total estimated Cost ($), if new material used	Amount of reused material	Cost of reused material ($)	% of material reused	Total cost material ($)
Steel						
Wood						
Traffic Signs						
Lighting fixtures						

Standard/Resource:

- Section 5.7.14 "Aluminum Sign Recycling and Chromate Coating Elimination" and Section 5.7.3 Recycled Concrete Material/Aggregate (RCM/RCA) of Chapter 5 "Pavement, Materials, and Recycling"

Criteria 1.2.5: Regional Materials (3 Points)

Description:

Regional extracted materials are the raw materials taken from a 500-mile radius of the project site. Regionally manufactured materials are assembled as finished products within 500 miles radius of the project site (USGBC, 2009).

Intent:

"To increase demands for materials and products that are extracted and manufactured within the region, thereby supporting the use if indigenous resources and reducing the environmental impacts resulting from the transportation" (USGBC, 2009).

Requirements:

a) Use materials or products that have been extracted or recovered, as well as manufactured, within 500 miles. If only a fraction of a product or material is extracted, harvested, or recovered and manufactured locally, then only that percentage (by weight) can contribute to the regional value.

b) Establish a project goal for locally sourced materials, and identify materials and material suppliers that can achieve this goal. During construction, ensure that the specified local materials are available, and quantify the total percentage of local materials used. Consider a range of environmental, economic and performance attributes when selecting products and materials.

c) % Regional Materials = (Cost of Regional Material/ Total Materials Cost) x100

Points Criteria:

- Calculate the quantity of material by weight or volume, which is transported from within 500 miles.
- 3 points will be awarded, if 25% of all the materials are regional materials.

Table 3-10 - Example Calculations for Calculating Regional Material

Material	**Distance between product and manufacturer (miles)**	**Unit**	**Total amount of material**	**Total material cost ($)**	**Value qualifying as Regional ($)**
Cement		lb			
Steel		lb			
Lighting Fixtures		Quantity			
Fill		cyd			
Total cost of regional material					
Total material cost					
% Regional materials					**%**

Standard/Resource:

- Material and Resources Credit 5 of LEED® 2009

Category 1.3- Other

This section describes the miscellaneous criteria, which have environmental impacts on the bridges due to its design. These criteria can be renewable energy use, use of bikes/pedestrian lanes and design for future expansion and reduction in Green House Gas (GHG) emission and energy consumption.

Criteria 1.3.1: Renewable Energy Use (1 Points)

Description:

The major sources of sustainable energy are solar, wind, geothermal, bio-mass or low-impact hydro sources. Visit http://www.green-e.org/energy for details about the Green-e Energy program.

Intent:

The objective is to reduce the electrical consumption and promote the use of renewable energy technologies.

Requirement:

Employ strategies to provide bridge's electricity from renewable sources, as defined by the Center for Resource Solutions' Green-e Energy product certification requirements. These purchases shall be based on the quantity of energy consumed, not the cost. Determine the energy needs of the bridge during its operation and investigate opportunities to engage in a sustainable energy contract. Following will help in reducing electrical consumption above and beyond typical measures. Particularly,

a) Solar/ battery powered bridge lighting or warning signs.

b) Retrofit existing sign lighting with high efficiency types.

c) Use of LED bridge lighting.

Points Criteria:

- 1 point for using renewable energy systems.

Standard/Resource:

- ANSI/ ASHRAE/ IESNA Standard 90.1-2007 (Exterior Lighting)

Criteria 1.3.2: Bicycle/Pedestrian Pathways (2 Points)

Description:

Bicycle facilities denote improvements and provisions to accommodate or encourage bicycling. The definition of a pedestrian includes not only a person traveling by foot but also people with disabilities for whom walking and mass transits are often the primary mode chosen for independent travel (AASHTO, 2004).

Providing bicycle and pedestrian pathways has large number of environmental benefits. This type of commutation produces no emission, does not use petroleum-based fuels and reduces noise pollution (USGBC, 2009).

Intent:

The objective of this credit is to promote the use of alternative transportation through bicycling and walking and thus minimize pollution and energy demand.

Requirements:

a) Develop plans to include both sidewalks and bicycle pathways (Hunt, 2004).

b) Appoint bicycle and pedestrian coordinator in order to promote the maximum use of non-motorized modes of transportation (FHWA, 2012). Non-motorized transportation program of federal highway administration can be found in “Bicycle and Pedestrian Legislation in Title 23 United States Code (U.S.C.), Federal Highway Administration”.

c) Provide safe bicycle and pedestrian pathways during replacement or rehabilitation phase of the bridge.

Points Criteria:

- 1 point will be awarded, if bike lanes are provided
- 1 point will be awarded, if pedestrian pathways are provided

Standard/ Resource:

- Bicycle and Pedestrian Legislation in Title 23 United states Code (U.S.C), Office of Planning, Environment and Reality (HEP), FHWA

Criteria 1.3.3: Lane Adaptability (1 Point)

Description:

Bridges should be designed considering future traffic conditions. The increased traffic can increase the load on the bridges which may deteriorate the bridge, if bridge is not designed for carrying additional traffic capacity which may result in additional maintenance activities. Therefore, a framework should be made to provide additional lanes in the future for any unforeseen conditions.

Objective:

To provide framework for additional lanes for any unforeseen conditions.

Requirements:

a) Design the bridge so that two or more lanes can be added without strengthening the substructure. Develop preliminary construction plans for the addition of lanes in the future.

b) Design the structural elements so that they can bear additional loads created by the additional lanes. Therefore, consider using high performance materials, additional materials or high strength materials in the design (Hunt, 2004).

Points Criteria:

- 1 point will be awarded, if provisions for adding one or more travel lanes in the future are mentioned in design plan.

Standards/Resources:

- High-Performance Materials for Substructures, Foundations, and Earth Retaining Systems Workshop, FHWA, Publication Number: FHWA-HRT-08-058, February 2009.

Criteria 1.3.4: Life Cycle Cost Analysis (5 Points)

Description:

Life cycle cost analysis is an important technique, which assist transportation agencies in making investment decisions (NCHRP, 2003). It is a set of economic principles and computational procedures for comparing initial and future costs to arrive at most economical strategy for insuring that a bridge will provide the services for which it was intended.

Intent:

“To estimate the overall costs of project alternatives and to select the design that ensures the facility will provide the lowest overall cost of ownership consistent with its quality and function” (Fuller, 2010)

Requirements:

Perform the calculations for life cycle cost analysis of a bridge project in accordance with National Cooperative Highway Research Program (NCHRP) report 483 “Bridge Life Cycle Cost Analysis”. It is encouraged to compare various design alternatives.

Points Criteria:

- 5 points will be awarded for conducting LCCA of complete bridge.

Standards/Resources:

- National Cooperative Highway Research Program, 2003. “ Bridge Life Cycle Cost Analysis Report 483”

CHAPTER 4 METHODOLOGY, DATA COLLECTON AND ANALYSIS

4.1 CHAPTER OVERVIEW

This Chapter deals with the research methodology adopted to reach consensus for establishing weights to the categories Design, Construction, Maintenance and awarding points to various criteria to rate sustainable bridge. The Delphi approach was chosen to obtain quantitative results for this research study and consisted of two rounds of survey. The surveys were conducted from the professionals and experts working in Design, Construction, Maintenance and Environmental section in MDOT.

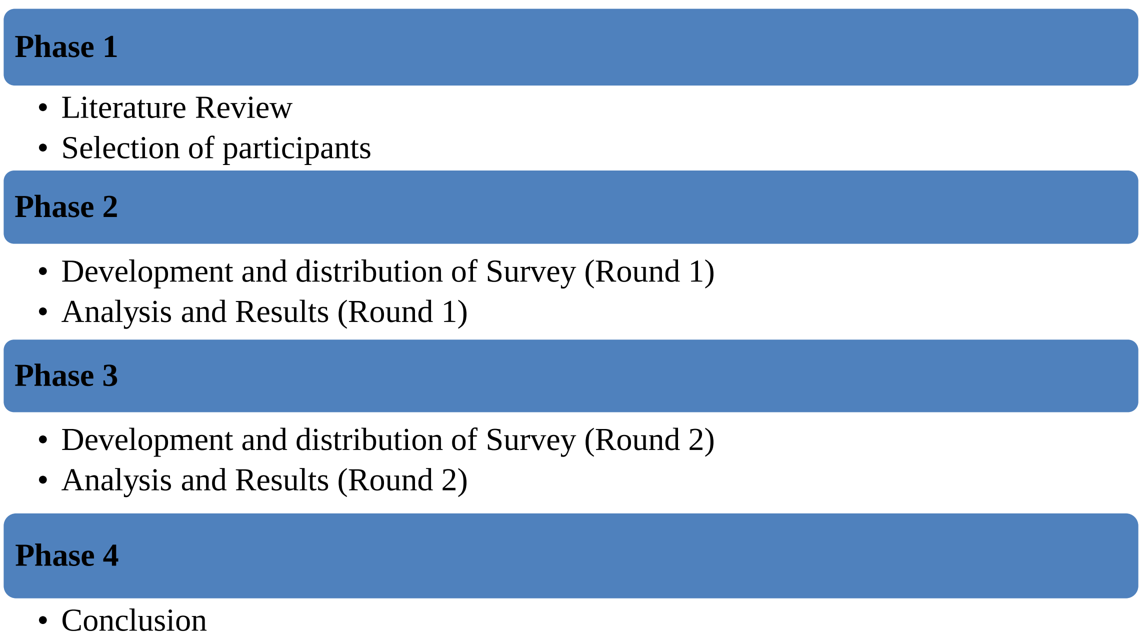

Figure 4-1 Phases in Research Methodology

4.2 PHASES IN RESEARCH METHODOLOGY

The overall research study was segmented into four phases. This includes literature review, development and distribution of survey Round 1, Round 2 and conclusion. The research methodology can be summarized in the Figure 4-1 phases in research methodology.

In Phase 1, a comprehensive literature review on Delphi approach assisted in selection of participants. This review, already discussed in Chapter 2, facilitated in understanding the current practices and analyzing the data, obtained from questionnaire. Phase 2 entails the development and distribution of first questionnaire and completion and return of Round 1 questionnaire. In Phase 3, the second questionnaire was developed for Round 2 and distributed among the participants along with results from Round 1. Finally, the last phase i.e. the research conclusion incorporates all the percentages and weights assigned to each criterion.

4.2.1 Phase 1: Literature Review and Selection of Participants

After carrying out the comprehensive literature review on the Delphi techniques, the following requirements for the participants were listed and send to MDOT, in order to obtain feedback on the number of participants willing to take the survey.

Table 4-1 describes the characteristics and the minimum requirements for the participants to undertake the survey.

Table 4-1 - Characteristics and Requirements for Participants

(Hallowell, 2010)

Characteristics	Minimum Requirements
Identifying Potential Experts	a) Membership in nationally recognized committee in the focus area of the research b) Primary writer of publications in ASCE journals c) Known participation in similar expert based studies
Qualifying panelists as experts	Experts must satisfy at least two of the following criteria in the topics related to research: • Primary of secondary writer of at least three peer-reviewed journal articles; • Invited to present at a conference; • Member or a chair of a nationally recognized committee; • At least 5 years of professional experience in the construction industry bridge design; • Faculty member at an accredited institution of higher learning; • Writer or editor of a book or book chapter on the topic of construction, safety and health or risk management; • Advanced degree in the field of civil engineering, CEM, or other related fields (minimum of a BS); • Professional Engineer (P.E.).
Number of panelists	8-12 (Minimum 8) • Design: 2 • Construction: 2 • Maintenance: 2 • Materials: 1 • Environmental Engineering: 2

The participants selected had prior experience in Bridge Design, Construction, Maintenance and Environment. A total number of ten individuals agreed to take part in the survey; four from Design, two from Construction, one from Maintenance and two from Environmental Department. All the participants have an experience of over 10 years. The pie chart 4-2 shows the qualification of the participants i.e. only three participants hold a Masters degree. As far as, the sustainability practices are concerned, only two participants out of ten have prior experience in any kind of project.

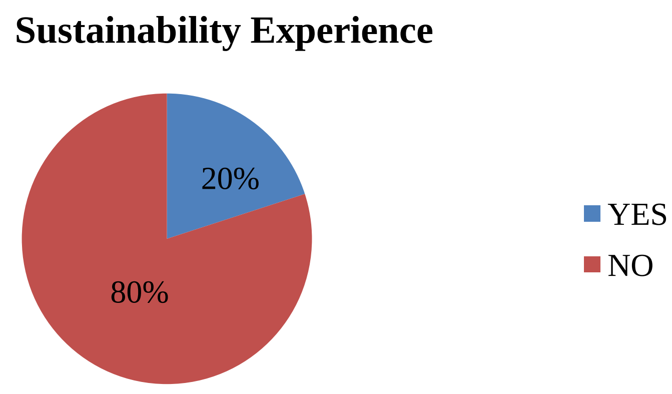

Figure 4-2 Qualification Chart of the participants

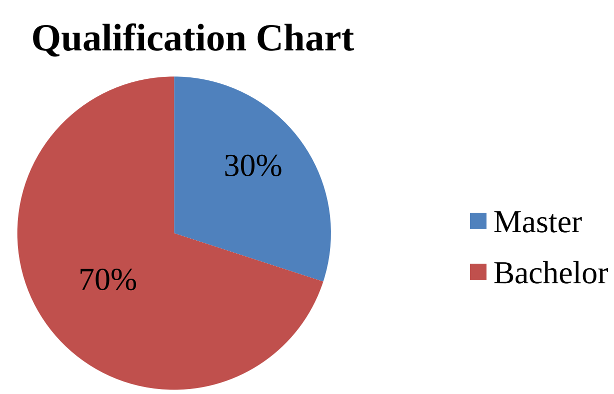

Figure 4-3 Prior Sustainability Experience of the participants

4.2.2 Phase 2 and Phase 3: Development and Distribution of Survey/ Results and Analysis

The purpose of multiple rounds is twofold. The first aim is to reach consensus by reducing variance in responses. The second purpose is to improve precision. Both of these objectives are achieved through the use of controlled feedback and iteration.

Analysis and Results (Round 1)

Initially, the author conducted a comprehensive analysis and developed a framework, as discussed in Chapter 3, for achieving sustainability in bridge design, construction and maintenance. In Round 1, the first survey was developed and sent to MDOT officials in order to gather their opinion on Sustainable Design, Construction and Maintenance for bridges. The participants were asked to provide their expert/ professional opinion by ranking and awarding percentages to each criterion in Design, Construction and Maintenance section. After receiving responses, the raw data was statistically analyzed and expressed in terms of frequency response, mean and standard deviation.

After the analysis, it was observed that:

a) The maximum frequency response i.e. nine was recorded in Site category under Design section.

b) The least frequency response i.e. six was recorded in the overall rating of the framework.

c) The lowest standard deviation was viewed in “Snow and Ice Control” criteria under Maintenance section, which indicates that all the participants strongly agreed to one value.

d) Also, the standard deviation was high especially in Construction section.

In statistics and probability theory, standard deviation shows how much variation or "dispersion" exists from the average (mean, or expected value). A low standard deviation indicates that the data points tend to be very close to the mean, whereas high standard deviation indicates that the data points are spread out over a large range of values.

4.2.3 Analysis and Results and (Round 2)

In the second round, each participant received the same Survey and was requested to repeat the percentage allocation process after taking the Round 1 result i.e. Mean into account. They were free to change their percentages allocation based on the group result or stick to the same as they did in Round 1. All the participants from Round 1 undertook the survey for Round 2. At the end of Round 2, it was observed that all the participants repeated the same score from Round 1.

4.3 CONCLUSION

The main goal of the Delphi technique was to establish the degree of consensus among the participants regarding the importance of each criterion in Design, Construction and Maintenance section. A brief summary of the results of Delphi process was emailed to MDOT. This included a table showing Round 1 and 2 percentages points allocated to each category. Figure 4-4 to 4-8 shows survey results that include mean percentages and standard deviation error bar for sustainability framework.

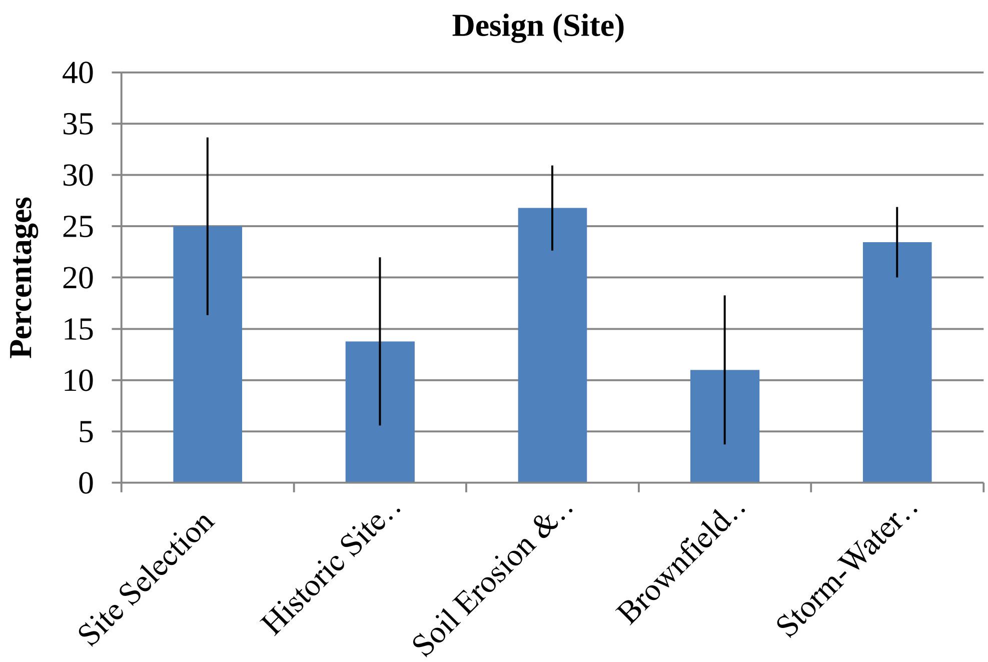

Figure 4-4 Mean percentages and Standard deviation error bar (Site)

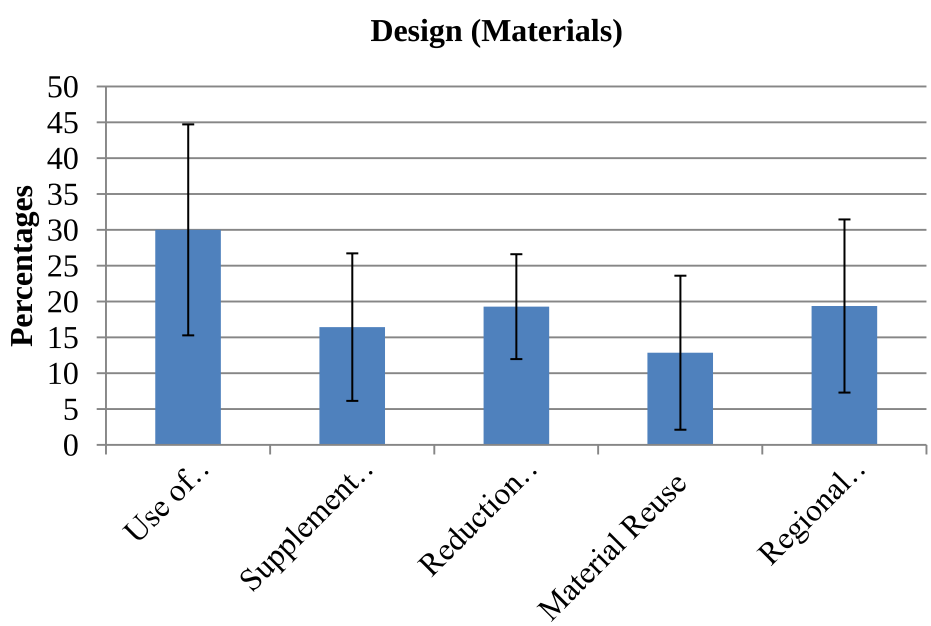

Figure 4-5 Mean percentages and Standard deviation error bar (Materials)

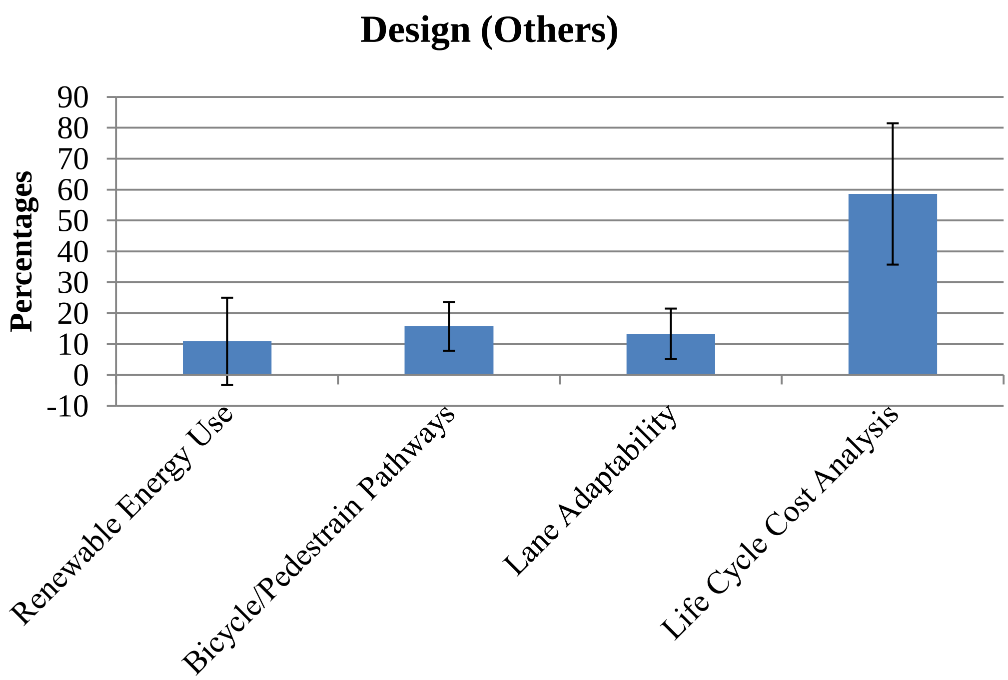

Figure 4-6 Mean percentages and Standard deviation error bar (Others)

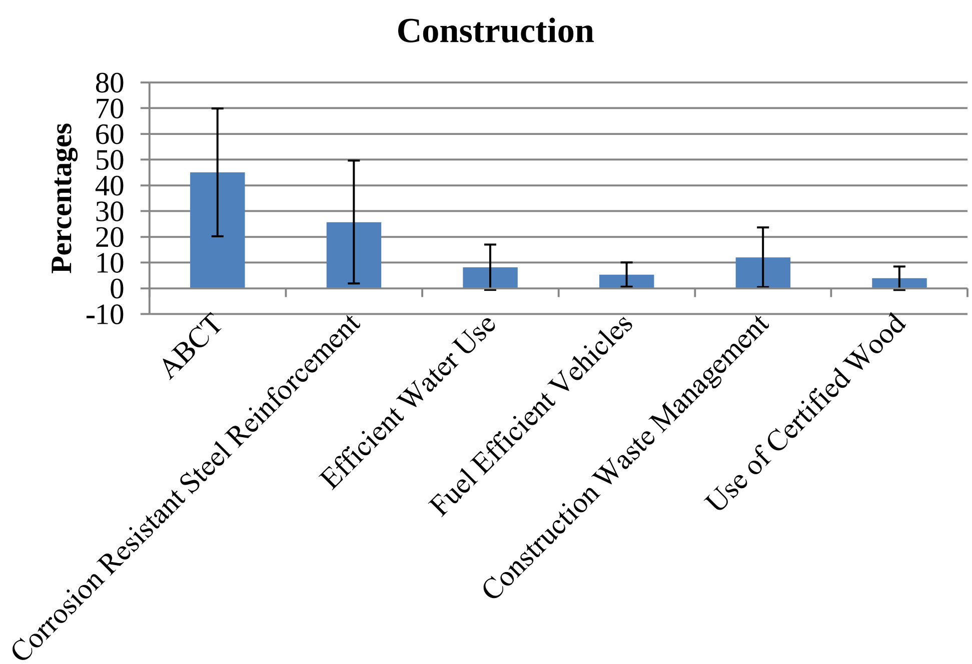

Figure 4-7 Mean percentages and Standard deviation error bar (Construction)

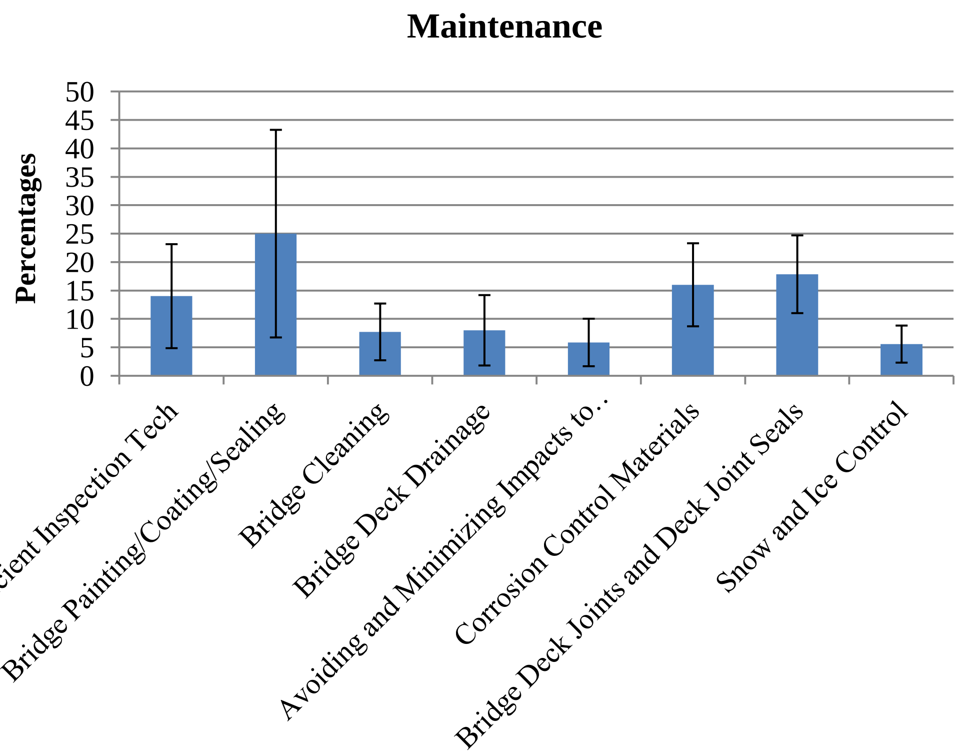

Figure 4-8 Mean percentages and Standard deviation error bar (Maintenance)

4.3.1 Response Rate

It was observed that the highest response i.e. nine was recorded in Site category under Design section and the least response i.e. six was recorded in assigning percentages to overall rating of Design, Construction and Maintenance section. The Table 4-2 shows the response rate by the participants in each section and Table 4-3 shows the overall response rate by the participants. It is obvious that the response rate shown in Table 4-2 is different from response rate in Table 4-3. The reason for such difference is that all the participants did not take part in the complete survey. They rather took part in the sections related to their concern field. For example, a participant working in Design department only filled the Design section of survey. However, some participants took part in rating the overall sustainability framework, as they had some prior experience in other sections. Table 4-2 and Table 4-3 show the individual and overall response rate respectively. The highest response rate (90%) was recorded in site category, while overall response rate for sustainable framework is low (60%).

Table 4-2 - Response Rate by Participants in Round 1 and 2

Section	Design			Construction	Maintenance
Category	Site	Material	Others		
Total (n=10)	10	10	10	10	10
Frequency	9	7	7	7	7
Response Rate	90%	70%	70%	70%	70%

Table 4-3 - Overall Response Rate by Participants in Round 1 and 2

Section	Design	Construction	Maintenance
Total (n=10)	10	10	10
Frequency	6	6	6
Response Rate	60%	60%	60%

In this study, the available pool of experts at the funding agency was limited to ten. Among those experts, only 60% participated in this study despite the agency's repeated calls. Although, the response rate is fairly high, the restricted pool of available experts for the study compromised the final number of respondents. It is still important to highlight that, the study reached an adequate number of respondents based on literature. A comprehensive study conducted by (Rowe G, 1999) indicated that the number of participants vary from three to eighty and need to be selected at the beginning of study.

4.3.2 Discussion

The purpose of Delphi process was to assign points to each criterion in the sustainability framework. The response from Round 1 and 2 were compiled and percentage allocation to each criterion was analyzed. The overall consensus in this study was reached after two rounds of survey applications. As, all the participants submitted the same scores in Round 2, which indicated that further survey rounds deemed unnecessary.

In Delphi method, after the first round of survey, the feedback is usually provided to the participants in statistical terms such as mean, median or standard deviation. A summary in Hallowell (2010) indicates that three out of seven studies did not explain any feedback, while the rest four used standard deviation as a measure of consensus. The literature review indicates that there is no description available on the level of standard deviation that represents the achievement of consensus. Also, consensus can be decided if a certain percentage of the votes falls within a prescribed range (Miller, 2006). A summary of case studies in Mary (2000) shows that frequency distributions are often used to assess agreement and the criterion of at least 51% responding to any given response category is used to determine consensus (Mary K, 2000).

In this study, as presented in Appendix B, the mean percentages were calculated for each major category (design, construction and maintenance) and criteria of sustainability framework. A total of 100 points were selected for entire sustainability framework and then, these 100 points were divided among design, construction and maintenance categories, according to the mean percentages obtained from Delphi survey. After the allocation of points to each major category, it was accomplished that Design section was rated to be the most important and hence, this section was assigned 47 points. Construction and Maintenance section received 31 and 22 points respectively. Similarly, the points in each major category, design (47), construction (31) and maintenance (22) were distributed among each criterion, according to the mean percentages assigned to that particular criteria. After the statistical analysis, it was observed that lowest standard deviation (3.25%) was recorded in snow and ice control criteria, while accelerated bridge construction technique (ABCT) criteria has a high standard deviation (24.83%). Furthermore, other criteria such as LCCA (22.86%) in construction and bridge painting/coating/sealing (18.25%) in maintenance have high standard deviation, which indicates that the dataset is more variable than expected and are spread out over a large range of values. The probable reasons for such a high deviations are; firstly, the participants seem to differ among themselves on the impact of certain criteria to the overall sustainability framework and secondly, the limited sample size reduced the precision level.

Therefore, it is proposed that, in future, further structured interviews with the bridge experts should be conducted to reduce standard deviation for these criteria to make results practical and realistic. However, Hallowell (2008) in a Delphi study considered 5% deviation as a measure of consensus. If similar deviation rate (5%) is considered as acceptable for this sustainability framework, there are seven criteria that fall under this category. The remaining 21 criteria have a standard deviation of over 5% and need to be re-evaluated after conducting structured interviews. Table 4-4 shows the criteria with a standard deviation of under 5%.

Table 4-4 Criteria with Standard Deviation under 5%

Criteria	Description	Standard Deviation (%)	Acceptable (If under 5%)
1.1.3	Soil Erosion & Sedimentation Control	4.14	Yes
1.1.5	Storm Water Management	3.43	Yes
2.4	Fuel Efficient Vehicles	4.71	Yes
2.6	Use of Certified Wood	4.56	Yes
3.3	Bridge Cleaning	4.99	Yes
3.5	Avoiding and Minimizing Impacts to Fish and Wild Life	4.18	Yes
3.8	Snow and Ice Control	3.25	Yes

Meanwhile, the data from these surveys can still be used as a vital guideline to assign scores to sustainable framework and study the impact of each criterion on design, construction and maintenance of sustainable bridges.

Figure 4-4 shows the overall evaluation of sustainability framework after percentage point allocation.

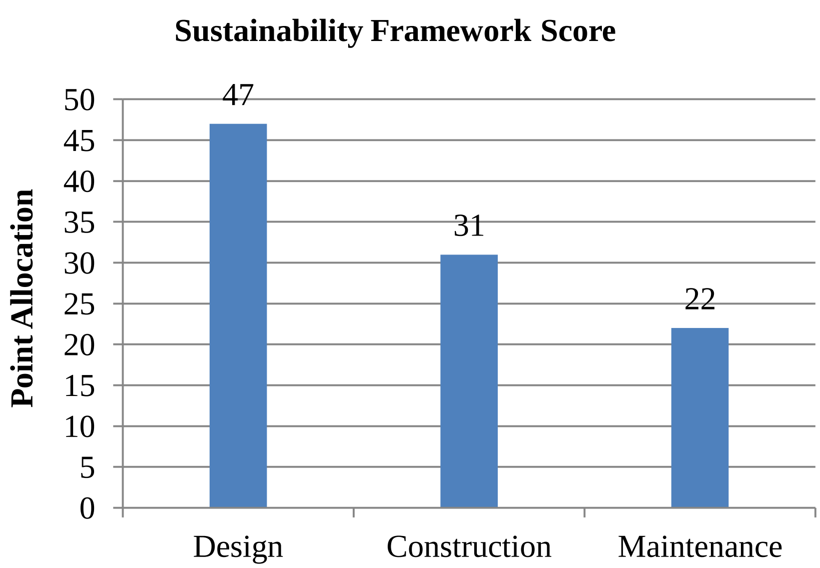

Figure 4-9 Points Allocation to Sustainability Framework

The Design section entails three sub-categories i.e. Site, Material and Others. The total score of 47 points assign to Design section was further subdivided among Site (22 points), Material (16 points) and Others (9 points), according to the mean percentages shown in table B-1 in Appendix B. The similar approach was adopted to allocate points within these three sub-categories. In Site category, criteria Site Selection and criteria Soil Erosion and Sedimentation were assigned 6 points each, which is the maximum. Figure 4-10, Design section, shows the points allocated to each criteria in Design Section.

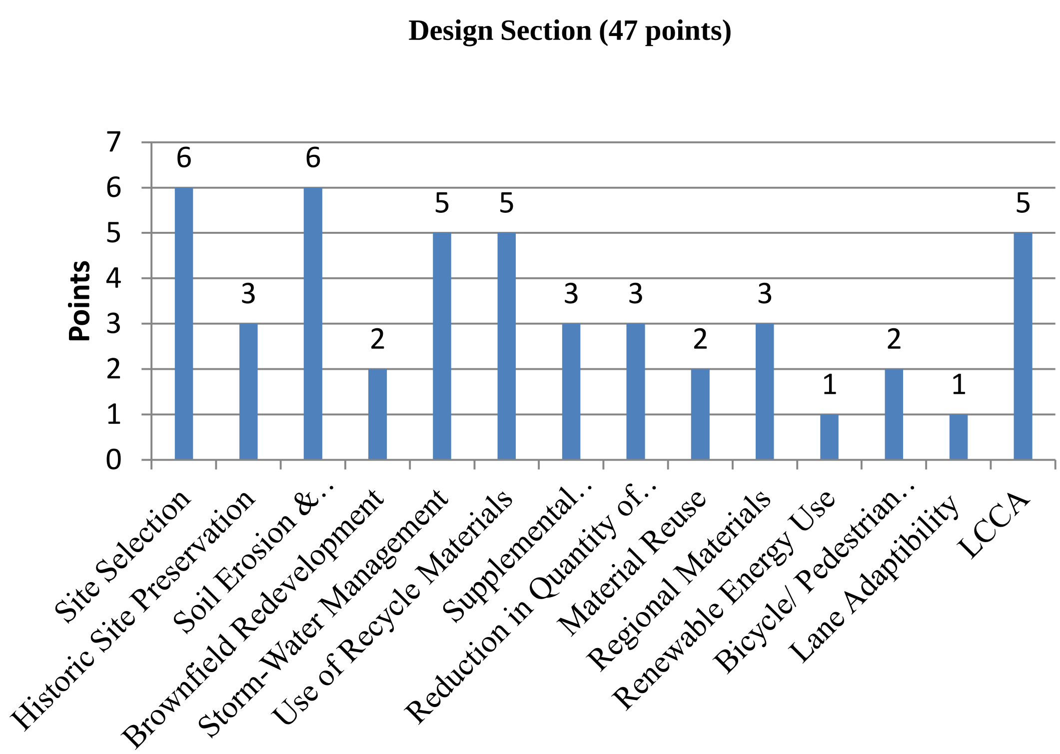

Figure 4-10 Points Allocation in Design Section

The Construction section includes six criteria and was awarded 31 points in the overall framework rating. A total of 14 points were assigned to criteria Accelerated Bridge Construction Techniques, demonstrates that the criteria has the enormous impact on this section whereas, criteria use of certified wood received only one point. The criteria Corrosion

Resistant Steel Reinforcement collected 8 points, and were rated as the second most important criteria in this section.

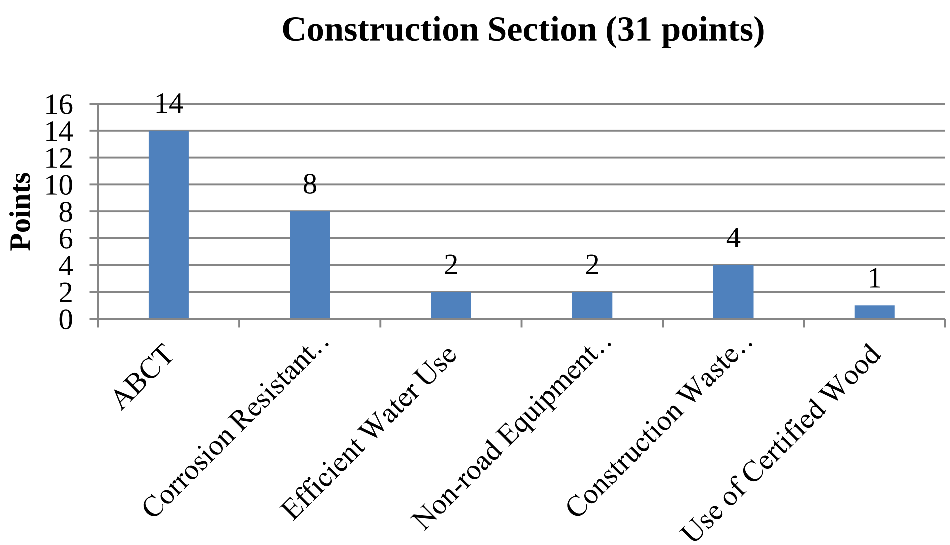

Figure 4-11 Points Allocation in Construction Section

The Maintenance section includes eight criteria and was awarded 22 points in the overall framework rating. A total of 6 points were assigned to criteria Bridge Painting and Coating, demonstrates that the criteria has enormous impact on maintenance category whereas, criteria like Avoiding and Minimizing impacts to Fish and Wildlife and criteria Snow and Ice Control received only one point. The Criteria Bridge Deck Joint and Deck Joint Seals collected 4 points, and were rated as the second most important criteria in this section.

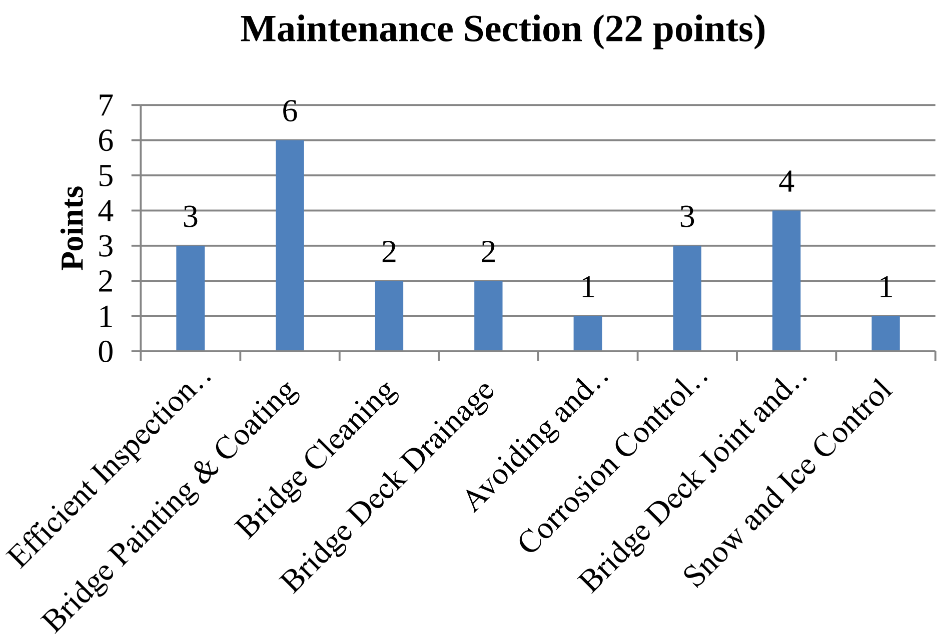

Figure 4-12 Points Allocated in Maintenance Section

4.4 CHAPTER SUMMARY

The chapter provided a discussion on research methodology, data analysis, results and findings. In this Chapter, after the successful development of sustainable framework for green bridges, the Delphi process was conducted in two rounds to establish consensus among the participants and to allocate the weights to each criteria in Design, Construction and Maintenance section. The conclusion of the Delphi process also marks the establishment of the objective 3.

CHAPTER 5 LIFE CYCLE COST ANALYSIS (LCCA)

5.1 CHAPTER OVERVIEW

This Chapter describes the methodology and procedure for calculating the life-cycle costs of highway bridges, to assist MDOT's engineers in decision making on Design, Construction and Maintenance of bridges in Michigan.

5.2 METHODOLOGY AND PROCEDURE - LCCA PROCEDURE

This section identifies the procedural steps involved in conducting life-cycle cost analysis (LCCA). They include:

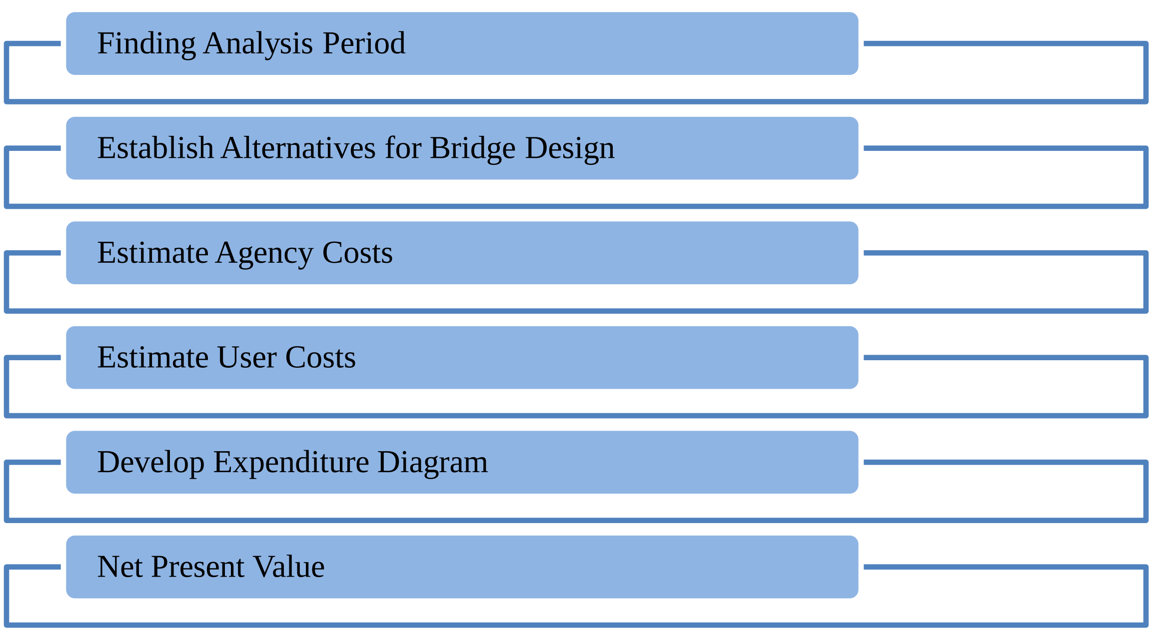

Figure 5-1 Phases in computing LCCA

While the steps are generally sequential, the sequence can be altered to meet specific LCCA needs. The following sections discuss each step.

5.2.1 Finding Analysis Period.

The analysis period is a key variable and generally, selected on the basis of both physical elements to be analyzed and the type of decision to be made. Generally, it should be at least as long as the best-estimate service life of the element. The current service lives of highway bridges in North America may be approximately 30 to 50 years, while AASHTO specifies the service life of new bridges should be 75 years. (Hawk, 2003)

National Bridge Inventory (NBI) systems provide the data and analysis techniques to evaluate bridge condition and performance to identify cost effective strategies for short and long-term capital projects and maintenance programs. Table 5-1 describes the overall condition rating of the deck.

Table 5-1 - Rating for a bridge superstructure

Code	Description
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION - no problems noted
7	GOOD CONDITION - some minor problems
6	SATISFACTORY CONDITION - structural elements show minor deterioration
5	FAIR CONDITION - all primary structural elements are sound but may have minor corrosion, cracking or chipping. May include minor erosion on bridge piers.
4	POOR CONDITION - advanced corrosion, deterioration, cracking or chipping. Also significant erosion of concrete bridge piers.
3	SERIOUS CONDITION - corrosion, deterioration, cracking and chipping, or erosion of concrete bridge piers has seriously affected deck, superstructure, or substructure. Local failures are possible.
2	CRITICAL CONDITION - advanced deterioration of deck, superstructure, or substructure. May have cracks in steel or concrete, or erosion may have removed substructure support.
1	"IMMINENT" FAILURE CONDITION - major deterioration or corrosion in deck, superstructure, or substructure, or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	FAILED CONDITION - out of service - beyond corrective action
N	N Not applicable

The below listed Table 5-2 provides a useful information for bridge preservation activities. (MDOT, 2012) For example, a relatively short period may be adequate for determining when a deck overlay should be scheduled, while a longer period of two to three decades is more likely to be appropriate for deck replacement for a bridge.

Table 5-2 - Bridge preservation activities (modified from MDOT Scoping Manual)

Preservation Action	Bridge Selection Criteria	Expected Service Life
Replacement		
Total Replacement	NBI Rating of 3 or less, or when cost of rehabilitation exceeds cost of replacement, or when bridge is scour critical with no countermeasures available	**70 yrs**
Superstructure Replacement	NBI Rating for Superstructure of 4 or less, or when cost of rehabilitating superstructure & deck exceeds replacement cost.	**40 yrs**
Deck Replacement	Use guidelines in MDOT's *Bridge Deck Preservation Matrix.*	
• **Epoxy Coated Steel**	NBI Rating of 4 or less for deck surface and deck bottom, or when deck replacement cost is competitive with rehabilitation.	**70 yrs**
• **Black Steel**		**40 yrs**
Substructure Replacement (Full or Partial)	NBI Rating of 4 or less for abutments, piers, or pier cap, or there is existence of open vertical cracks, signs of differential settlement, or presence of active movement, or bridge is scour critical with no countermeasures available.	**40 yrs**
Rehabilitation		
Concrete Deck Overlays	Guidelines in MDOT's Bridge Deck Preservation Matrix	
• **Deep**	NBI Deck Rating < 5 for surface and > 5 for bottom	**25 yrs**
• **Shallow**	NBI Deck Rating < 5 for surface and > 4 for bottom	**12 yrs**
• **HMA /Membrane**	NBI Deck Rating < 5 for surface and > 4 for bottom	**8 yrs**
• **HMA Cap**	NBI Deck Rating < 5 for surface and < 4 for bottom	**3 yrs**

Preventive Maintenance		
Complete Painting	NBI Rating for paint condition is 3 or lower, or in response to Inspector's work recommendation for complete painting	**15 yrs**
Zone Painting	NBI Rating for paint condition is 5 or 4, or less than 15% of existing paint area has failed and remainder of paint system is in good or fair condition.	**10 yrs**
HMA Overlay Cap without Membrane	NBI Rating of 3 or less for deck surface and deck bottom. Temporary holdover to improve rideability for a bridge in the 5 year plan for rehab / replacement.	**3 yrs**
Concrete Deck Patching	Deck Surface Rating of 5, 6, or 7 with minor delamination and spalling, or in response to Inspector's work recommendation	**5 yrs**

5.2.2 Establish alternatives for bridge design.

The second step in conducting the LCCA of bridges is to define the alternatives for bridge design and evaluate against the base case. The alternatives must be developed in adequate details and any number of alternatives can be developed for a bridge project. The goal should be to develop roughly two to three alternatives for a project. (Hawk, 2003)

Typically, each design alternative will have an expected initial design life, periodic maintenance treatments, and possibly a series of rehabilitation activities. It is important to identify the scope, timing, and cost of these activities. (FHWA, 1998)

The classic example of selection of analysis period and management of rehabilitation/ replacement timing activities can be found in a report published at University of Michigan titled "*Life-Cycle Cost Model for Evaluating the Sustainability of Bridges Decks*". In this thesis, a case study was conducted on two alternatives i.e. conventional concrete (CC) joints and engineered cementitious composite (ECC) link slabs and the Life Cycle Cost (LCC) model was developed to evaluate the sustainability of bridge decks. The useful life of bridge deck was assumed 30 years when constructed with CC and 60 years when ECC is used. The costs were estimated over a 60-year analysis period. (Richard, 2004) The rehabilitation and replacement activities and their timings identified at the beginning of analysis are listed below.

Table 5-3 - Overview of construction activities (extracted from Richard F Report on LCC model for evaluating sustainability of bridge decks)

CC		ECC	
Construction Activity	**Frequency**	**Construction Activity**	**Frequency**
Deck replacement	30 years	Deck replacement	60 years
Joint replacement	Every 15 years	Link slab replacement	Every 60 years – when a deck replacement occur
Deck resurfacing	Every 15 years – when a joint replacement occur	Deck resurfacing	Every 20 years
Bridge patching and repair	Every 5 years following a deck resurfacing	Bridge patching and repair	Every 7 years following a deck resurfacing

5.2.3 Estimate Agency Cost

The agency costs are defined as "*all those costs associated with the alternatives, incurred by the agency during the analysis period*" (Hall, 2003). According to Bridge LCCA, guidance manual (Hawk, 2003), the key agency costs typically include:

- Design, engineering and regulatory,
- Acquisitions, takings and other compensation,
- Construction,
- Maintenance and repair,
- Contract incentives and disincentives,
- Demolition, removal and remediation,

- Inspections,
- Site and administration services,
- Replacement and rehabilitation and
- Miscellaneous agency actions.

The additional detailed discussions of agency costs are provided in the Bridge LCCA Guidance Manual. The primary step in estimating agency costs is to determine construction quantities/unit prices. Unit prices can be determined from historical data on previously bid jobs of comparable scale. Only those agency costs that are significantly different for the different alternatives need to be considered in the life-cycle cost analysis. (Hall, 2003) Engineering and administration costs, for example, may be excluded if they are the same for all alternatives.

5.2.4 Estimate User Cost

User costs are defined as "*the costs incurred by the user over the life of the project*". User costs are an aggregation of the following cost components (Hawk, 2003):

- Traffic congestion delays,
- Traffic detours and delay-induced diversions,
- Highway vehicle damage,
- Environmental damage,
- Business effect and
- Miscellaneous routine user actions.

More precise discussion of user costs is provided in Bridge LCCA Guidance Manual. Furthermore, computer programs such as NCHRP's Bridge Life Cycle Cost Analysis (BLCCA) software are also available for use in analyzing user costs for bridge highway projects.

5.2.5 Develop expenditure diagram

These diagrams are graphical representations of expenditures over time and are commonly developed for each design strategy in visualizing the extent and timing of expenditures. (NCHRP, 2003)

Figure 5-2 shows a typical expenditure diagram. The expenses associated with each project alternative are sketched along the vertical axis while the horizontal axis represents the related time. In general, costs are depicted as upward arrows at the appropriate time they occur during the analysis period, and benefits are represented as savings or downward arrows. Under these conditions, the LCCA objective becomes finding the alternative design strategy that meets the best performance requirements at the lowest life-cycle cost.

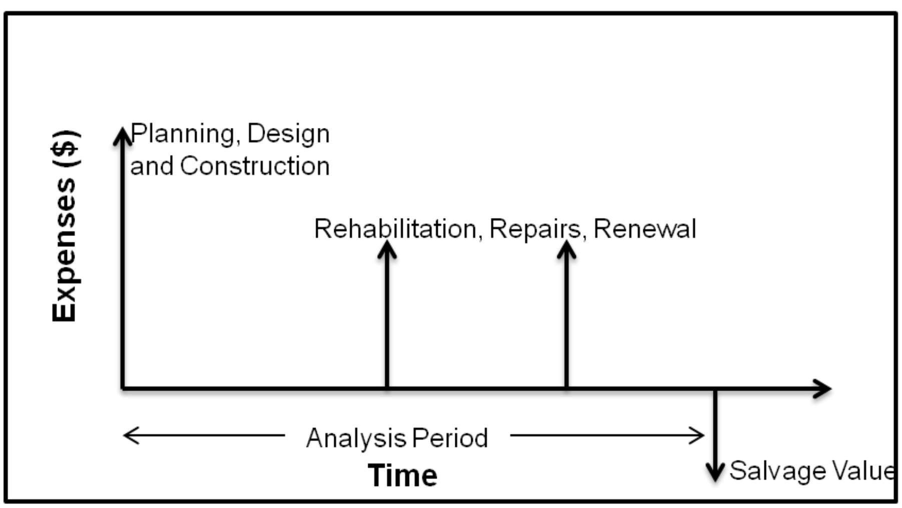

Figure 5-2 Expenditure Diagram for Bridge Design

5.2.6 Net Present Value (NPV)

All the alternatives considered in a life-cycle cost analysis needs to be compared using a common measure of economic worth. The economic worth of an investment may be measured using NPV:

Net Present Value: the conversion of all cash flows, using a discount rate, to an equivalent single sum at time zero.

$$NPV = FV / (1 + DR)^N$$

where, NPV = Net Present Value

FV = Future Value of an expenditure made at time N

DR = Discount Rate

N = Number of periods between NPV and FV

Discount Rate

The rate used to discount future cash flows to the present value is a key variable and used to determine discount factors. MDOT uses a 4% discount rate for its construction projects, as per the federal government's recommendation for long-term discount rates. (MDOT, Pavement Design and Selection Manual, 2000) The Office of Management and Budget (OMB) publishes these values in its Circular A-94; typical discount rates range between 3% and 5%. MDOT must apply the guidelines issued by the OMB which are updated by occasional revision of Appendix C. An up-to-date Appendix C can be found at the website http://www.whitehouse.gov/omb/ by searching for "discount rate".

5.3 CASE STUDY

5.3.1 Overview

MDOT provided the research team with bidding documents and data on different bridges in Michigan, to perform Life Cycle Cost Analysis and find out the best alternative for the bridge superstructure. These bridges either require repair/ rehabilitation or replacement. A Life Cycle Cost Analysis was conducted on a concrete bridge to evaluate the sustainability of superstructure. This research compares agency cost of two superstructures: one using Conventional Concrete Mix and the other using High Performance Concrete mix in superstructure. The agency cost includes initial construction cost, repair, maintenance and disposal cost. These costs were estimated over an analysis period of 75 years.

5.3.2 Structure Description

The structure considered for the LCCA is located on I-96 EB over Grange Road in Clinton County, 3.5 miles south-east of Ionia. The bridge needs superstructure replacement. The structure must be able to carry the loads prescribed in AASHTO HS-20 specifications, and it must last at least 75 years. The further details of the structure were found in Table 5-4 using National Bridge Inventory (NBI) website:-

Table 5-4 - Bridge Details

Description	Details
NBI Structure Number	000000000001789
Route Sign Prefix	Interstate
Year Built	2007
Record Type	Roadway is carried ON the structure
Service On Bridge	Highway
Service Under Bridge	Highway, with or without pedestrian
Latitude	42 48 47.16 N
Longitude	84 47 18.90 W
Material Design	Pre-stressed concrete
Design Construction	Stringer/ Multi-beam or Girders
Structure Length	37.5 m
Approach Roadway Width	13.4 m
Lanes on Structure	2
Average Daily Traffic	19469
Year of Average Daily Traffic	2007
# of Spans in Main Structure	3
Structural Evaluation	Better than present mini criteria
Sufficiency Rating	95.2 %

Design Alternatives

In this case study, the author, worked on a concrete superstructure, considering two alternatives: Table 5-5 below shows a comparison between conventional concrete mix and high performance concrete mix.

Table 5-5 - Design Alternatives

Alternatives	Details
Base Case – Conventional Concrete Mix	Pre-stressed Concrete I-Beam – 28 inch
	Deck repair at 25 and 50 years
	Demolition at 75 years
Alternative Case – High Performance Concrete	Pre-stressed Concrete I-Box – 28 inch
	Deck repair at 40 years
	Demolition at 75 years

Alternative 1 – Conventional Concrete

The conventional concrete deck normally requires complete deck replacement after 70 – 75 years and repair after each 25 years. Therefore, in a lifespan of 75 years, a bridge using conventional concrete requires two repairs. Figure 5-3 below explains the events associated with CC mix during its entire life.

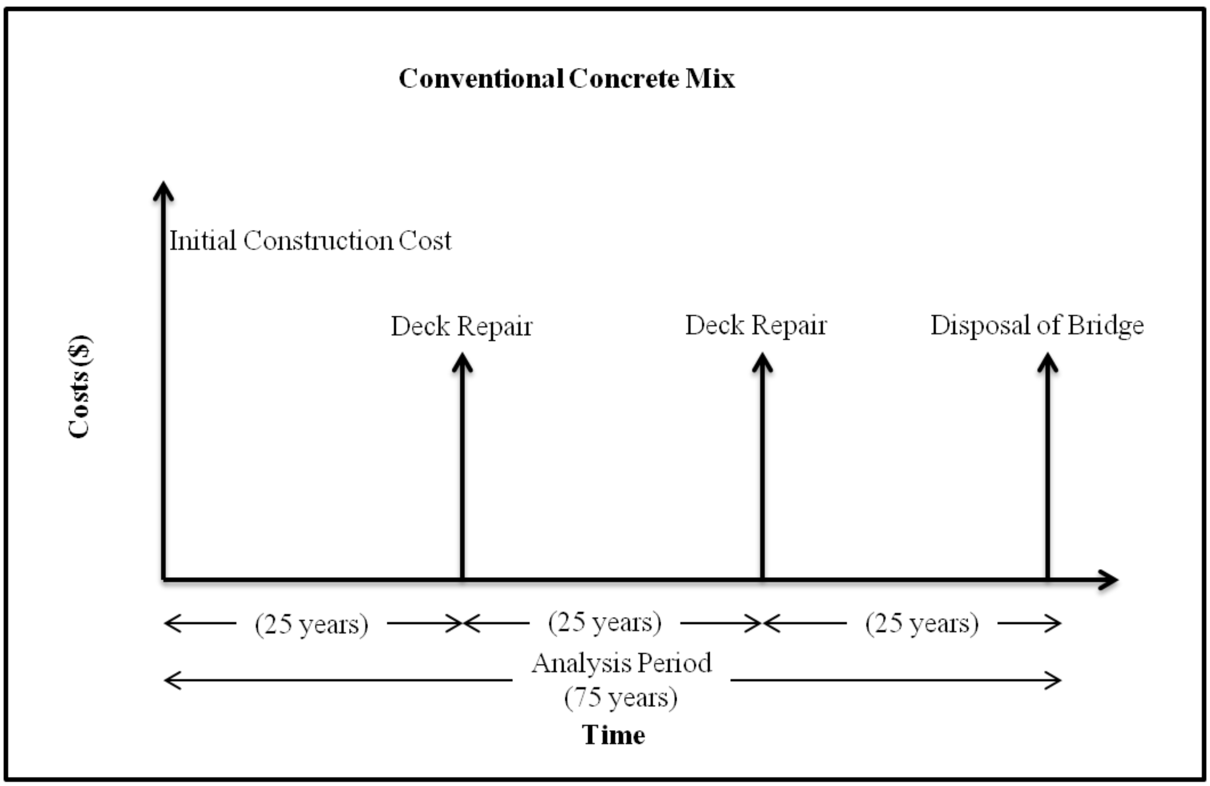

Figure 5-3 Schedule of activities in life of conventional concrete mix

The bridge work details like quantities and unit prices are extracted from bidding documents provided by MDOT. The following table 5-6 shows the break-down of agency cost associated with a bridge. It includes Initial construction cost, repair, maintenance and disposal cost.

Table 5-6 - Initial Construction Cost of Conventional Concrete Mix

Description	Unit	Quantity	Unit Cost	Total Unit Cost	Total Cost
Structures Rem Portions	LS	1	137000	137000	**1662013.97**
Structures Rem Portions	LS	1	137000	137000	
Backfill Structure, CIP	Cyd	786	16.22	12748.92	
Exacavtion Fdn	Cyd	1263	9.86	12453.18	
Erosion Control, Silt Fence	Ft	1300	1.91	2483	
Underdrain, Fdn, 4 inch	Ft	472	5.27	2487.44	
Conc Quality Initiative, Structure	Dlr	11320	1	11320	
Steel Sheet Piling, Temp	Sft	122	19.09	2328.98	
Steel Sheet Piling, Left in Place	Sft	3080	25	77000	
Conc Quality Assurance, Structure	Cyd	703	12.11	8513.33	
Substructure Conc	Cyd	384	365	140160	
Superstructure Conc	Cyd	128	209.74	26846.72	
Conventional Superstructure Conc, Night Casting	Cyd	191	178.84	34158.44	
Superstructure Conc, Form, Finish, and Cure	LS	1	28800	28800	
Superstructure Conc, Form, Finish, and Cure	LS	1	29000	29000	
Superstructure Conc, Form, Finish, and Cure, Night Casting	LS	1	72000	72000	
Conc Surface Coating	LS	1	73000	73000	
Conc Surface Coating	LS	1	73000	73000	
Expansion Joint Device	Ft	202	136.34	27540.68	
False Decking	Sft	23318	0.71	16555.78	
Reinforcement, Steel, Epoxy Coated	Lb	133188	1.05	139847.4	
Bridge Ltg, Oper and Maintain	Cyd	382	3.43	1310.26	
Bridge Ltg, Fur and Rem	LS	1	3000	3000	
Bridge Ltg, Fur and Rem	LS	1	3000	3000	
Substructure Horizontal Surface Sealer	Syd	66	18	1188	

Table 5-6 (Cont'd)

Conventional Superstructure Conc, Night Casting	**Cyd**	**191**	**178.84**	**34158.44**	
High Performance Superstructure Conc, Form, Fin and Cure Night Casting	LS	1	90000	90000	
Bearing, Elastometric, 2 3/4 inch	Sft	26	101.48	2638.48	
Bearing, Elastometric, 3 1/4 inch	Sft	58	138.75	8047.5	
Prest Conc I-Beam, Furn, 28 inch	Ft	1924	125	240500	
Prest Conc I-Beam, Erec, 28 inch	Ft	1924	10	19240	
Joint Waterproofing	Sft	432	4.55	1965.6	
Joint Waterproofing, Expansion	Sft	304	6.46	1963.84	
Reflective Marker, Perm Barrier	Ea	24	12.99	311.76	
Bridge Railing, Aesthetic, Type 4, Det	Ft	552	85	46920	
Adhesive Anchoring of Horizontal Bar	Ea	176	13.8	2428.8	
Adhesive Anchoring of Vertical Bar, 3/4 inch	Ea	50	13.62	681	
Reinforcement Mechanical Splice	Ea	1040	32	33280	
Filler Wall Conc	Cyd	30	634.02	19020.6	
Slope Paving Header	Ft	442	61.71	27275.82	
Slope Paving, Conc	Syd	1170	52	60840	

Table 5-7 - Operation, Repair and Maintenance Cost of Conventional Concrete

Operation Repair and Maintenance					
Description	**Unit**	**Quantity**	**Unit Cost**	**Total Unit Cost**	**Total Cost**
Thin Epoxy Overlays	Syd	600.8	60	36048	**36048**
Concrete Surface Rem	Syd	600.8	12.68	7618.144	**7618.144**
Hydro-demolition (1st & 2nd Pass)	Syd	600.8	112.1	67349.68	**67349.68**
Bridge Deck Surface Construction & thick Concrete Overlays	Syd	600.8	31.86	19141.488	**19141.988**

Table 5-8 - Bridge Disposal Cost

	Disposal Cost				
Description	**Unit**	**Quantity**	**Unit Cost**	**Total Unit Cost**	**Total Cost**
Disposal of Bridge	Sft	5407.2	50	270360	**270360**

Total Life Cycle Cost of Conventional Concrete Mix

A life Cycle Cost Analysis (LCCA) is undertaken to evaluate the total performance of construction, repair, maintenance and disposal activities for Conventional Concrete mix. The use of LCCA enabled the research team to assess the total life cycle cost of a bridge deck. Table 5-9 below explains the total life cycle cost associated with Convention Concrete Mix when different repair and maintenance activities are incurred at different points in time.

Table 5-9 - Total Life Cycle Cost – Conventional Concrete

Event	Description	Year	Misc Costs	Total Cost
Event 1	**Initial Construction**	1	Complete Cost	1662013.97
Event 2	**Deck Repair**	25	Maintenance and Repair Cost	36048
Event 3	**Deck Repair**	50	Maintenance and Repair Cost	94109.812
Event 4	**Disposal of Bridge**	75	Disposal Cost	270360
Total Life Cycle Cost				**2062531.782**

Alternative 2 - High Performance Concrete (HPC) Mix

The second alternative i.e. High Performance Concrete Mix has a service life that varies from 3 to 10 times the service life of conventional concrete and yields 65% reduction in the CO_2 emissions. HPC requires only one time repair after 40 years. Figure 5-4 below explains the events associated with HPC during its entire life.

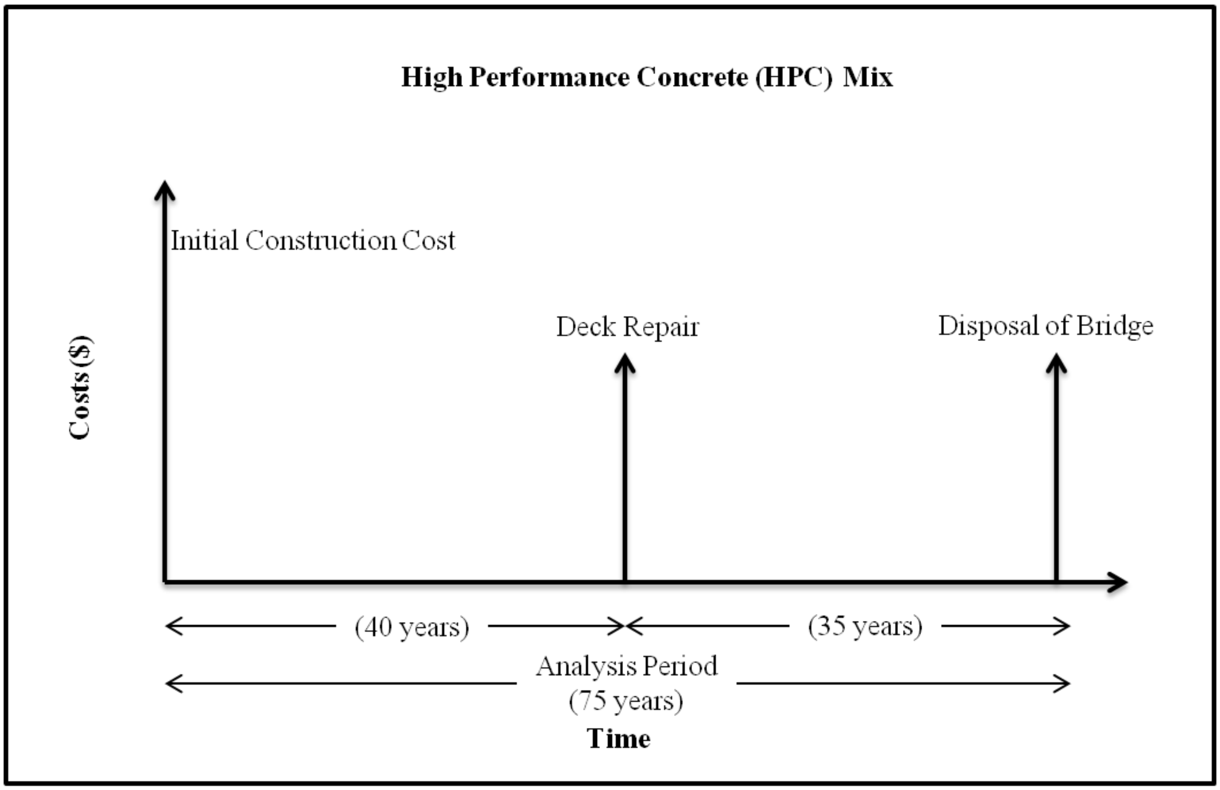

Figure 5-4 Schedule of activities in life of High Performance Concrete mix

During a life cycle of 75 years, it is assumed that Conventional Concrete mix deck will be replaced with a similar type of deck. At the end of life cycle, the end of service life of High Performance Concrete deck is not reached and still has residual value. This value can be included as a negative in Life Cycle Cost calculations to account for remaining service life. The table below gives details about the agency cost associated with High Performance Concrete Mix.

Table 5-10 - Initial Construction Cost of High Performance Concrete Mix

Detailed Calculations of Initial Construction Cost					
Description	**Unit**	**Quantity**	**Unit Cost**	**Total Cost**	**Total Cost**
Structures Rem Portions	LS	1	137000	137000	**1680602.09**
Structures Rem Portions	LS	1	137000	137000	
Backfill Structure, CIP	Cyd	786	16.22	12748.92	
Exacavtion Fdn	Cyd	1263	9.86	12453.18	
Erosion Control, Silt Fence	Ft	1300	1.91	2483	
Underdrain, Fdn, 4 inch	Ft	472	5.27	2487.44	
Conc Quality Initiative, Structure	Dlr	11320	1	11320	
Steel Sheet Piling, Temp	Sft	122	19.09	2328.98	
Steel Sheet Piling, Left in Place	Sft	3080	25	77000	
Conc Quality Assurance, Structure	Cyd	703	12.11	8513.33	
Substructure Conc	Cyd	384	365	140160	
Superstructure Conc	Cyd	128	209.74	26846.72	
Superstructure Conc, Night Casting	Cyd	191	230	43930	
Superstructure Conc, Form, Finish, and Cure	LS	1	28800	28800	
Superstructure Conc, Form, Finish, and Cure	LS	1	29000	29000	
Superstructure Conc, Form, Finish, and Cure, Night Casting	LS	1	72000	72000	
Conc Surface Coating	LS	1	73000	73000	
Conc Surface Coating	LS	1	73000	73000	
Expansion Joint Device	Ft	202	136.34	27540.68	
False Decking	Sft	23318	0.71	16555.78	
Reinforcement, Steel, Epoxy Coated	Lb	133188	1.05	139847.4	
Bridge Ltg, Oper and Maintain	Cyd	382	3.43	1310.26	
Bridge Ltg, Fur and Rem	LS	1	3000	3000	
Bridge Ltg, Fur and Rem	LS	1	3000	3000	
Substructure Horizontal Surface Sealer	Syd	66	18	1188	

Table 5-10 (Cont'd)

High Performance Superstructure Conc, Night Casting	**Cyd**	**191**	**225**	**42975**
High Performance Superstructure Conc, Form, Fin and Cure Night Casting	LS	1	90000	90000
Bearing, Elastometric, 2 3/4 inch	Sft	26	101.48	2638.48
Bearing, Elastometric, 3 1/4 inch	Sft	58	138.75	8047.5
Prest Conc I-Beam, Furn, 28 inch	Ft	1924	125	240500
Prest Conc I-Beam, Erec, 28 inch	Ft	1924	10	19240
Joint Waterproofing	Sft	432	4.55	1965.6
Joint Waterproofing, Expansion	Sft	304	6.46	1963.84
Reflective Marker, Perm Barrier	Ea	24	12.99	311.76
Bridge Railing, Aesthetic, Type 4, Det	Ft	552	85	46920
Adhesive Anchoring of Horizontal Bar	Ea	176	13.8	2428.8
Adhesive Anchoring of Vertical Bar, 3/4 inch	Ea	50	13.62	681
Reinforcement Mechanical Splice	Ea	1040	32	33280
Filler Wall Conc	Cyd	30	634.02	19020.6
Slope Paving Header	Ft	442	61.71	27275.82
Slope Paving, Conc	Syd	1170	52	60840

Table 5-11 - Operation, Repair and Maintenance Cost of HPC Mix

Operation Repair and Maintenance					
Description	**Unit**	**Quantity**	**Unit Cost**	**Total Unit Cost**	**Total Cost**
Thin Epoxy Overlays	Syd	600.8	60	36048	**36048**

Table 5-12 - Disposal Cost of Bridge

Bridge Disposal Cost					
Description	**Unit**	**Quantity**	**Unit Cost**	**Total Unit Cost**	**Total Cost**
Disposal of Bridge	Sft	5407.2	50	270360	**270360**

Total Life Cycle Cost of High Performance Concrete Mix

The total Life Cycle Cost is the sum of all costs involved in initial construction, repairing, maintaining and disposing to the owner, users and third parties.

Table 5-13 - Life Cycle Cost of HPC Mix

Event	Description	Year	Misc Cost	Cost
Event 1	Initial Construction	1	Complete Cost	1680602.09
Event 2	Deck Repair	40	Maintenance and Repair Cost	36048
Event 3	Disposal of Bridge	75	Disposal Cost	270360
	Total Life Cycle Cost			**1987010.1**

Comparison of Conventional Concrete Mix and High Performance Concrete Mix

It is obvious from the chart that the initial construction cost of HPC Mix ($1,680,602.09) is higher than the Conventional Concrete Mix ($1,662,013.97). The difference in initial construction cost between two alternatives is $18,500.12.

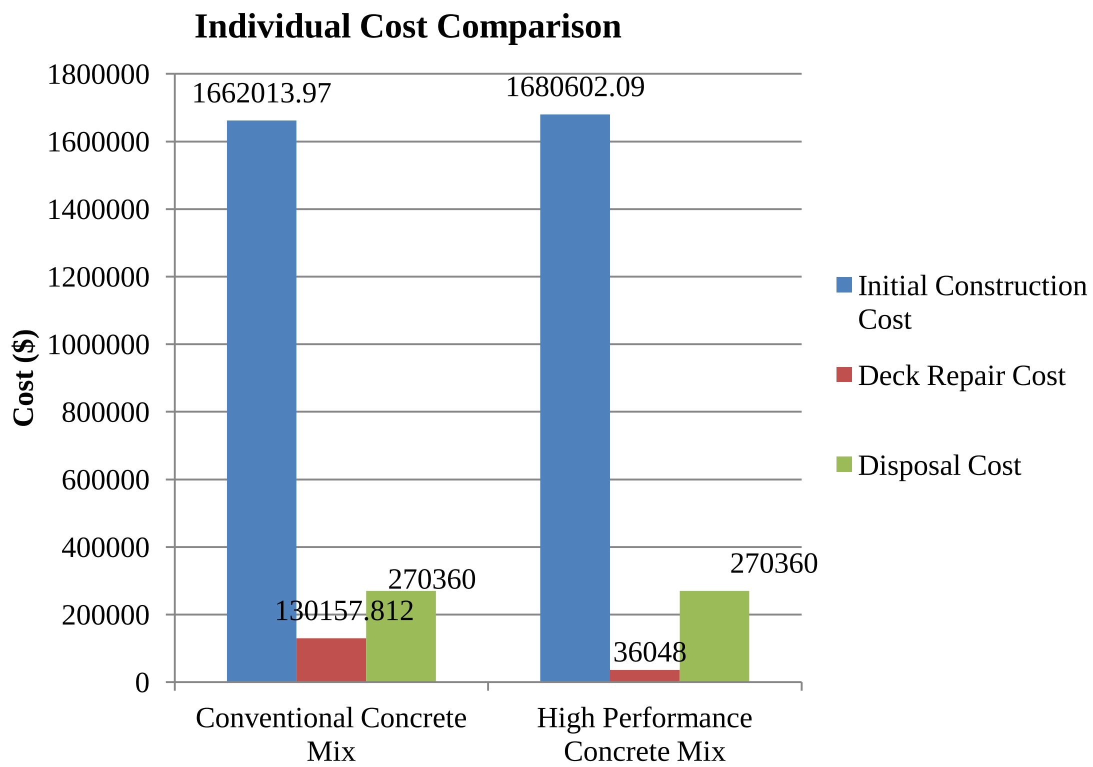

Figure 5-5 Comparison of Individual Costs

But, when evaluating the overall life cycle cost of both alternatives, the analysis illustrates that the total Life Cycle Cost of HPC Mix is $1,987,010.1 while Conventional Concrete Mix is $2,062,531.782. The difference in total life cycle cost of both alternatives is $75,521.682. Consequently, it is concluded that HPC Mix may have high initial construction cost but the total life cycle cost is reasonably low as compare to Conventional Concrete Mix. Therefore, according to LCCA, HPC is the best option towards building a sustainable environment and promoting green bridges concept.

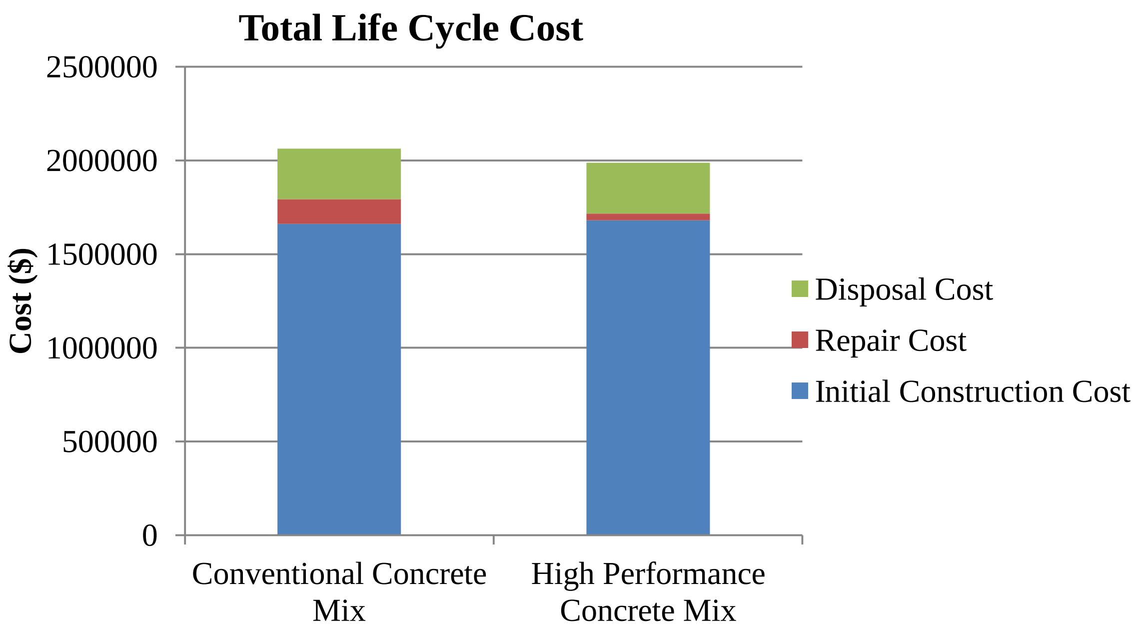

Figure 5-6 Total Life Cycle Cost

The use of HPC Mix in bridges results in an extended service life and low life cycle cost. Furthermore, HPC has shown better performance in reducing the carbon emissions and has less repair and maintenance cost than Conventional Concrete. For more complete analysis, a sensitivity analysis should be performed on the LCCA results to assess the impact of the discount rate on Life Cycle Cost.

5.4 CHAPTER SUMMARY

This Chapter provides comprehensive procedure to conduct LCCA for bridges. The vital components in LCCA of bridges include finding a suitable analysis period, defining different bridge alternatives, selection of an appropriate discount rate, and precise estimation of agency and user costs.

In the end, the Chapter presents a comparison on total life cycle cost of Conventional Concrete Mix and High Performance Concrete mix in superstructure. The total life cycle cost included initial construction cost, repair cost, maintenance and disposal cost. In this case study, only agency cost was considered owing to lack of information available on the bridge.

CHAPTER 6 SUMMARY AND CONCLUSIONS

6.1 CHAPTER OVERVIEW

This last Chapter presents a summary of the research study, a review of the research objective outlined in Chapter 1, and research outputs and conclusions. Finally, the chapter concludes with the recommendations for future research areas.

In the past few years, after applicability of sustainable practices in the building construction industry, bridge engineers have also integrated several sustainable construction practices in bridges. The sustainable techniques adopted by the US DOTs are growing rapidly due to large amount of investment involved in the bridge construction industry. In addition, the majority of existing bridges in the US are either structurally deficient or need rehabilitation/replacement due to lack of periodic maintenance. This research study will help the bridge construction industry to evaluate a bridge project and also assist in adopting new sustainable practices in design, construction, and maintenance, which will increase service life of bridge, reduce maintenance cost and cause minimum impact to the neighboring environment. The initial construction cost of green bridges is high but the total life cycle cost is greatly reduced.

6.2 SUMMARY OF CHAPTERS

Chapter 1, Introduction, presented background information on green bridges, the need statement, the research goals and objectives, research limitations and contributions, and research methodology. In addition, it discussed the expected research conclusion.

Chapter 2, Literature review, focused on the qualitative analysis of the existing literature and finding the gaps. The researched literature comprised of three major segments: the sustainability concept, Delphi method, and life cycle cost analysis of bridges. The sustainability concept included the evaluation of current sustainability assessment system for green buildings, highways and bridges.

Chapter 3, Framework for assessing sustainability in bridge design, construction and maintenance, discussed the development of a sustainability framework for bridge design, construction, and maintenance. The framework was divided into three categories: design, construction, and maintenance. The design category, the focus in this thesis, further entailed three sub-categories i.e. site, materials and others. There are a total number of 28 criteria; 14 in the design category, 6 in the construction category and 8 in the maintenance category.

Chapter 4, Methodology, data collection and analysis, presented an overview of the Delphi method, data collection and survey outputs. In addition, the Chapter highlighted the requirements and selection of participants, development, and distribution of survey.

Chapter 5, Life cycle cost analysis, presented the procedure to conduct LCCA of bridges and performed a case study on bridge superstructure using two different materials i.e. conventional concrete and HPC. The total life cycle cost was calculated.

6.3 SUMMARY OF RESEARCH OBJECTIVES ACHIEVED

6.3.1 Objective 1 – Summarize existing sustainability rating systems related specifically to green buildings, highways and bridges.

In this objective, the literature was divided into three categories: green buildings, highways and bridges. In addition, various sustainability assessment systems, such as USGBC's Leadership in Energy and Environmental Design (LEED®), New York State Department of Transportation's (NYSDOT) Leadership in Transportation and Environmental Sustainability (GreenLITES) Project Design Certification Program and U.S. Department of Transportation's Sustainable Highways Self-Evaluation Tool were reviewed and summarized. The comprehensive study of these sustainability assessment systems lead to the development of sustainable framework for green bridges in design, construction and maintenance.

6.3.2 Objective 2 - Develop a generic framework for green and sustainable bridge design, construction, and maintenance.

The conclusion of objective 1 guided to the development of a framework for gauging sustainability in green bridges. The description, intent, and standards/resources for each criterion were defined. The sustainability framework consisted of three parts; Design, Construction and Maintenance.

These three main categories were sub-divided into different criteria. The design category entailed three sections, i.e. site, material and other, and overall contained a total number of 14 criteria, while construction category has 6 criteria and maintenance category included 8 criteria.

6.3.3 Objective 3 - Conduct surveys and interviews, and assign points/weights to all criteria of suggested framework using the Delphi Method

To achieve this objective, the literature related to Delphi was reviewed. Several journal articles, papers and publications were studied. Similarly, special requirements for the selection of the participants were laid. The method was employed to collect opinions and responses of MDOT's design, construction, maintenance and environmental professionals and experts. It ran for two rounds and took approximately six weeks to develop a consensus among the participants.

The quantitative results obtained from the survey were used to assign points to all categories and criteria developed in objective 2.

6.3.4 Objective 4 - Conduct a life cycle cost analysis (LCCA) of green bridges

This objective focused on setting up guidelines and conducting LCCA of bridges. It included defining LCCA for bridges, selection of accurate input parameters, and detailed approach for conducting LCCA. Overall, this section discussed a consistent methodology for efficiently evaluating agency costs for sustainable bridge construction projects and compared total life cycle cost of a superstructure of a bridge using High Performance Concrete (HPC) and Conventional Concrete (CC).

6.4 AREAS OF FUTURE RESEARCH

This section provides a list of several future research areas. It includes proposing a suitable certification level, inclusion of agency cost in conducting the LCCA of bridges, LCCA of other criteria in the framework and evaluating the cost benefits of green bridges. The details of each future research areas are explained below:

a) Certification Level: In order to distinguish green bridge and award an appropriate certification to a bridge project, there is a need to develop a certification level. This can be done by evaluating various bridge projects and developing a distribution curve to choose different award levels.

b) Inclusion of user costs in LCCA: The research only compared the agency costs associated with the initial construction, repair, maintenance and disposal of a bridge project. Considering user and vulnerability costs in the analysis will undeniably make a huge impact to the total life cycle cost of a bridge project.

c) LCCA of criteria: LCCA of each criterion in design, construction and maintenance categories will assist in identifying the importance of every sustainability criteria and will make scoring system more reliable and realistic.

d) Cost benefits of sustainable bridges: In order to accurately estimate the cost benefits associated with a bridge project, various bridge models need to be developed to compare the total life cycle performance of a sustainable bridge with a traditional bridge.

6.5 SUMMARY

This research focuses on the implementation of sustainable practices in bridge design, construction and maintenance, and develops a sustainability framework to evaluate bridge projects. In addition, the Delphi technique is employed to assign points to all categories and criteria in this sustainability assessment system. Furthermore, this research compares—in detail—the total life cycle cost of two bridge superstructures; conventional concrete and high performance concrete to help understand the significance of sustainable materials in the bridge construction industry.

An advanced research study at the national level is required to establish a standard sustainable assessment to accurately evaluate bridge projects in the future. In the meantime, the rating system proposed in this thesis can be used as a pilot version to evaluate bridge projects.

APPENDICES

APPENDIX A

DELPHI SURVEY - IMPLEMENTATION OF SUSTAINABLE DESIGN, CONSTRUCTION, AND MAINTENANCE FOR BRIDGES

APPENDIX A

IMPLEMENTATION OF SUSTAINABLE DESIGN, CONSTRUCTION, AND MAINTENANCE FOR BRIDGES

My name is **Abdul Basir Awan**. I am a graduate student in Structural Engineering Program at Michigan State University, East Lansing, **Email**: basirmce@gmail.com, **Phone** # 517-505-9883 I am presently working with Professor Kasim Armagan Korkmaz, Ph.D. on the research topic "Life Cycle Cost Analysis and Delphi Survey for Bridges to Assist Sustainable Design, Construction, and Maintenance Framework of Bridges in Michigan".

"Implementation of Sustainable and Green Design and Construction Practices for Bridges" project aimed to develop a sustainable approach to bridge design, construction, and maintenance processes. The research team conducted a comprehensive analysis and developed a framework for achieving sustainability in bridge design, construction and maintenance.

This survey aims to gather expert/ professional's opinions on the "Implementation of Sustainable design, construction and maintenance for bridges". The results will be used to assign weights/ percentages to all criteria in Design, Construction and Maintenance category, previously developed for sustainable bridges in Michigan, which will be reported back to MDOT in a follow-up survey. The results of both surveys will be used in prospective analysis.

Principal Investigator's Name and Department: Kasim Armagan Korkmaz, Ph.D, School of Planning, Design and Construction, 201 Q Human Ecology Building. **Email**: akorkmaz@msu.edu **Phone**: 517-353-8756

Both surveys are anonymous, and do not include any personal questions. The survey will likely take about 20 minutes of your time.

Participation is voluntary; you may choose to discontinue your participation at any time without consequence.

Please respond no later than **29th of June 2012**.

Participant Signature   Date: (mm/ dd/ year)

A. Background Information

1. What is the highest level of education you attained?

- ☐ Some College
- ☐ Bachelor’s Degree
- ☐ Master’s Degree
- ☐ Ph.D.
- ☐ Others (If Other, please explain in space below)

2. How would you describe your role in your organization?

- ☐ Top Management
- ☐ Middle Management
- ☐ Expert/ Analyst
- ☐ Other (If Other, please explain in space below)

3. Which of the following job titles describes you best?

- ☐ Structural Engineer
- ☐ Construction Engineering & Management
- ☐ Material Engineer
- ☐ Maintenance Engineer
- ☐ Pavement Engineer
- ☐ Bridge Engineer
- ☐ Policy Maker
- ☐ Other (If Other, please explain in space below)

4. How many years of work experience do you have?

- ☐ 1 – 5 years
- ☐ 6 – 10 years
- ☐ 11 – 15 years
- ☐ 16 – 20 years
- ☐ 21 – 25 years
- ☐ 26 – above

5. Which department/ section are you currently working in?

- ☐ Design
- ☐ Construction
- ☐ Maintenance

☐ Other (If Other, please explain in space below)

6. How long have you been working in the department/ section, you mentioned above?

☐ 1 – 2 years
☐ 3 – 5 years
☐ 6 – 8 years
☐ 9 - above

7. Are you presently a member in a nationally recognized committee in the focus area of the work or a registered professional? (e.g. ASCE Site Safety Committee, Professional Engineer (P.E), Certified Safety Professional (CSP))

☐ No
☐ If Yes, please indicate your membership committee and year of membership

8. Have you ever worked on a project which involves "Sustainable practices in highways or bridges"?

☐ No
☐ If Yes, please describe briefly about your experience. Be specific like what guidelines for sustainability were followed, if any.

B. Framework for Assessing Sustainability in Bridges

The framework was divided into three sections;

- Design,
- Construction,
- Maintenance.

Design

The design section entails site, materials and others.

Reference: For details, please see Page # 23 of report "*Implementation of sustainable design, construction and maintenance for bridges*".

Construction

This section is based on construction techniques, water use, renewable energy, construction waste, and fuel efficiency.

Reference: For details, please see Page # 46 of report "*Implementation of sustainable design, construction and maintenance for bridges*".

Maintenance

The third section, maintenance highlights sustainability issues in bridge painting, cleaning, drainage and impacts on aquatic and wildlife.

Reference: For details, please see Page # 52 of report "*Implementation of sustainable design, construction and maintenance for bridges*".

The description, intent, requirements and standards have been established for each criteria by consulting various references such as American Association of State Highway and Transportation Officials (AASHTO), American Standard for Testing Materials (ASTM), Environmental Protection Agency (EPA), LEED®, 2009. The further details of the sustainability framework can be found in the manual provided to MDOT after the culmination of task 3.

B.1. Design

This category focuses on the measures that can be taken during the design of the bridges. Creating plans and employing methods in the design that result in achieving sustainability will be the intent of this category. The design principles will be consistent with MDOT policy and standards. The aim of this section is to introduce criteria which can affect the environmental sustainability and economic cost due to design of bridges. The design section is divided into sites, materials and other which are further subdivided into various criteria.

Please, first rank the criteria within the sections and then, assess the impact of each criterion by assigning the relative percentages to all criteria.

Please indicate your opinion of the importance of each of the following practices for achieving the environmental sustainability in the bridge design and add your comments.

Table A-1 Sustainability Framework - Design

DESIGN					
a. Site					
Criteria Pg #	**Title**	**Description**	**Rank**	**%**	**Comment**
1.1.1 Pg 25	Site Selection	To select sites that does not have impacts on the environment due to the location.			
1.1.2 Pg 26	Historic Site Preservation	To avoid development of historic sites and reduce the socio-cultural environmental impact from the location of a bridge on a site.			
1.1.3 Pg 27	Soil Erosion & Sedimentation Control	To reduce pollution such as soil erosion that may be due to wind or water, sedimentation and dust and particulate matter generation during construction activities.			
1.1.4 Pg 29	Brownfield Redevelopmen t	To rehabilitate contaminated sites and reduce pressure on undeveloped land.			
1.1.5 Pg 30	Storm-Water Management	To reduce the quantity of pollution and run-off from storm-water that is discharged into surface waterways or storm-sewers.			
	Total			**100**	

Table A-1 (Cont'd)

b. Materials					
Criteria Pg #	**Title**	**Description**	**Rank**	**%**	**Comment**
1.2.1 Pg 33	Use of Recycle Materials	To increase the demand for materials that incorporate recycled materials, thereby reducing environmental impacts resulting from extraction and processing of virgin materials.			
1.2.2 Pg 34	Supplemental Cementitious Materials	To replace a certain percentage of Portland cement used in concrete mixes.			
1.2.3 Pg 35	Reduction in Quantity of Materials	To reduce the amount of material, used in the construction of bridges by using innovative civil engineering techniques.			
1.2.4 Pg 37	Material Reuse	To reuse bridge materials and attachments to reduce demand for virgin materials and reduce waste			
1.2.5 Pg 38	Regional Materials	To increase demands for materials and products that are extracted and manufactured within the region, thereby supporting the use if indigenous resources and reducing the environmental impacts resulting from the transportation			
	Total			**100**	

Table A-1 (Cont'd)

c. Others					
Criteria Pg #	**Title**	**Description**	**Rank**	**%**	**Comment**
1.3.1 Pg 38	Renewable Energy Use	To reduce the electrical consumption and promote the use of renewable energy technologies.			
1.3.2 Pg 40	Bicycle/ Pedestrian Pathways	To promote the use of alternative transportation through bicycling and walking and thus minimize pollution and energy demand.			
1.3.3 Pg 42	Lane Adaptability	To provide a framework for additional lanes for any unforeseen conditions.			
1.3.4 Pg 43	Life Cycle Cost Analysis	To estimate the overall cost of the project alternatives and select the design that ensures the facility will provide the lowest overall cost of the ownership consistent with its quality and function			

In your opinion, what percentage of Site, Material and Other section will have an influence on the Design category. Based on your knowledge and professional experience, please rank the relative importance out of total 100%

- **Site**

- **Material**

- **Others**

B.2. Construction

Construction is an important phase which incorporates building of an entire structure. A successful project includes timely completion, cost-effectiveness and quality. These criteria will help in promoting a sustainable environment and lessening the impacts on nature by integrating recycled or reused materials, efficient water use, managing waste material on-site, utilizing sustainable energy resources and employing fuel efficient vehicles in the construction process. Others criteria can be use of innovative techniques like Accelerated Bridge Construction techniques (ABCT) to ensure timely completion of a project, as weather is an important factor in Michigan.

To your knowledge, how important are the following activities in promoting environmental sustainability, decreasing the environmental pollution, conserving nature and leading to a cost-effective and long-lasting bridge?

Please, first of all, rank the criteria within the sections and assign relative percentages and to what extent do you agree with each statement, please add comments?

Table A-2 Sustainability Framework - Construction

CONSTRUCTION					
Criteria Pg #	**Title**	**Description**	**Rank**	**%**	**Comment**
2.1 Pg 44	Accelerated Bridge Construction Techniques	To open a cost-effective, long-lasting bridge to traffic with increased safety and reduced traffic disruption in a shortened construction period			
2.2 Pg 45	Corrosion resistant steel reinforcement	To prevent bridge reinforcement from corrosion by penetration of chloride thus preventing the bridge from early deterioration and extending the service life of the bridge.			
2.3 Pg 47	Efficient Water Use	To conserve water through efficient use during bridge construction.			

Table A-2 (Cont'd)

2.4 Pg 48	Fuel Efficient Vehicles	To use fuel-efficient vehicles throughout the construction process, thus reducing the energy demands and carbon emission.			
2.5 Pg 49	Construction Waste Management	To divert waste generated in construction and demolition from disposal and in landfills and incineration			
2.6 Pg 50	Use of Certified Wood	To encourage best forest management practices			
	Total			**100**	

B.3. Maintenance

This section outlines the requirements of inspection technologies, bridge painting, cleaning, deck drainage and impacts to fish and wild life that should be met in order to reduce environmental impacts associated with this.

To your knowledge, how important are the following activities in enhancing the service life, reducing life cycle cost of the bridges and lessening maintenance requirements.

Please, first of all, rank the criteria within the sections and assign relative percentages to each criterion and to what extent do you agree with each statement, please add comments?

Table A-3 Sustainability Framework - Maintenance

MAINTENANCE					
Criteria Pg #	**Title**	**Description**	**Rank**	**%**	**Comments**
3.1 Pg 52	Efficient Inspection Technologies	To use efficient inspection technologies and processes for proper maintenance action decision thus enhancing the service life and reducing life cycle cost of the bridges.			

Table A-3 (Cont'd)

3.2 Pg 54	Bridge Painting/Coating/Sealing	To prevent bridge components from deterioration due to corrosion thus increasing the age of bridges.			
3.3 Pg 57	Bridge Cleaning	To clean components of bridges vulnerable to dirt, bird drop accumulation etc. thus increasing efficiency of the bridge components and lessen maintenance requirements.			
3.4 Pg 59	Bridge Deck Drainage	To avoid impacts on the deck structure and reinforcing bars due to inefficient drainage.			
3.5 Pg 60	Avoiding and Minimizing Impacts to Fish and Wild Life	To avoid impacts on fish and wild life due to maintenance activities.			
3.6 Pg 61	Corrosion Control Materials	To prevent or minimize the corrosion of bridge elements due to the penetration of sodium chloride.			
3.7 Pg 62	Bridge Deck Joints and Deck Joint Seals	To eliminate bridge deck joints, when possible.			
3.8 Pg 63	Snow and Ice Control	To implement snow and ice control techniques and to reduce the environmental impacts			
	Total			**100**	

Based on your professional experience, please indicate the relative percentages for the following categories out of a total 100% **e.g.** design – 20%, construction – 35% and maintenance – 45% etc.

- **Design**

  [ ]

- **Construction**

  [ ]

- **Maintenance**

  [ ]

General comments and thoughts concerning the survey:

APPENDIX B

SURVEY RESULTS

APPENDIX B

Table B-1 Survey Results

DESIGN		ROUND 1 & 2			
Site		Results			
Criteria	**Title**	**Frequency**	**Mean**	**Median**	**Std Dev**
1.1.1	Site Selection	9	25	25	8.66
1.1.2	Historic Site Preservation	9	13.7	14	8.19
1.1.3	Soil Erosion & Sedimentation Control	9	26.77	25	4.14
1.1.4	Brownfield Redevelopment	9	11	10	7.26
1.1.5	Storm-Water management	9	23.44	25	3.43
	Total		100	99	
Materials					
Criteria	**Title**	**Frequency**	**Mean**	**Median**	**Std Dev**
1.2.1	Use of Recycle Materials	7	30	25	14.71
1.2.2	Supplemental Cementitious Material	7	16.42	20	10.29
1.2.3	Reduction in Quantity of Materials	7	19.28	20	7.31
1.2.4	Material Reuse	7	12.85	10	10.74
1.2.5	Regional Material	8	19.37	19.37	12.08
	Total		97.94	94.37	
Others					
Criteria	**Title**	**Frequency**	**Mean**	**Median**	**Std Dev**
1.3.1	Renewable Energy Use	7	10.87	5	14.12
1.3.2	Bicycle/Pedestrain Pathways	7	15.71	15	7.86
1.3.3	Lane Adaptability	7	13.28	10	8.19
1.3.4	Life Cycle Cost Analysis	7	58.57	70	22.86
	Total		98.44	100	

Title	**Frequency**	**Mean**	**Median**	**Std Dev**
Site	7	46.42	50	13.75
Material	7	34.28	30	19.24
Others	7	19.28	20	13.67

Table B-1 (Cont'd)

CONSTRUCTION					
Criteria	**Title**	**Frequency**	**Mean**	**Median**	**Std Dev**
2.1	ABCT	7	45	30	24.83
2.2	Corrosion Resistant Steel Reinforcement	7	26.42	20	23.04
2.3	Efficient Water Use	7	8.14	5	8.80
2.4	Fuel Efficient Vehicles	7	5.28	5	4.71
2.5	Construction Waste Management	7	12	5	11.60
2.6	Use of Certified Wood	7	3.85	2	4.56

MAINTENANCE					
Criteria	**Title**	**Frequency**	**Mean**	**Median**	**Std Dev**
3.1	Efficient Inspection Tech	7	14	18	9.14
3.2	Bridge Painting/Coating/Sealing	7	25	20	18.25
3.3	Bridge Cleaning	7	7.71	10	4.99
3.4	Bridge Deck Drainage	7	8	8	6.19
3.5	Avoiding and Minimizing Impacts to Fish and Wild Life	7	5.85	5	4.18
3.6	Corrosion Control Materials	7	16	20	7.30
3.7	Bridge Deck Joints and Deck Joint Seals	7	17.85	20	6.84
3.8	Snow and Ice Control	7	5.57	5	3.25

OVERALL RATING				
Title	**Frequency**	**Mean**	**Median**	**Std Dev**
Design	6	47.21	45	11.24
Construction	6	30.55	31.65	14.20
Maintenance	6	22.21	25	10.46

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