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Implementation of Sustainability in Bridge Design, Construction and Maintenance

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16. Abstract

The focus of this research is to develop a framework for more sustainable design and construction processes for new bridges, and sustainable maintenance practices for existing bridges. The framework includes a green rating system for bridges. The green rating system is divided into three sections, which are design, construction and maintenance. The three sections are further divided into various criteria. For each criterion the description, intent, and requirements have been established. The requirements were established after reviewing various industry standards. The Delphi survey was conducted at MDOT divisions to assign point values to sections and the criteria. The results of the Delphi survey and scorecard of the rating system are shown in the relevant appendix and/or sections. The certification levels for the rating system are established to categorize sustainable bridges. A bridge can be categorized as Non-Green, Certified, Green, Total Green, and Evergreen, depending on the total score obtained by the project. LCA and LCCA guidelines are also developed to support the sustainability of bridge projects. LCA guidelines include the steps to calculate GHG emissions in a bridge project. It was made an inventory of construction materials and equipment that can be used in bridge projects, and found their emission factors in literature, historical databases, or by using computer tools. Certain products emit less GHG compared to conventional products. Recycled materials such as fly ash, blast furnace slag cement, high performance concrete, and steel produce much less emissions than traditional materials. Sustainable products are listed along with their emission factors and can be used to calculate GHG emissions. LCCA guidelines include steps to calculate the life cycle cost of bridges.

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EXECUTIVE SUMMARY

IMPLEMENTATION OF SUSTAINABLE AND GREEN DESIGN AND CONSTRUCTION PRACTICES FOR BRIDGES

By

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A bridge constitutes a large investment of capital, materials, and energy and is associated with significant social, economic, and environmental impacts. Applying sustainable practices to bridge design, construction, and maintenance can enable an environmentally responsible and effective use of resources for this large investment. The focus of this study is to develop a framework that assists transportation engineers and managers in developing more sustainable design and construction processes for new bridges, and sustainable maintenance practices for existing bridges. This framework consists of a green rating system, which is divided into three categories, which are design, construction, and maintenance. The last two sections are further divided into various criteria. For each criterion, the description, intent, and requirements have been established. The requirements are established based on various industry standards such as the Environmental Protection Agency (EPA), American Association of State Highway and Transportation Officials (AASHTO), Federal Highway Administration (FHWA), LEED®, and current bridge engineering standards. The certification levels for the rating system are established based on research panel discussions and interviews with MDOT experts to categorize sustainable bridges. A bridge can be categorized as Non-Green, Certified, Green, Total Green, and Evergreen, depending on the total score obtained by the bridge project. Lastly, the guidelines were developed to estimate GHG emissions in bridge projects and the Life Cycle Cost of bridges to support the framework.

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CHAPTER 1
INTRODUCTION

1.1 Overview

Sustainable practices are key components in almost every aspect of our lives; green strategies are now being incorporated in everything from foods to building cars and building engineering structures (Louis, 2010). A bridge constitutes a large investment of capital, materials, and energy and is thus associated with significant environmental impact. In addition to design and construction, bridge maintenance is an important issue in the United States. Sustainability is a long-term approach that can enable environmental protection and process improvements (EPA, 2012). Thus, the application of sustainable practices for bridge design, construction, and maintenance can enable an environmentally responsible construction and effective use of resources for this large investment.

Many Department of Transportation (DOT) bridge designers and constructors have explained various environmentally sustainable alternatives (ASBI 2007, Hong et. al., 2006). The U.S. Department of Transportation states, “DOT is committed to becoming a leader in sustainability. The U.S. Department of Transportation incorporating sustainable practices in the department’s mission helps to promote energy and natural resource conservation, decrease Greenhouse Gas (GHG) emissions, reduce pollution and contamination releases, enhance the workplace by minimizing hazardous materials and chemicals and strengthen the national interest by encouraging energy independence” (USDOT, 2011).

In recent years, DOTs have made a great effort to implement sustainable applications in bridge design, construction, and maintenance in order to achieve their goals in an environmentally responsible and cost-effective manner. The Oregon Department of Transportation is a leader in sustainability planning and initiatives and has a sustainability program focused on health and safety, social responsibility, environmental stewardship, land use and infrastructure, energy/fuel use and climate change, material resource flow, and economic health (ODOT, 2012). Similarly, other DOTs like MDOT, Texas DOT, and New York DOT have taken steps to implement sustainability practices in the design, construction, and maintenance of highways and bridges. These DOTs are implementing sustainability practices either through the application of sustainable materials or using green rating systems. MDOT has recently expressed their interest in developing a framework that can be used to categorize sustainable bridges and involve the application of sustainable materials, standards that aim to reduce environmental pollution, and other concepts that contribute towards sustainability.

During this study, feedback has been taken from MDOT and the framework is developed based on MDOT requirements; therefore, this study relates to bridges in Michigan. This framework can assist MDOT in implementing sustainable approaches in bridge projects. The research study consists of five major parts: 1) literature review, 2) development of sustainable and green framework, 3) conducting surveys using the Delphi method 4) life cycle assessment 5) life cycle cost analysis. The methodology adopted to achieve these objectives is organized in Figure 1.1. Firstly, sustainable practices that are followed in buildings, bridges and other sectors, were compiled through an extensive literature review. Then, it was determined which of those practices can also be used for bridges. A list was formed of sustainable practices suitable for bridges with guidance and feedback from MDOT, based on their requirements.

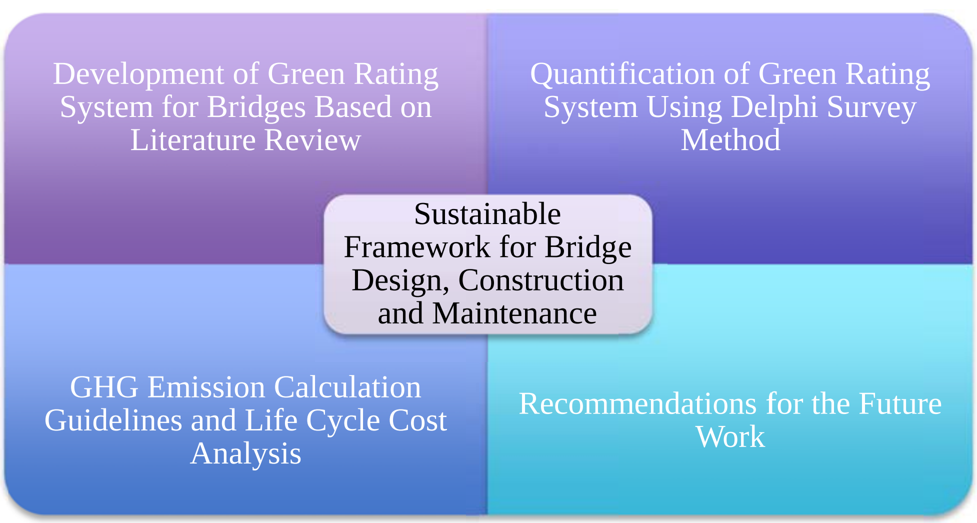


Figure 1.1: Steps in the Research Study

Chapter 1, “Introduction”, discusses the importance of sustainability, a research goal, and objectives used to accomplish the goal. The research methodology used is also shown. Chapter 2, “Literature Review”, compiles all the current sustainable practices followed in building construction projects, bridge projects, and other sectors. Literature was reviewed related to sustainable theoretical practices, existing green rating systems in the United States, LCA applications to compute GHG emissions in construction projects, and LCCA applications. Chapter 3, “Framework for Assessing Sustainability in Bridge Design, Construction and Maintenance”, includes the development of framework to implement sustainability in bridge projects. This includes the development of a green rating system for the bridges, quantifying that green rating system, and determining certification levels to categorize sustainable bridges. Chapter 4, “GHG Emission Calculation Guidelines Based on LCA Methodology”, evaluates the framework and supports sustainable decision-making. This includes the development of an Excel based tool that can be used to compute estimated GHG emissions due to materials and equipment used in bridge projects. Chapter 5, “Results and Conclusions”, discusses the summary of results and provides recommendations for future work.

1.2 Need Statement

The built environment has great impact on the natural environment, economy, and human health (EPA, 2010). By incorporating green strategies, a large number of environmental, economic, and social benefits are seen. The EPA lists the potential benefits of green buildings, which include enhancement and protection of biodiversity and ecosystems, improving air and water quality, reducing waste streams, conserving and restoring natural resources, reducing operating costs, minimizing strain on infrastructures, and improving overall quality of life (EPA, 2010).

Despite billions of dollars in federal, state, and local funds directed toward the maintenance of existing bridges. 69,223 bridges (11.5% of total highway bridges in the U.S.) are classified as "structurally deficient", requiring significant maintenance, rehabilitation, or replacement (Shoup et. al., 2011). More than 13% of Michigan bridges are considered structurally deficient under the federal rating system and need significant repairs. Approximately 11,000 bridges in Michigan are about 41 years old and approaching their 50-year life (Helms, 2011).

Since many of these bridges are approaching their maximum service life, they need to be replaced. All the activities, such as the construction of new bridges, repair, rehabilitation, and replacement of the existing bridges, are associated with considerable environmental impact. Therefore, sustainable applications that can reduce environmental impact need to be developed and implemented.

Activities involved in construction have a significant environmental footprint, especially in terms of greenhouse gas (GHG) emissions and energy consumption (Orabi et. al, 2012). The Environmental Protection Agency (EPA) ranks the construction industry third in generation of GHG emissions with 6% of all industry related emissions in the United States (EPA, 2009). Transportation is a vital part of the economy but also a significant source of GHG emissions. It involves a large number of construction activities, which directly or indirectly release greenhouse gases, water, and land pollutants. Several studies have focused on measuring the environmental impacts of construction activities and finding ways to minimize these impacts. There has been a recent need to adopt methodologies that aim at reducing such impacts and contribute to sustainability. Therefore, this study is necessary to develop a framework for bridges that can be used as a guideline to achieve sustainability.

1.3 Research Methodology

The developed research methodology lists the steps necessary to accomplish the goal, as shown in Figure 1.2. First, literature related to current sustainable practices followed in building construction, bridge construction, and other sectors were reviewed. Then it was determined which of those practices can also be used in bridge construction projects. Based on content analysis or the literature review, an overall framework including a green rating system for bridges was developed. Feedback on the rating system is taken regularly from MDOT until they suggest no further modifications. After the framework was approved by MDOT, the rating system was quantified using the results of the Delphi survey conducted at MDOT divisions. At last, guidelines for calculating GHG emissions in bridges and conducting LCCA of bridges were developed to support the sustainability of bridge projects.

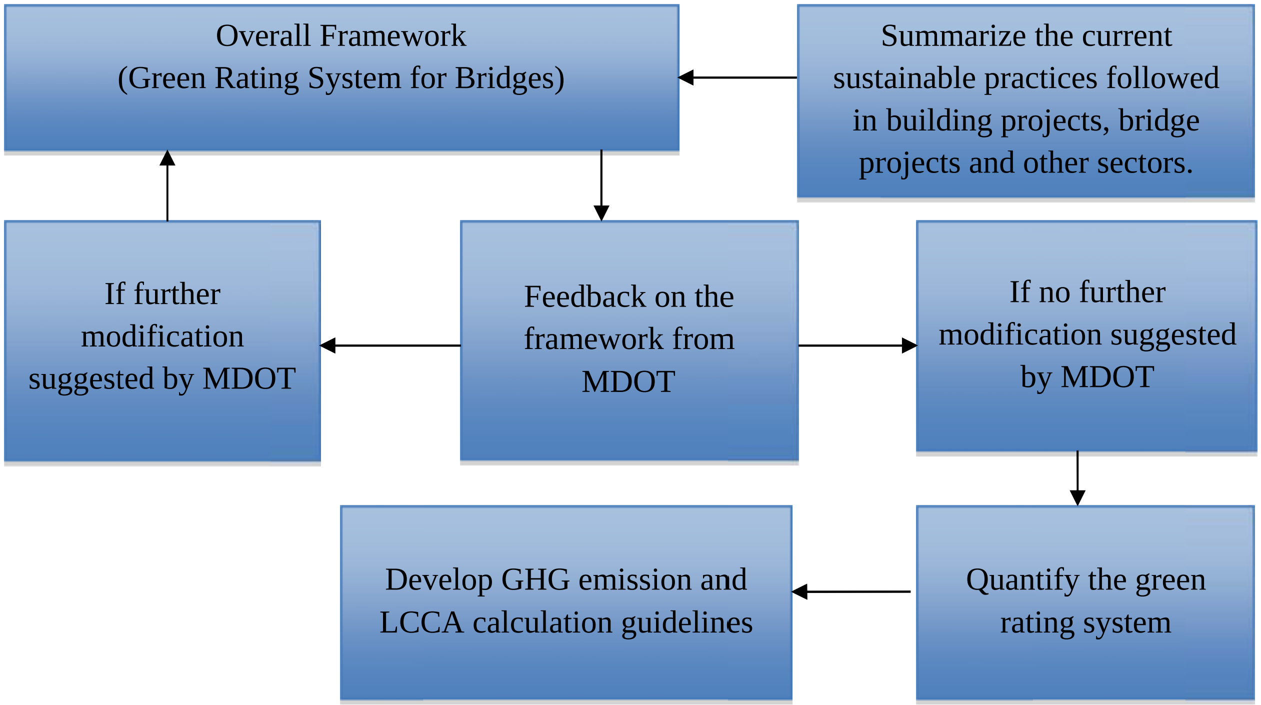


Figure 1.2: Research Methodology

1.4 Summary

As discussed in Chapter 1, sustainable construction is a key component in sustainable development. Any bridge project should be executed in such a way that sustainability is incorporated in every stage including design, construction, and maintenance. Sustainability is about balancing what is beneficial to people, while considering what is economically sound and environmentally compatible. Implementing sustainable approaches may increase the project cost, however it may be warranted when all external cost are considered (NYSDOT, 2008). Climate change, energy use, environmental impacts, and limits to financial resources for transportation infrastructure are major global concerns. It requires new approaches to planning, designing, constructing, operating, and maintaining transportation solutions and systems (AASHTO, 2009). There are various practices followed at design, construction, operation, and maintenance levels. Many DOTs are concerned with the sustainability triple bottom line as well as the implications for mitigation and adaptation to climate change (AASHTO, 2009). The focus of this research study is to develop a framework that assists transportation engineers and managers develop more environmentally sustainable design and construction processes for new bridges, and sustainable maintenance practices for existing bridges.

CHAPTER 2
LITERATURE REVIEW

2.1 Literature Review Categories

The current sustainable practices in bridge design, construction, and maintenance are the most important sources upon which sustainability guidelines are developed. In this chapter, literature is reviewed to form three categories as shown in Figure 2.1. The first category reviews literature on current sustainable practices in bridge design, construction, and maintenance by consulting articles, theses, books, journals, and magazines. The second category reviews literature on major existing Green Rating Systems in United States such as LEED V.3 (USGBC, 2009), Envision^{TM} Rating System (ISI, 2012), GreenLITES Certification System (NYSDOT, 2008), and Sustainable Self-Highway Evaluation Tool (FHWA, 2012). Another green rating system for bridges developed by Lauren R. Hunt was also reviewed. The third category focuses and summarizes the existing literature related to LCA and LCCA applications.

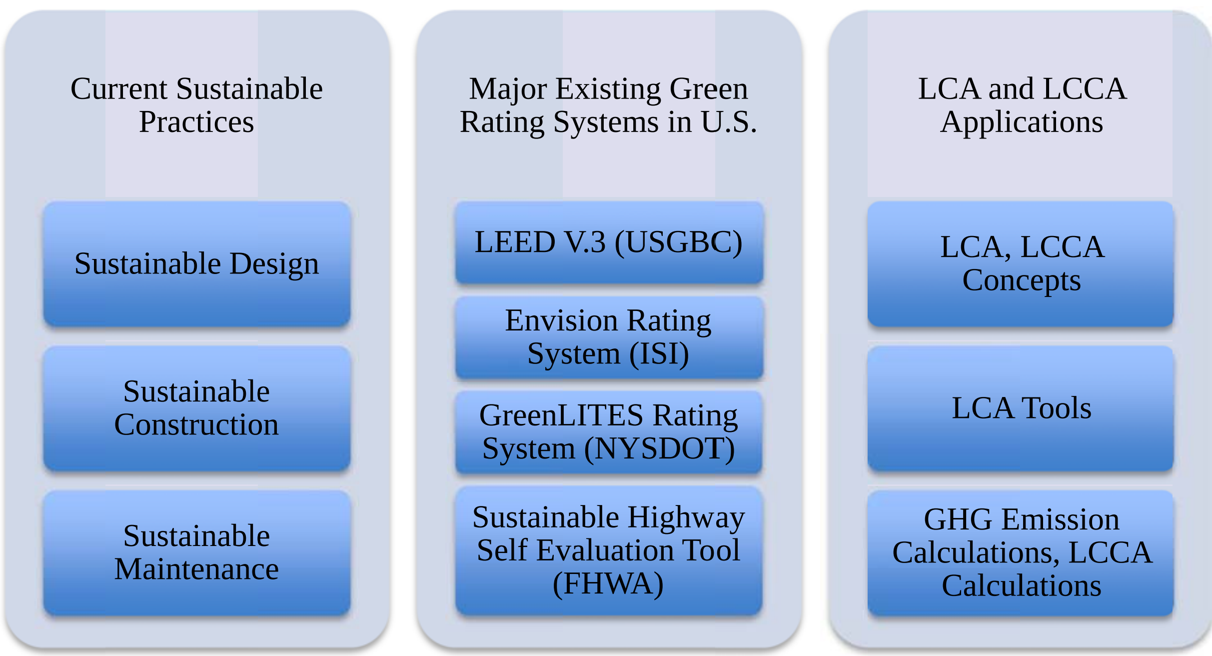


Figure 2.1: Literature Review Categories

2.2 Sustainability Overview

Sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own need” (WCED, 1987). Since buildings in the U.S. contribute 39% of all carbon dioxide (CO_2) emissions, 40% of raw material use, and 72% of the total electricity consumption (EPA, 2009), sustainability is increasingly adopted by the U.S. building industry with motivation to reduce the environmental impacts. Several tools have been developed to serve the building industry for sustainable design and construction: green building rating systems such as the U.S. Green Building Council’s (USGBC, 2009) Leadership in Energy and Environmental Design (LEED®), life cycle cost analysis (LCCA), and life cycle assessment (LCA). These tools can also be applied to bridge design, construction, and maintenance to make new and existing structures more environment friendly in the long run, in other words more sustainable.

In the United States, sustainability assessment systems are mostly available for buildings and there is lack of guiding and/or measuring sustainability practices for bridges (Whittemore, 2010). The United States Green Building Council (USGBC) is a non-profit organization dedicated to sustainable building design and construction. USGBC’s Leadership in Energy and Environmental Design (LEED®) is a rating system, used as a national standard for the design, construction, and operation of sustainable or green buildings. From 2005 to 2008, green building construction increased dramatically from 2% to 20% of overall construction (McGraw Hill Construction, 2012). Although, LEED® rating system is only used for buildings, some useful metrics are also applicable to bridge sustainability assessment (Whittemore, 2010). A sustainable bridge can be defined as the one that is “conceived, designed, constructed, and maintained, and eventually put out of service in such a fashion that these activities demand as little as possible from the natural, material, and energy resources from the surrounding community” (Whittemore, 2010).

Sustainability can be explained under:

1) Structural Sustainability,

2) Environmental Sustainability in the context of bridges.

The structural sustainability, in the American Concrete Institution (ACI) Fall 2010 Convention, it is stated as, "A structural sustainable concrete bridge should provide an overall life of 100 to 150 years"; “They should have minimum of shrinkage (plastic, drying, chemical shrinkage) and cracking". For example use high performance concrete (HPC) to minimize dry shrinkage and use saturated lightweight aggregates for internal curing for the promotion of hydration in order to minimize shrinkage and cracking. HPC should have other optimum concrete characteristics such as low water/cement ratio and high flexural strength. “Long service life of bridge decks over 100 years can be achieved with low shrinkage, low permeability HPC, compared to only 20 years for normal strength concrete decks.” (ACI, 2010). Although structural sustainability is important, the focus is on environmental sustainability of bridges. Environmental sustainability deals with the environmental impacts of the product or the process in all life cycle stages of the bridge, i.e., to measure the environmental impacts and performance of the product or process over the design, construction, use, maintenance, and disposal stages (EPA, 2006). The following sections expand on the environmental aspect of sustainability for bridges.

2.3 Current Sustainable Practices

A number of articles, theses, journals, books, and magazines were consulted to review current sustainable approaches in bridge design, construction, and maintenance. This section describes methodologies and approaches used to assess sustainability. The current sustainable practices are reviewed in three categories, which are a) Sustainable Bridge Design, b) Sustainable Bridge Construction and, c) Sustainable Bridge Maintenance.

2.3.1 Sustainable Design

The design of a bridge is an important phase where most decisions can impact later stages. Incorporating sustainability approaches and methods in the design stage is important for achieving sustainability. For example, site selection, material selection for design, service life design, span arrangement, substructure type, geometry, and foundation types are some of the factors that should be taken into consideration during the design stage; alternative ways are usually considered to achieve sustainability.

Lounis and Daigle (2007) compared the environmental benefits of high performance concrete decks (HPC) and normal performance concrete (NPC) bridge decks. It was found that the construction of HPC structures results in a reduction in the number of maintenance and repair actions, which in turn will result in a reduction in both materials and energy consumption as well as in a reduction of CO_2 emissions and waste production. A simplified life cycle environmental analysis of two bridge decks was undertaken by focusing on two impacts: a) emissions of CO_2 and b) waste production (or landfill use). In terms of environmental impact, it is estimated that the HPC deck alternative yields a reduction of 65% in CO_2 emissions compared to the normal concrete deck. It was also found that based on the onset of corrosion as the end of service life criterion, the HPC deck alternative incorporating SCMs has a service life that can vary from 3 to 10 times the service life of a normal concrete deck having the same water-to-cementitious materials ratio (Lounis and Daigle, 2007).

High service life design requires the designer to explore outside the current codes, evaluate environmental loading, and establish material performance over a long period; this calls for extrapolation of current knowledge of climate and material properties as well as the extrapolation of material deterioration models (Connal, 2009).

Sustainability objectives for bridges can also be best accomplished by ensuring durable bridges with a long service life and low maintenance inputs that, on a whole-of-life basis, minimize material consumption over the long term. It is likely that such a bridge also has the lowest whole-of-life economic cost (Connal, 2009).

There is need for concrete durability design. Reinforced concrete and pre-stressed concrete bridges, which are exposed to aggressive environments, are affected by the corrosion of steel due to carbonation and the ingression of chlorides. Chloride ingression has been formulated on the assumption that it would occur by ionic diffusion. Based on concrete mix, cementitious content was determined and the additional materials such as fly ash and slag have been used to reduce the heat of hydration and greenhouse gas emission, thereby increasing the durability.

Another factor that decreases the durability of the structure is carbonation. The primary concern is for superstructure elements. Its passive iron oxide layer decreases the PH value of concrete, reinforcing protection from corrosion. Therefore it is important to reduce the effect of carbonation, which can be reduced by using high quality concrete and sufficient depth of cover. To achieve a long bridge life, the following are important factors to consider: selection of good quality of concrete, selection of greater cover for reinforcement, provision of electrical continuity for reinforcement in substructure element, and good detailing to enable compaction of concrete, along with good vibration and subsequent curing during construction to ensure a dense layer of cover concrete (Connal, 2009).

Materials play an important role in sustainability and a number of research studies have been conducted to determine sustainable properties of materials. Steel bridges offer numerous advantages contributing to sustainability. Offsite production in fabrication plants results in minimum waste. Use of automated production, using robotic welders, results in a safe environment. A single clear span for a bridge is one of the best environmental solutions, and avoids permanent piers in the river. Steel is a recyclable material that can be recycled and reused multiple times without affecting its structure or properties. It promotes the management of sustainable resources. It minimizes the effect on the local community, as steel components are manufactured offsite. Selecting steel ensures reduced energy consumption and CO_2 level emissions, as shown in Table 2.1.

Table 2.1: Embodied Energy and CO_2 Levels for Steel (BCSA and Corus, 2009)

	Steel Sections	**Steel Plate**
Embodied CO_2	0.762 tCO_2/t	0.919 tCO_2/t
Embodied Energy	0.762 tCO_2/t	0.919 tCO_2/t

Use of weathering steel minimizes the need for future maintenance and any associated road closures (BCSA;Corus, 2009). Weathering steels are high strength, low alloy steels that can provide greater protection against corrosion. Since copper is used as an alloy, it provides a mechanism that prevents atmospheric corrosion. FHWA emphasizes the use of steel in bridge construction as it improves the performance and research (Kozy and Triandafilou, 2011).

TxDOT has built over 100 weathering steel bridges since 1970. A research study was conducted for TxDOT that includes field visits where different samples were collected in order to examine the presence of protective oxide film, section loss, and presence of chlorides, cause and control of staining, and any other apparent corrosion and aesthetic performance issues. It was found that uncoated weathering steel is a quality material for TxDOT bridges as it provides a good protective oxide film forms, protecting the steel from further corrosion (McDad et. al., 2000).

GRP decks have great significance in the sustainability of bridges. It is a composite steel hybrid structure that requires minimal maintenance and is very economical. In the long term, road users should benefit from reduced delay and disruption since the bridge will need minimal maintenance. Fast installation with less disruption to traffic and reduced long-term maintenance are two compelling reasons for the selection of a composite bridge deck over concrete. GRP offers several advantages over conventional bridge materials such as reinforced concrete, including the following: higher strength to weight ratio; high degree of pre-fabrication possible; faster installation; and corrosion resistance (Jacob, 2008).

The transportation industry uses alternative materials in the construction of pavement; they are currently using bulk materials such as natural and fine aggregates. Materials including industrial by-products, concrete aggregates, old asphalt pavement, scrap tires, fly ash, steel slag, and plastics are often used as alternate materials for natural aggregates. These materials are best used for their environmental suitability, recyclability, and sustainability in concrete and road pavement applications, as well as their environmental impact on surface and ground waters. Many types of products result in the creation of large quantities of solid waste materials (SWMs). Many of these SWMs remain in the environment for long periods of time and cause waste disposal problems. Existing landfills are reaching maximum capacity and new regulations have made the establishment of new landfills difficult. Disposal cost continues to increase while the number of accepted wastes at landfills continues to decrease. Use of industrial by-products in the construction of transportation networks can contribute to sustainable development (Kassim et. al. 2008).

Currently, industrial by-products (such as fly ash, steel slag, plastics, and scrap tires) are used as substitutes for natural aggregates in road construction. Various solid wastes that have been used in several highway applications for sustainability considerations are bag-house fines, blast furnace slag, carpet fiber dusts, coal bottom ash/boiler slag, coal fly ash, contaminated soils, flue gas desulfurization scrubber material, foundry sand kiln dusts, mineral processing wastes, and municipal solid waste incinerator ash (Kassim et. al. 2008).

Other practices that are considered to contribute to sustainable design are longer spans, high strength, more durability-better long term performance, and smaller cross-sectional area; use of high performance composites: fiber reinforced polymers (FRP), FRP wraps used for rehabilitation projects; use of aluminum as light weight bridge decks results in 80% lighter deck than concrete and is more corrosion resistant, requires fewer welds than steel thus reducing potential failure points; use of high performance steel, for example a new grade of steel: hps-485w which results in increased toughness, superior weldability and high corrosion resistance; using hybrid designs results in 17% weight savings, 11% cost savings (Gilbertson, 2008).

2.3.2 Sustainable Construction

There are two main processes during construction the stage, which are responsible for energy consumption and emissions. These are a) Transportation and b) Operation. In a normal life cycle, main transportation operations occur ‘‘to site’’, ‘‘from site’’, and “on site”. An evaluation of energy released during transportation, the average distance traveled, and the fuel efficiency of vehicles that travel to and from the site are considered in this life cycle (Pacheo and Campos, 2010). Energy consumed during construction operations is another important factor. Energy consumption is calculated using the weight of equipment, energy it consumes per hour of operation, and the construction duration of a typical bridge deck (Pacheo and Campos, 2010).

Different road equipment such as trucks and other vehicles are used during construction operations to transport materials to and from site, which consumes fuel and release wastes to atmosphere. Non-efficient fuel vehicles can increase fuel consumption and also releases GHG emissions. Similarly, various non-road construction equipment such as excavators, bulldozers, compactors, pressure washers, cement and mortar mixers, pumps, trenchers, rollers and other construction equipment used during operation consumes fuel and releases energy. Air emissions from construction equipment contribute significantly to the degradation of the environment. Therefore, it is imperative to use equipment that produces fewer emissions than conventional ones. "Non-road engines are all internal combustion engines except motor vehicle (highway) engines, stationary engines (or engines that remain at one location for more than 12 months), engines used solely for competition, or engines used in aircraft. The non-road standards cover mobile non-road diesel engines of all sizes used in a wide range of construction, agricultural and industrial equipment" (EPA, 2004). So, non-road equipment is used in construction and not on roads like cars, buses, etc.

The EPA recommends non-road construction equipment to "have engines that meet the current U.S. Environmental Protection Agency (EPA) Tier emission standards (Tier 3/Interim Tier 4 as of April 2011) in effect for non-road engines of the applicable engine power group"; and "have diesel retrofit devices for after-treatment pollution control verified by EPA or the California Air Resources Board (CARB) for use with non-road engines" (FHWA, 2012). Using alternative fuels such as biofuels and material recycling have been considered green practices.

Reducing fuel use can be an effective step in reducing GHG emissions. Diesel contributes to 22.37 lbs of CO_2/gallon and gasoline contributes to 19.54 lbs. of CO_2/gallon. Similarly, propane and natural gas contribute to 12.66 lbs. CO_2/gallon and 11.7 lbs. CO_2/1000 cu.ft. These numbers show that a significant amount of CO_2 emissions are associated with fuel use. LCA helps in determining the total emissions and could provide support in investigating various strategies to reduce these emissions. If ways are implemented to reduce fuel use by 3%, 2.02 MMT of CO_2 emissions will be reduced. Using biofuels for trucks and non-road equipment can reduce significant GHG emissions (EPA, 2009).

The accelerated bridge construction technique is an innovative approach that contributes greatly towards sustainability. Accelerated construction is used to achieve the construction of structures in the shortest possible time while decreasing delays and traffic disruption. It is not merely building structures rapidly but also entails a variety of techniques, processes, and technologies to reduce congestion due to construction while improving quality. These techniques are used for the construction of new bridges and also the replacement of existing bridges (Ralls, 2007). Using precast bent caps, precast columns, precast deck panels, precast barriers, prefabricated trusses, precast abutments, retaining walls and footings allow manufacturing to take place in a controlled environment, thereby reducing impacts to traffic and environmental impacts (FHWA, 2012).

2.3.3 Sustainable Bridge Maintenance

Bridge maintenance is a major part of a bridge life cycle. There are a number of activities involved in bridge maintenance that may have significant impacts on the environment. Bridge maintenance usually includes short-term fixes, medium-term fixes, and long-term fixes. Short-term fixes include capital preventive maintenance (CPM). It applies lower-cost treatments to slow the deterioration rate, maintain or improve the functional condition, and extend the pavement's service life. Medium term fixes includes rehabilitation. Rehabilitation is the application of structural enhancements, such as multiple course resurfacing or concrete pavement repairs, that improve the roadway or overlaying of a bridge deck and superstructure repair. Long-term fixes include reconstruction/replacement. Replacement refers to the replacement of the bridge deck, super structure, or the entire bridge (MDOT, 2011).

Many attempts have been made to reduce the number of maintenance activities, which in turn reduce environmental impacts. The use of durable materials extends the service life of bridge components, thus decreasing the need for future maintenance activities. High performance structural materials and FRP can be used to design bridges for more durability (Tang, 2004). Efficient inspection technologies should be used to properly assess the condition of bridges in a timely manner so that necessary maintenance actions can be taken. Use of efficient inspection technologies can ensure improved data quality while simultaneously controlling the cost of data collection. Further development and evaluation of improved visual inspection procedures, innovative nondestructive testing methods, and automated methods to gather and manage data should be encouraged (Hearn et. al., 2008).

FHWA categorizes bridges as structurally deficient or functionally obsolete based on their conditions and ratings. Bridge eligibility for rehabilitation or replacement is determined by a rating formula. This information is used by FHWA to develop National Bridge Inventory (NBI). In order to estimate the future maintenance and repair needs, a bridge management system (BMS) can be used. BMS provides the comprehensive management of a bridge system. It also improves the type and quality of data that is collected, stored, managed, and used in a bridge system analysis, the realistic and reliable forecast of future needs, and logical methods for setting priorities for current needs (WSDOT, 2010).

The focus should be more on quantitative assessment of bridge performance rather than visual inspections and condition ratings. A variety of permanent sensors can be installed on bridges that can automatically detect the data with the change in chemical and electrical properties of materials related to deterioration, aging in coatings, and changes in service environment or exposure. Sensors report to wireless networks and data can be analyzed; deterioration can be detected automatically by computer workstations (Hearn et.al, 2008).

2.4 Existing Major Green Rating Systems

Since the focus of this study is to develop a green rating system for bridges, which can be used to define and measure sustainability in bridges, various major green rating systems currently used in the United States were reviewed. These green rating systems are developed mostly for buildings and highways. Brief overviews of the existing green rating systems are as follows.

2.4.1 LEED (2009) - New Construction

Leadership in Energy and Environmental Design (LEED®) is a rating system for the design, construction, and operation of sustainable buildings. It was developed by the USGBC in 1998. This rating system was mainly developed to define and measure green buildings. So far, USGBC has generated 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. The latest, LEED® version 3.0 is currently used for existing and new commercial, residential, and institutional buildings.

Since its inception in 1998, USGBC has grown to encompass more than 24,662 projects in the United States and 30 other countries, covering over 1.627 billion ft^2 of development area; this shows the impact and wide recognition for LEED® in U.S. and around the globe.

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 as follows: 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. There are four certification levels developed in the rating system as shown in Table 2.2.

Table 2.2: LEED V.3 Certification Levels (USGBC, 2009)

Certification Level	Score Range
Certified	40-49
Silver	50-59
Gold	60-79
Platinum	80 and above

Certain credits can be adopted from the LEED® 2009 rating system to develop the rating system for bridges. The factors considered in analyzing the sustainability of buildings are location, materials, water, energy, and indoor air quality; 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. His analysis explained the useful metrics from LEED® 2009 that can be taken to define and measure sustainability in bridges. Some useful metrics can be extracted to define sustainable bridges.

For instance, when crediting for water use and quality, how the hydraulic openings will affect the upstream and downstream floodplains and the type of systems in place ensure the smallest amount possible of potable water is consumed and the runoff from the structure is of the highest quality (Whittemore, 2010). Therefore, such requirements are to be established after reviewing the standards; this ensures the optimum use of water and its quality. Likewise, certain other credits and prerequisites from LEED® can be adopted in the rating system for bridges. These are Construction activity pollution prevention, Site selection, Brownfield Redevelopment, Storm-water Management-Quantity Control, Storm-water Management-Quality Control, Recycled Content, Material Reuse, On-Site Renewable Energy, and Regional Materials.

2.4.2 Envision™ Rating System by Institute of Sustainable Infrastructures

The Institute for Sustainable Infrastructure (ISI) developed a new rating system to evaluate sustainable infrastructure projects. This rating system evaluates the sustainability for a wide range of infrastructure, including bridges. ISI was formally launched in 2011 and introduced a rating system that was developed by a working group from the American Council of Engineering Companies (ACEC), American Public Works Association (APWA), and American Society of Civil Engineers (ASCE).

Envision is an objective and comprehensive framework that describes criteria that can influence the project elements, and processes that can significantly influence the outcome of the infrastructure project and its impacts on the environment. Not only has it focused on environmental, social, and economic performance, but the overall delivery of the infrastructure project. This rating system promotes project management and business strategy for sustainable infrastructure solutions. Envision evaluates the sustainability of a wide range of civil infrastructure projects vital to our communities and protecting the environment, and will award and recognize projects that meet that goal. The system will evaluate and score existing infrastructure and serve as a goal for new and renovating projects to achieve (ISI, 2012). The Envision rating system is divided into 10 sections: Project pathway contribution, Project strategy and management, Communities: long and short term effects, Land use restoration, Landscapes, Ecology and Biodiversity, Water resources and environment, Energy and Carbon, Resource management including waste, and Access and Mobility. These are the 10 criteria that include 74 sub-criteria, each of which is assigned point values to rate the sustainable infrastructure.

2.4.3 GreenLITES Project Design Certification Program by NYSDOT

The New York State Department of Transportation has developed a GreenLITES (Leadership in Transportation and Environmental Sustainability) certification program for implementing sustainability in transportation projects. The GreenLITES Project Design Certification Program, created by NYSDOT in 2008, includes the development of a green rating system to define and measure sustainability in highways. It shows their commitment to improving the quality of transportation infrastructures by minimizing environmental impacts and reducing the depletion of resources.

The rating system is based on five categories, which are sustainable sites, water quality, materials and resources, energy and atmosphere, and innovation. It has four certification levels; Certified, Silver, Gold, and Evergreen. The project rating may fall into any category based on the cumulative score obtained. The cumulative score is the sum of the points of each criterion. It was formed after the U.S. Green Building Council's LEED program and the University of Washington's Greenroads program, and is useful in determining sustainability in transportation infrastructure projects. Many of the criteria are also directly applicable to bridges (NYSDOT, 2008). “The program is also intended to be a model for other department sustainability initiatives, providing a benchmark to follow for incorporating greater levels of sustainability into the department's work” (NYSDOT, 2008).

2.4.4 Sustainable Highway Self-Evaluation Tool

INVEST is a self-evaluation tool developed by FHWA and a web-based collection of criteria that allows states to integrate sustainability in transportation projects. It is a voluntary tool and can be used by state and various stakeholders to measure sustainability of transportation projects. FHWA’s INVEST can help transportation agencies and organizations integrate sustainability practices in transportation projects and provide practitioners a means to evaluate sustainability in their transportation projects, as it provides information and techniques to integrate sustainability best practices. It is developed with input from state and local transportation agency officials and staff and professional organizations such as AASHTO and ASCE. FHWA is continually updating this tool as transportation sustainability advances. It is divided into three main categories: planning and process criteria, project development criteria, and operations and maintenance criteria. A total of 61 criteria are described under these categories. This rating system can also be used as a benchmark to develop a rating system specifically for the bridges (FHWA, 2012).

2.5 Current MDOT practices in Bridge Design, Construction, and Maintenance

Current MDOT applications related to bridge design, construction, and maintenance were reviewed. In addition, current MDOT practices related to sustainable applications have been compiled. The construction of a bridge mainly involves three stages, i.e., design, construction, and maintenance. These stages are all related to each other: design practices affect the construction stage and design and construction stages affect maintenance over the lifetime of a bridge. The design stage of a bridge commences with the selection of materials, span arrangements, girder spacing, bearing types, substructure type and geometry, and foundation types. Design of the deck slab, interior and exterior girders, bearing, abutments, piers and foundations are the main steps in design. The bridge design should consider construction and long-term maintenance costs (AASHTO 2003).

All these design parameters coupled with environmental conditions, such as location and site, lead to various procurement and construction applications in the next stage. In the long run, maintenance processes to keep bridges operational and safe also are affected by all the decisions made in the design and construction stages. When considering bridge maintenance, preservation techniques should also be considered. Over time preservation treatments can reduce the overall cost of bridge maintenance. All decisions made in the life cycle of a bridge, especially those that are made early in the process, impact consequent stages. They all need to be critically analyzed for environmental and economic effects during the life cycle of a bridge. Therefore, examining current MDOT practices is vital in this study to determine the key decisions made in the design, construction, and maintenance of bridges. Current MDOT practices were established by studying the MDOT bridge design manual, MDOT soil erosion and sedimentation control manual, MDOT drainage manual, MDOT scoping manual, capital preventive maintenance manual, material source guide and MDOT P/PMS task manual. These manual and guides can be accessed at http://www.michigan.gov/mdot/0,1607,7-151-9622_11044_11367---,00.html.

2.5.1 MDOT Design Practices

The following design practices of MDOT were studied in detail:

a) General Information Site Condition: Temporary support systems and construction methods, clear zone considerations, concrete QA/QC.
b) Preliminary design calculations: Design specifications, design methods, and design stress.
c) Design: In design practices bridge materials, span arrangements; girder spacing, bearing types, substructure type and geometry, and foundation type were examined (MDOT, 2012).

2.5.2 MDOT Construction Practices

a) Erosion and Sedimentation Control:

The primary intent is to protect the waters of the state by minimizing erosion and controlling sediment. MDOT adopts soil erosion and sedimentation control program, which consists of a commitment to environmental stewardship responsibilities, appropriate staff training, and specifications and project plans that address erosion control issues (MDOT, 2006). The program is divided into three phases, which are planning, design, and construction.

b) Maintenance Activities and Projects:

Since maintenance activities also have the potential impacting lakes, streams, and wetlands, MDOT also conducts soil erosion and sedimentation control measures in maintenance projects. Appropriate SESC measures and NPDES requirements will be included when planning, designing, and completing maintenance projects and activities involving earth disturbances, regardless of size and location. An earth change plan is also prepared for the maintenance.

c) MDOT Storm-Water Management:

MDOT has large transportation network and associated drainage system, which accumulate a large amount of contaminants. These contaminants may be washed away by the rain or snow melts and may enter streams, rivers, and lakes. Excess contaminants may cause public health concerns and harm aquatic and animal life. MDOT developed a storm water management plan (SWMP) to reduce or eliminate the storm water pollution. The SWMP describes procedures and practices used throughout the planning, design, construction, operation, and maintenance of the transportation infrastructure to limit the discharge of pollutants (MDOT, 2012).

2.5.3 MDOT Bridge Maintenance Practices

MDOT uses a mix of fixes strategy for bridge maintenance. This strategy uses the combination of long-term fixes, medium term fixes, and short term fixes. Long-term fixes include reconstruction/replacement. Replacement refers to replacement of the bridge deck, super structure, or the entire bridge. Medium term fixes includes rehabilitation. Rehabilitation is the application of structural enhancements, such as multiple course resurfacing or concrete pavement repairs, that improve the roadway or overlaying of a bridge deck and superstructure repair. Short-term fixes include capital preventive maintenance (CPM). It applies lower-cost treatments to slow the deterioration rate, maintain or improve the functional condition, and extend the pavement's service life. The mix of fixes strategy is used to improve the condition of the bridges and increase the service life of bridges.

2.6 Life Cycle Assessment Applications

2.6.1 Background of LCA Applications

EPA defines LCA (also known as life cycle analysis, eco balance, and cradle-to-grave analysis) as a cradle-to-grave approach for assessing systems that evaluates all stages of a product's life. It provides a comprehensive view of the environmental aspects of the product or process. “The term “life cycle” refers to the major activities in the course of the product’s life-span from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required to manufacture the product” (EPA, 2006).

In simple words, LCA is a methodology that is used to analyze environmental impacts of products through all its life cycle stages. An ideal life cycle would account for all phases of the product. This is called the cradle to grave approach. Similarly, LCA has different stages: cradle to gate, which includes the raw material acquisition to production stage and gate to gate, which includes only the production stage. The decision makers in the industry use LCA for planning environmental strategies, product development, marketing, product comparisons, eco-labeling, etc. (GaBi, 2012).

2.6.2 Bridge LCA

A bridge's life cycle plays an important role in determining the sustainability of the system. Life cycles can be evaluated in terms of environmental or economic impacts. Assessing the life cycle can help us become more aware of sustainable solutions for bridges. Life-cycle models, whether through assessments, inventories, or cost analysis, are complex and rely on consistent and available historical information. In simple words, LCA is a method to assess the environmental performance of the product or a process over its life cycle. The use of a product throughout its life cycle may have many negative impacts on the environment. Some of the terms that are measured to assess the environmental performance of the product (Trusty, 2006) are toxic releases to air, water, and land, fossil fuel depletion, CO2 emissions, non-renewable energy use, global warming potential, acidification and acid deposition, nutriphication/eutrophication of water bodies, and stratospheric ozone depletion.

GHG emissions are one of the major contributors to negative impacts to the environment; the main focus of this study is to develop guidelines for determining GHG emissions or the carbon footprint of bridges. Guidelines for calculating GHG emissions are based on LCA methodology. It is well known that a bridge construction project involves large number of products and processes. Cement is the most common material used in large quantity in construction. Cement is a highly energy intensive material (Worrell et. al., 2001). It consumes and releases a high amount of energy into its surroundings during all life cycle stages: raw material extraction, transportation to manufacturing facility, manufacturing, packaging, transportation to site, use, maintenance, and disposal. Cement production is energy intensive and accounts for 5% of global anthropogenic CO2 emissions (Worrell et. al., 2001) and significant levels of SO2, NOx, particulate matter, and other pollutants. Similarly, different products and products release a significant amount of GHG emissions during their life cycle. Therefore, it is imperative to calculate the GHG emissions of these products and processes using LCA approach and investigate strategies to reduce these emissions. Since GHG emissions can be calculated based on LCA methodology, it is important to review the LCA concepts and applications. A number of LCA studies had been made and extensive literature recently published. Singh et al. (2011) made a systematic compilation of all the Construction-LCA related literature and presented its structured review. This research work reviews the literature in four major categories: LCA applications for construction products selection; LCA applications for construction systems/process evaluation; LCA tools and databases related to the construction industry; and LCA methodological developments related to the construction industry. Current challenges for using LCA in construction are discussed and potential areas for future research are highlighted (Syal et. al., 2011). This study gives details of the LCA methodologies and databases for LCA.

An integrated LCA-LCCA model was developed and applied on a highway overpass bridge deck, and two alternative bridge deck designs were compared. The model is applied to alternative concrete bridge deck design options: one conventional steel reinforced concrete bridge deck with mechanical steel expansion joints and the other an SRC deck with engineered cementetious composite (ECC) link slabs. Factors or indicators important in evaluating sustainability include life cycle energy, greenhouse gas emissions, agency, rehabilitation, social, construction-related user delay costs, and environmental pollutant damage costs; these are quantified for both systems over a 60 year bridge design life. The integrated model consists of two integrated elements: life cycle inventory analysis and life cycle cost model of agency and social costs. They are further integrated into the factors that characterize the infrastructure system. These indicators are evaluated for a 60-year total service life with a traffic flow rate of 35,000 cars per day in each direction. Studies show that the ECC link slab system has a 37% cost advantage over the conventional system, as it consumes 40% less total primary energy (Kendall et. al., 2008).

LCA approaches can be used to analyze the impacts of requirements of credits in the rating system. In the conducted research study, individual credits within the LEED program were critically analyzed using life cycle approach. A case study was conducted to measure life cycle energy consumption and solid waste generation to analyze the impacts of implementation of LEED requirements (Scheuer and Keoleian, 2002).

LCA approaches can be integrated into LEED. Lloyd described that USGBC has recognized the benefits of using quantitative and holistic life cycle information and an "LCA into LEED" program has been initiated to determine how best to integgrate LCA into LEED Building for Economic and Environmental Sustainability (BEES). BEES is a LCA software tool developed by National Standards of Intitute and Technology that takes a life cycle approach to building materials and focuses on both life cycle environmental and cost data. It was shown that BEES can be used to integrate LCA into LEED (Lloyd, 2005).

There are two ways to conduct an LCA - using an input-output based LCA, or a process based LCA. Economic input-output based LCAs are based on economic transactions and resource interactions between an exhaustive set of economic sectors. The Economic Input-Output Life Cycle Assessment (EIO-LCA) method estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in the economy and it is one technique for performing a life cycle assessment, an evaluation of the environmental impacts of a product or process over its entire life cycle (Hendrickson et al. 1998).

EPA has developed a report that gives an overview of sources and the magnitude of construction and GHG emissions and ways to reduce them. The opportunities to reduce GHG emissions are presented based on best available sources and information. EPA describes that fuel selection, equipment idling, electricity use, equipment maintenance, equipment selection and material recycling are construction activities that result in GHG emissions and have the most influence on a contractor's ability to affect emissions. Similarly, material selection, employee commuting, materials shipment, and vegetation removal have some influence; site selection, structural design, and performance have little influence (EPA, 2009).

Recycling and reusing materials is emphasized as GHG emissions released during the manufacturing and transportation of the construction materials are avoided. Therefore, recycled materials should be used on the project, such as fly ash, blast furnace slag, and recycled steel. Fly ash and blast furnace slag can be used as supplemental cementitious materials and replace a portion of the cement. The emission factor of such blended cement is greatly reduced. Table 2.3 shows the environmental impact score of the traditional Portland cement and the blended cement (Huntzinger and Eatmon, 2009). The software tool SimaPro was used to assess the environmental impact score of the two types of cement using LCA methodology. It can be seen that use of blended cement reduces GHG emissions by 21.6% (Huntzinger and Eatmon, 2009). Also, recycling steel reduces GHG emissions and saves energy by 56%. Recycling 1 ton of steel conserves 2,500lb of iron ore, 1,400lb of coal, and 120lb of limestone (West, 2012).

Table 2.3: Comparison of Environmental Impacts of Two Types of Cement (Huntzinger and Eatmon, 2009)

Environmental Impact Category	Traditional Portland Cement	Blended Cement
Greenhouse	0.088	0.069
Acidification	0.043	0.034

2.6.3 Available LCA Tools

LCA tools are the applications to conduct LCA of construction products and systems. These can be used to quantify energy and material usage, as well as quantification of environmental releases across all the life cycle stages. LCA tools can be widely used for environmental labeling, product environmental improvement, ecodesign, and policy evaluation (Menke et. al., 1996). Menke, Davis and Vigon (1996) identified a comprehensive list of 37 LCA tools and the related literature was reviewed. LCA tools measure the environmental impacts primarily across a set of five environmental indicators: fossil fuel use, global warming potential, toxic releases to air, toxic releases to water, and solid waste generation. Mukherjee and Cass (2011) surveyed GHG impact assessment tools shown in Table 2.4 and classified them according to the institution type, such as academic tools, government, and industry.

Table 2.4: GHG Impact Tools (Adopted from (Mukherjee and Cass, 2012))

Institution Type	GHG Impact Tools		
	Life Cycle Assessment	**Emission Calculators**	**Rating/Point Systems**
Government	NREL-LCI	SGEC Tool	FHWA Self-Evaluation Tool
Academic State	EIO-LCA PaLATE	Road Construction Emission Model GreenDOT	Greenroads GreenLITES I-LAST
Industry	SimaPro AsPECT	CHANGER e-CALC AggRegain	Greenroads™

2.7 LCCA Applications

2.7.1 Introduction

A bridge is generally considered a significant component of a transportation system and requires periodic repair and maintenance. Consequently, it represents a long-term and multi-year investment. Bridge management refers to the various activities of planning, design, operation, and maintenance that determine how a bridge is configured throughout its service life. The specific application of LCCA to bridge management depends on the specific character of bridges and on availability of data for estimating values of key parameters influencing the life-cycle cost of a particular bridge (Hawk, 2003). LCCA is presently the most common tool used to make a sensible decision in selecting the lowest cost and the best performance alternative. "*LCCA is a set of economic principles and computational procedures for comparing initial and future costs to arrive at the most economical strategy for ensuring that a bridge will provide the services for which it was intended*" (Hawk, 2003).

It enables the entire cost comparison of various design alternatives and brings it to a logical decision. In addition to the initial cost, all pertinent costs (user, repair, maintenance, etc.) that occur throughout the service life of a bridge are included. LCCA has received increasing attention as a tool to assist transportation agencies in making investment decisions as well as in managing assets (FHWA, 1994).

LCCA of a bridge project can be summarized into the following steps. The first step determines the analysis period or scenarios and the schedules initial and future activities involved in the project design. The second step establishes alternatives for realizing the structural and performance objectives of a project. The third step estimates the agency and user costs of these activities. The best-practice LCCA calls for inclusion of both costs. The fourth step includes the compiling and computation of life cycle cost. Using a discount rate, these costs are converted into dollars and summed for each alternative. The final step is analyzing the results and selecting the best and the most cost effective alternative. The flowchart given in Figure 2.2 shows the basic steps involved in conducting LCCA for bridges.

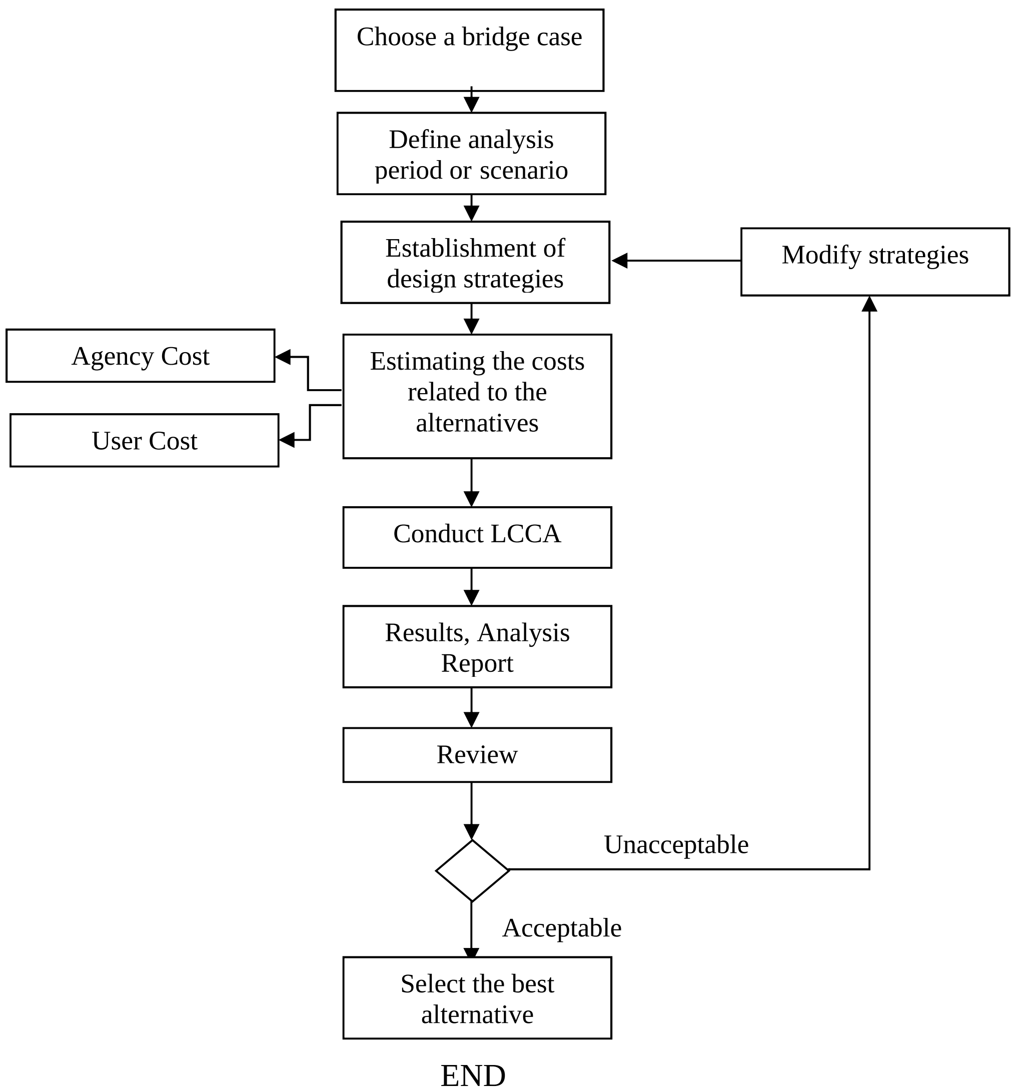


Figure 2.2: LCCA of Bridges (Hawk, 2003)

2.7.2 Steps in LCCA

It is particularly vital to set up the alternatives for a bridge project prior to conducting the LCCA. These chosen alternatives should be distinctly different, provide a reasonable, viable, and cost-effective solution to the project. A minimum of two different project alternatives should be incorporated into the LCCA. Listed below are some of the possible steps involved in performing the LCCA of bridges. A brief description of every step is also mentioned for guidance.

Choosing a bridge case:

The selected bridge is described in terms of the characteristics relevant to (Hawk, 2003).

- Life Cycle Cost
- National Bridge Inventory (NBI) data
- Traffic Volume
- Inspection Reports
- Design Details.

Define analysis period or scenario:

It is defined as "*the time horizon over which future costs are evaluated*". The time period should be selected on the basis of both the physical elements to be analyzed and the type of decision to be made. Generally, the planning horizon 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).

Establish alternative bridge design strategies:

A Design Strategy is the combination of initial bridge design and necessary supporting maintenance and rehabilitation activities. It is important to identify the scope, timing, and cost of these activities (FHWA, 1998). Each action have also estimated agency and user costs, also subject to uncertainty; estimation of these costs is a later step.

Estimate costs:

Each of the actions that together compose a design strategy entail agency and user costs. The estimated cost is a crucial component of the bridge LCCA (Hawk, 2003). Construction quantities and costs are directly related to the initial design and subsequent rehabilitation strategy. The first step in estimating agency costs is to determine construction quantities/unit prices. Agency costs include all costs incurred directly by the agency over the life of the project, while user costs are incurred by the highway users over the life of the project. User costs are an aggregation of three separate cost components:

- Vehicle operating costs (VOC), which are costs related to the consumption of fuel and oil, and wear on tires and other vehicle parts.
- User delay costs due to reduced speeds and/or the use of alternate routes.
- Crash costs (also called accident costs), i.e., damage to the user's vehicle and/or other vehicles and/or public or private property, as well as injury to the user and others.

Conduct LCCA:

The analysis focuses on the relationship between costs, timings of costs, and discount rates employed. Once all costs and their timing have been developed, future costs must be discounted to the base year and added to the initial cost to determine the Net Present Value (NPV) for the LCCA alternative.

Review results:

The analyst should review the net present value distributions to ensure they "make sense" in light of expectations and experience.

Select the best alternative:

The main objective of conducting the LCCA is to identify a design strategy with least life cycle cost and the best performance for a project. At the end of analysis, usually the lowest life cycle cost alternative is selected.

CHAPTER 3

FRAMEWORK FOR ASSESSING SUSTAINABILITY IN BRIDGE DESIGN, CONSTRUCTION AND MAINTENANCE

3.1 Definition of the Framework

Based on the detailed content analysis discussed in the previous sections, the framework is divided into three sections: 1) Design, 2) Construction, and 3) Maintenance. The design section entails site, materials, and others while the 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. Each category is divided into various criteria. The description, intent and requirements have also been established. Table 3.1 shows the list of criteria and construction standards that were used to establish the requirements for each criterion. The lists of criteria were obtained based on detailed content analysis. The final list of the criteria included in the framework is based on MDOT suggestions, which are based on their requirements for bridges in Michigan.

Table 3.1: Criteria Table

Criteria	Title	Intent	Standards
1. Design 1.1 Site			
Criteria 1.1.1	Site Selection	To avoid environmental impacts due to the location of a site.	Appendix M of Construction General Permit of US department of Environmental Protection Agency (EPA). http://www.epa.gov/npdes/pubs/cgp_appendixm.pdf; Appendix D of EPA's Construction general permit. http://www.epa.gov/npdes/pubs/cgp_appendixd2011.pdf.
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.	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	To reduce pollution such as soil erosion, sedimentation and dust and particulate matter generation resulting due to construction activities.	Principles of Runoff Control for Roads, Highways, and Bridges; Erosion, Sediment and Runoff Control for Roads and Highways, Environmental Protection Agency (EPA); http://water.epa.gov/polwaste/nps/runoff.cfm; Part 1.1.2: Soil Erosion and Sedimentation Control, Chapter 9, Storm-water Best Management Practices (BMP's); Michigan Department of Environmental Quality (MDEQ).

Table 3.1 (cont'd)

Criteria	Title	Intent	Standards
Criteria 1.1.4	Brownfield Redevelopment	To rehabilitate contaminated sites and reduce pressure on undeveloped land.	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	To reduce the quantity of pollution and run-off from storm-water that is discharged into surface waterways or storm-sewers.	Michigan Department of Environmental Quality (MDEQ); Chapter 9, Storm-water Best Management Practices, MDOT Drainage Manual; MDOT Soil Erosion and Sedimentation Control Manual.
	1.2 Materials		
Criteria 1.2.1	Use of Recycled Materials	To increase the demand for materials that incorporate recycled materials, thereby reducing environmental impacts resulting from extraction and processing of virgin 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 and Maintenance" 3.12.3

Table 3.1 (cont'd)

Criteria	Title	Intent	Standards
Criteria 1.2.2	Supplemental Cementitious Materials	To reduce the embodied energy associated with the cement by replacing a part of it with supplemental cement. 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.
Criteria 1.2.3	Reduction in Quantity of Materials	To reduce the quantity of materials in bridges to avoid environmental impacts associated with the life cycle of materials.	Development of Rating System for Sustainable Bridges" MS Thesis, Massachusetts Institute of Technology, MA by Lauren Hunt, 2004
Criteria 1.2.4	Material Reuse	To reuse bridge materials and attachments to reduce demand for virgin materials and reduce waste.	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	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	Material and Resource Credit 5 of LEED® 2009.

Table 3.1 (cont'd)

Criteria	Title	Intent	Standards
		1.3 Other	
Criteria 1.3.1	Renewable Energy Use	To promote the use of renewable energy on site thus reducing economic and environmental impacts associated with non-renewable energy use.	ANSI/ ASHRAE/ IESNA Standard 90.1-2007 (Exterior Lighting).
Criteria 1.3.2	Bicycle Pedestrian Pathways	To promote the use of alternative transportation in order to reduce energy demand and reduce pollution due to automobile use.	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	To provide a framework for additional lanes for any unforeseen conditions.	High-Performance Materials for Substructures, Foundations, and Earth Retaining Systems Workshop, Bridge and Structures Research and Development (RandD), Federal Highway Administration Research and Technology, FHWA, Publication Number: FHWA-HRT-08-058, February 2009.
Criteria 1.3.4	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.	NCHRP, National Cooperative Highway Research Program, 2003. "Bridge Life Cycle Cost Analysis Report 483".

Table 3.1 (cont'd)

Criteria	Title	Intent	Standards
2. Construction			
Criteria 2.1	Accelerated Bridge Construction Techniques	The objective is to reduce the construction time of the project thereby reducing environmental and traffic mobility impacts.	Federal Highway Administration (FHWA).
Criteria 2.2	Corrosion Resistant Steel Reinforcement	To prevent bridge reinforcement from corrosion by penetration of sodium chloride thus preventing the bridge from early deterioration and extending the service life of the bridge.	Performance of epoxy-coated rebar in bridge decks volume 60-No. 2, FHWA; Stainless steel reinforcement, MDOT bridge design manual section 7.04; Epoxy coated rebar bridge decks; expected service life, MDOT bridge design manual section 12.
Criteria 2.3	Efficient Water Use	To conserve water through efficient use during bridge construction.	Specification C94 for Ready Mixed Concrete; Section 911 of 2012 MDOT standard specifications for construction.
Criteria 2.4	Non-road Equipment Emission Reduction	To reduce air emissions from non-road equipment.	Project Development Criteria 27, "Sustainable Highways Self Evaluation Tool" FHWA, US Department of Transportation, 2011

Table 3.1 (cont'd)

Criteria	Title	Intent	Standards
Criteria 2.5	Construction Waste Management	To divert waste generated in construction and demolition from disposal and in landfills and incineration.	Section 01 74 19 - Construction Waste Management, EPA.
Criteria 2.6	Use of Certified Wood	To encourage best forest management practices.	Designing and Building with FSC, Forest Stewardship Council, Forest Product Solutions.
		3. 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 associated environmental impacts.	AASHTO, 2009, Chapter 7, Bridge Maintenance, "Center of Environmental Excellence by AASHTO", www.environment.transportation.org; MDOT Bridge Inspection Manuals and MDIOT Inspection Manual, Michigan Department of Transportation.
	Bridge Painting/Coating	To prevent bridge components from deterioration due to corrosion thus increasing the age of bridges.	OSHA; CFR 29 1926.62, Lead in Construction; Zinc-Rich Bridge Coatings, FHWA Bridge Coatings Technical Note: Zinc-Rich Bridge Coatings; Clean Air Act Amendments; Society for Protective Coatings (SACE); National Association of Corrosion Engineers (NACE)

Table 3.1 (cont'd)

Criteria	Title	Intent	Standards
Criteria 3.2	Bridge Painting/Coating	To prevent bridge components from deterioration due to corrosion thus increasing the age of bridges.	OSHA; CFR 29 1926.62, Lead in Construction; Zinc-Rich Bridge Coatings, FHWA Bridge Coatings Technical Note: Zinc-Rich Bridge Coatings; Clean Air Act Amendments; Society for Protective Coatings (SACE); National Association of Corrosion Engineers (NACE); GS11 Green Seal Environmental Standard for Paints and Coatings.
Criteria 3.3	Bridge Cleaning	To clean components of bridges susceptible to dirt, bird-drop accumulation etc. thus increasing efficiency of the bridge components and lessen maintenance requirements.	Drainage System cleaning, Pavement Cleaning, MDOT Scoping Manual, Michigan Department of Transportation; "Part 7.1.3, Bridge Cleaning; Chapter 7, Bridge Maintenance, Center for Environmental Excellence by AAHSTO" American Association of State and Transportation Officials. NCDOT Guidelines for Managing Bridge Wash Water Version 1.0.
Criteria 3.4	Bridge Deck Drainage	To avoid impacts on the deck structure and reinforcing bars due to inefficient drainage.	Proper Drainage Reduces Roadway Problems. Nevada Milepost, Nevada's Technology Transfer Quarterly, Vol. 12, No. 1, (Spring 2002) p. 1.

Table 3.1 (cont'd)

Criteria	Title	Intent	Standards
Criteria 3.6	Corrosion Control Materials	To prevent or minimize the corrosion of bridge elements due to the penetration of sodium chloride.	MDOT standard specifications for construction section 712.03 Michigan State University Report, 2000, "Repair of Corrosion Damaged Columns Using FRP Wraps"
Criteria 3.7	Bridge Deck Joints and Seals	To minimize or eliminate poorly maintain bridge deck joints and seals thus maintaining the service life of the bridge.	Evaluation of various types of bridge deck joints, Final Report 510, Baker Engineering and Energy, Arizona Department of Transportation; Michigan Department of Environmental Quality (MDEQ).
Criteria 3.8	Snow and Ice control	To implement snow and ice control techniques to reduce associated impacts of snow and ice on the bridge.	Sustainable Highways Self-Evaluation Tool, FHWA, USDOT

3.2 Green Rating System for Bridges

To develop the framework, an extensive content analysis of MDOT's current practices was carried out as well as existing sustainability and bridge related sources. The following provided significant guidance in selecting and defining categories and credits for the framework: a significant research session 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 and a master's thesis on "development of a rating system for sustainable bridges". Moreover, current sustainable practices in design, construction, and maintenance followed by MDOT were reviewed. For this purpose, MDOT manuals such as scoping manual, design manual, drainage manual, and bridge preservation matrix were reviewed.

MDOT follows best management practices for storm water management (Quality and Quantity Control), measures to avoid soil erosion and control sedimentation, and efficient drainage systems. MDOT, under agreement with the MDEQ is also certified as a storm water management operator on all transportation related construction sites statewide, and requires project managers to attend training to keep certifications current. In addition to these, MDOT uses recyclable materials such as concrete incorporating wastes like fly ash and recycled-in-place asphalt pavements. Fiber Reinforced Plastics (FRP) is also used by MDOT for the bridge decks and other structural member applications. Various studies have demonstrated that FRP is more effective with regard to the amount of CO_2 emissions and is corrosion resistant material.

3.2.1 Category 1 - Design

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 are the intent of this category. The design principles are consistent with MDOT policy and standards. MDOT has already been practicing several sustainable techniques and has incorporated these environmentally responsible criteria in their design strategies. The design section is divided into sites, materials, and other, and further subdivided into various criteria. Guidance is given under each criterion for assigning points to the particular category.

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 preserves natural habitats and 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:

- Try to avoid sites, which are identified as habitats of any species on the federal or state threatened endangered lists. The criteria can be found in Appendix D of EPA's construction general permit (USGBC, 2009).
- Try to avoid placing footings and piers in water bodies to minimize environmental impacts. Consider choosing sites where the crossing distance is minimum (Hunt, 2004).
- In scenarios where bridges traverse a road, try to avoid placing footings within 50 feet of any water body such as seas, lakes, rivers, and streams that could support aquatic life, recreational or industrial use, consistent with the terminology of the clean water act (USGBC, 2009). Also, with bridges over water, avoid constructing or developing sites within 100 feet of wetlands as defined in Appendix M of construction general permit of the Environmental Protection Agency (EPA) (EPA, 2011).
- 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.

Scoring Criteria:

Three Points will be awarded for meeting any two requirements and six points for meeting all the requirements.

Standard/Resource:

- Appendix M of Construction General Permit: 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 and 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 on historic sites and reduce the socio-cultural environmental impact from the location of a bridge on a site.

Requirements:
Provide documentation showing the project team does not demolish any historical bridge as defined by section 106 of the National Historic Preservation Act.

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).

Section 106 of the National Historic Preservation Act primarily describes 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 built on a historic site, improvements should be made to the facilities and/ or access to the site (Hunt, 2004).

Scoring Criteria:
Three points will be awarded 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 plant growth and maintains biodiversity. Loss of soil may lead to water quality issues and inhibits biodiversity. Sedimentation is the deposit of soil particles or other pollutants in storm-sewers or adjacent water resources. It affects the flow capacity of the stream channels and increases turbidity levels. Turbidity reduces sunlight penetration in water, which reduces photosynthesis and in turn affects aquatic vegetation and decreases oxygen levels (USGBC, 2009). Air-borne dust generation is another major environmental problem and could lead to many human health problems. Construction activities may result in air-borne contaminants, including dust, mists, smoke, and fumes. This may lead to widespread lung diseases such as pneumoconiosis (WHO, 2011).

Intent:

The objective of this credit is to reduce pollution from 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; and the Environmental Protection Agency (EPA) to control the addition of pollutants to coastal waters and erosion and runoff control for bridges.

Scoring Criteria:

Two points will be awarded if one or more requirements are met.

Six points will be awarded 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:

Sites that 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 a project area contamination survey to identify and analyze environmental contamination information and take appropriate action accordingly to protect worker health and 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.

Scoring Criteria:

Two points will be awarded 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 the 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. Water from the precipitation, if does not infiltrate into the ground, takes the form of surface runoff and includes the contaminants from the surface, finally mixing 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 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 amount of storm-water run-off and pollution that is discharged into surface waterways or storm-sewers.

Requirements:

a) Implement a Storm-water Management Plan (SWMP), include plans to accomplish illicit discharge elimination, public education, and storm-water pollution prevention to meet the requirements of the 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 in

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.

Scoring Criteria:

Two points will be awarded for meeting the minimum requirements.

Five points will be awarded if all requirements are met.

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 to 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, the 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:

Figure 3.1 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 are excluded from the corresponding credit calculations. The divisions in the left most column show materials concrete, metal, deck and deck systems, foundations, etc. These are associated with material used in 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 Figure 3.1 is extracted from LEED 2009.

Material	Use of Recycle materials	Material Reuse	Regional materials	Reduction in quantity of material	Construction Waste Management
	Based on cost of qualifying materials as a percent of overall materials cost	Based on replacement value ($)	Based on cost of qualifying materials as a percent of overall materials cost	Based on weight or volume	Based on weight or volume. Include demolition and construction waste
Concrete					
Metal					
Deck and Deck System					
Foundations					
Abutments, Piers and Walls					
Railings					
Joints and Bearings					

Figure 3.1: Matrix for Calculating Requirements for Achieving Sustainability (USGBC, 2009)

Criteria 1.2.1: Use of Recycled Materials (5 Points)

Description:

Recycling is the 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 materials that incorporate recycled content, thereby reducing impacts resulting from the 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 its 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.

Scoring 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 criteria as given in Table 3.2:

Table 3.2: Scoring Criteria for Use of Recycled Materials

% Recycled Materials Used	Points Scored
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 and 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 with the fly ash portion not exceeding 15% (MDOT, 2003).

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

Intent:

To reduce the embodied energy associated with cement by replacing a portion 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 meet 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 based on the criteria shown in Table 3.3.

Table 3.3: Scoring Criteria for Supplemental Cementitious Materials

% Supplemental Cementetious Materials Used	Points Scored
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 and 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 the 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 such as 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).

Scoring Criteria:

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

Calculate the total quantity of materials when high strength, high performance materials were used on the project. Calculate the quantity if ordinary materials have been used. Calculation can be done by weight or volume. Calculate the percentage of material reduced by the use of high performance materials, as shown in Table 3.4.

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

Example:

Table 3.4: Calculation Example for Reduction in Quantity of Materials

Material Description	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						
Total quantity of all material used without employing any strategy						
% Reduction in Material						

Credit 1.2.4: Material Reuse (2 Points)

Description:

Re-use of demolished or salvaged materials should be encouraged. Reuse of material refers to materials that can be reused after the deconstruction or demolition of 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 foundation stabilization. The major sources of Recycled Concrete Material (RCM) are the 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.

Scoring Criteria:

Percentage of reused materials is calculated based on cost. The points in Table 3.5 are awarded based on the minimum percentage of reused materials used in the research project. Example calculation chart is provided in Table 3.6.

Table 3.5: Scoring Criteria for Material Reuse

% Reused materials	Points
5	1
10	2

Table 3.6: Example Calculations for Material Reuse

Material Description	Unit	Amount of total material required	Total estimated Cost ($), if new material used	Amount of reused material	Cost of reused material ($)	% of material reused	Total cost with reused material ($)
Steel	lb						
Wood	lb						
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 a 500-mile 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 as shown in example calculation in Table 3.7.
- Three points will be awarded, if 25% of all the materials are regional materials.

Table 3.7: Example Calculations for Regional Materials

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					%

Standards/Resources:

- Material and Resources Credit 5 of LEED® 2009

Category 1.3 - Other

This section describes the miscellaneous criteria, which have environmental impacts on bridges due to their design. These criteria can be renewable energy use, use of bikes/pedestrian lanes, design for future expansion, 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, biomass, 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 a 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. The 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.

Scoring Criteria:

One point will be awarded 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 a 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, thus minimizing pollution and energy demand.

Requirements:

a) Develop plans to include both sidewalks and bicycle pathways (Hunt, 2004).
b) Appoint a bicycle and pedestrian coordinator in order to promote the maximum use of non-motorized modes of transportation (FHWA, 2012). The non-motorized transportation program of the 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 the replacement or rehabilitation phase of the bridge.

Scoring Criteria:

One point will be awarded if bike lanes are provided.

One point will be awarded if pedestrian pathways are provided.

Standards/ Resources:

- 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 a bridge, which may deteriorate the bridge if it is not designed for carrying additional traffic, possibly resulting in additional maintenance activities. Therefore, a framework should be made to allow for additional future lanes in should any unforeseen conditions arise.

Intent

To provide a framework that allows for additional lanes should there be 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).

Scoring Criteria:

- One 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, Bridge and Structures Research and Development (RandD), Federal Highway Administration Research and Technology, 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 that assists transportation agencies in making investment decisions (NCHRP). It is a set of economic principles and computational procedures for comparing initial and future costs to arrive at the most economical strategy for ensuring that a bridge provides 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 the 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.

Scoring Criteria:

Five points will be awarded for conducting LCCA of a complete bridge.

Standards/Resources:

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

3.2.2 Category 2 - Construction

Construction is an important phase that incorporates the rehabilitation, replacement, or addition of an entire structure. A successful project includes timely completion, cost-effectiveness, and quality. The following sections define the criteria and standards recommended to incorporate in bridge projects during the construction phase. These credits help in promoting a sustainable environment and lessen 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.

Criteria 2.1: Accelerated Bridge Construction Techniques (ABCT) (14 Points)

Description:

Accelerated construction is used to achieve the construction of structures in the shortest possible time while decreasing delays and traffic disruption. It is not just building structures rapidly, but also entails a variety of techniques, processes, and technologies to achieve the desired result of reducing congestion due to construction, while improving quality. These techniques are used for the construction of new bridges and also the replacement of existing bridges (Ralls, 2007).

Intent:

The objective is to reduce the construction time of the project thereby reducing environmental and traffic mobility impacts.

Requirements:

Adopt one of the outlined techniques below:

Self-Propelled Modular Transports (SPMT): It offers numerous marketing strengths due to the straightforward, demonstrable, easily comprehendible nature of its value proposition. Saving time, money (in terms of the costs of travel delay), and possibly lives, by removing older structures and replacing them in minutes or hours with new structures constructed offsite is an obvious improvement over conventional methods (AASHTO, 2010).

Incremental Launching: In this method, a bridge is prefabricated in 50-100 feet long units under factory conditions behind an abutment and the bridge is launched by sliding it on bearings into the final position without the aid of scaffolding. The advantage is an overall lowered cost, due to less equipment and labor needed and less maintenance costs (Leshko, 2007). This can be done through super-structure roll in, super-structure lift in, and using pre-fabricated bridge elements and components.

Scoring Criteria:

Points can be scored based on the percentage of time saved by using ABC techniques as shown in Table 3.8. The points are awarded based on the time reduced due to the application of accelerated bridge construction techniques. The points are awarded based on the following criteria:

Table 3.8: Scoring Criteria for Accelerated bridge Construction Techniques

% Reduction in Time	Points Scored
0-10	3
11-25	5
26-40	7
41-60	10
61+	14

Standards/Resources:

- Accelerated Bridge Construction Techniques, U.S. department of Federal Highway Administration (FHWA).

Criteria 2.2: Corrosion Resistant Steel Reinforcement (8 Points)

Description:

Chloride salt-based deicing chemicals, the most common of which is sodium chloride, are used for snow and ice control on bridges. Sodium chloride can penetrate through cracks and over time, through diffusion, acts as catalyst for reinforcement corrosion. This is one of the primary reasons for deterioration of the structure. Adding corrosion resistant steel reinforcement helps establish a barrier that attempts to block the penetration of water, oxygen, and other elements that promote corrosion of the reinforcement (Boatman, 2010).

Intent:

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

Requirements:

a) Consider using corrosion resistant reinforcing steel such as epoxy coated reinforcement, stainless steel reinforcement, and stainless steel clad reinforcement.
b) The stainless steel industry share of CO_2 emissions could be around 12% of global emissions. Stainless steel contributes greatly towards sustainability and it leaves a reduced carbon footprint (Gopal, 2006).

Scoring Criteria:

Four Points will be awarded if epoxy coated reinforcement is used on the project and eight points will be awarded for both stainless steel reinforcement and epoxy coated reinforcement.

Standards/Resources:

- Performance of epoxy-coated rebar in bridge decks volume 60-No. 2, FHWA
- Stainless steel reinforcement, MDOT bridge design manual section 7.04
- Epoxy coated rebar bridge decks; expected service life, MDOT bridge design manual section 12

- ASTM E937 - 93(2011) Standard Test Method for Corrosion of Steel by Sprayed Fire-Resistive Material (SFRM) Applied to Structural Members
- ASTM A1035 (low carbon, chromium) – MMFX2
- Stainless steel conforming to ASTM A955 – UNS designations: S24100, S30400, S31603, S31653, S32101, S32201, S32205
- Stainless steel clad bars conforming to AASHTO MP13M

Criteria 2.3: Efficient Water Use (2 Points)

Description:

Water is one of the most valuable resources on the planet earth, and although the United States has a copious supply, it is not evenly distributed throughout the country. Recent droughts illustrate that many areas are severely undersupplied. A truck roughly utilizes 50 to 200 gallons of water in washing out (Lob, 2010). Therefore, innovative and cost-effective water efficiency strategies will help in saving this natural resource.

Intent:

The objective is to efficiently use water during bridge construction and incorporate water efficiency and conservation in equipment washing. It entails a considerable reduction in potable water use and employs on-site resources in order to lessen the municipal water supply demand.

Requirements:

Consider using gray water in making ready mix concrete (ASTM, 2009). Consult Section 911 of the 2012 MDOT Standard Specifications for the standard limits the amount of total solids, total organic content and alkalinity of non-potable water that can be used in concrete mix designs. Any gray water used that has values higher than those listed Table 911-1 will lower the concrete life expectancy and therefore cannot be used. Store, recycle, and reuse water already utilized for equipment washing (Lob, 2010). Other means to decrease the water usage could be using recycled water in Plant and truck washing, Plant and yard wash down, Slump adjustment Aggregate sprinklers.

Scoring Criteria:

Compute the quantity of gray water or recycled and reused water used on the project as a percentage of quantity of water if only municipal water is used. Points can be scored according to the percentage of water saved as shown in Table 3.9 using any of the outlined or other techniques.

Table 3.9: Scoring Criteria for Water Use Reduction

% Water reduced using water efficiency techniques	Score
20	1
30	2

Standards/Resources:

- Specification C94 for Ready Mixed Concrete
- Section 911 of the 2012 MDOT Standard Specifications

Criteria 2.4: Non-Road Equipment Emission Reduction (2 Points)

Description:

Air emissions from construction equipment contribute significantly to the degradation of the environment. Therefore, it is imperative to use such types of equipment, which produce less emissions than conventional ones. "Non-road engines are all internal combustion engines except motor vehicle (highway) engines, stationary engines (or engines that remain at one location for more than 12 months), engines used solely for competition, or engines used in aircraft. The non-road standards cover mobile non-road diesel engines of all sizes used in a wide range of construction, agricultural and industrial equipment" (EPA, 2004). So, non-road equipment is used in construction and not on roads like cars, buses, etc.

Intent:

The objective is to reduce air emissions from non-road equipment.

Requirements:

"Use non-road equipment that meet at least one of the following criteria" (FHWA, 2012).

a) Have engines that meet the current U.S. Environmental Protection Agency (EPA) Tier emission standards (Tier 3/Interim Tier 4 as of April 2011) in effect for non-road engines of the applicable engine power group.
b) Have diesel retrofit devices for after-treatment pollution control verified by EPA or the California Air Resources Board (CARB) for use with non-road engines."

Scoring Criteria:

One point will be awarded if 50% of the equipment meets the above requirement.

Two points will be awarded if 75% of the equipment meets the above requirement.

Standards/Resources:

- Project Development Criteria 27, "Sustainable Highways Self Evaluation Tool" FHWA, US Department of Transportation, 2011

Criteria 2.5: Construction Waste Management (4 Points)

Description:

Waste management entails identification, collection and removal of waste materials from the construction site to the appropriate land. A construction waste management plan is the first step in managing construction waste because it requires that contractors establish a system for tracking waste generation and disposal during construction.

Intent:

The objective is to divert construction and demolition debris from disposal in landfills and incineration facilities. Redirect recyclable recovered resources back to the manufacturing process and reusable materials to appropriate sites (USGBC, 2009).

Requirements:

Recycle and/or salvage nonhazardous construction and demolition debris. Develop and implement a construction waste management plan that, at a minimum, identifies the materials to be diverted from disposal and determine whether the materials will be sorted on-site or comingled. In addition, establish a comprehensive plan to assist the contractor in proper disposal of the hydro-demolition water. This plan entails the collection, management, and disposal of hydro-demolition water from a hydro-demolition process used for bridge deck restoration (North Carolina Department of Transportation, 2008). Calculations can be done by weight or volume, but must be consistent throughout. Develop a construction waste management plan that results in end of project rates for salvage/ recycling of 95 percent by weight of construction and demolition waste (EPA, 2007).

Scoring Criteria:

The points will be awarded based on percentage of total construction waste diverted from the landfills as shown in Table 3.10. An example for calculations is shown in Table 3.11.

Table 3.10: Scoring Criteria for Construction Waste Management

% Construction Waste Diverted	Points
20	1
40	2
60	3
80	4

Table 3.11: Example Calculations for Construction Waste Management

Material Description	Diversion	Quantity of Diverted Material	Unit
Concrete	Recycling	210.6	Tons
Steel	Steel Collector	6.5	Tons
Wood	Reuse	8.0	Tons
Mixed Waste	Landfill	52.0	Tons
Rubble	On-site Reuse	60.0	Tons
Total Construction Waste Diverted		337.1	Tons
Total of all Construction Waste		500.00	Tons
% of Construction Waste Diverted		**67.5 %**	

Standards/Resources:

- Section 01 74 19 - Construction Waste Management, EPA
- Section 03SP712(C), Special Provision for Managing Hydro-demolition Runoff Water, MDOT

Criteria 2.6: Use of Certified Wood (1 Point)

Description:

Forest Certifications have grown rapidly over the last decade. This practice is used to effectively use and manage nature's resources. "The Forest Stewardship Council (FSC) is an international not-for-profit, multi-stakeholder organization established in 1993 to promote responsible management of the world's forests. Its main tools for achieving this are standard setting, independent certification and labeling of forest products. This offers customers around the world the ability to choose products from socially and environmentally responsible forestry". "*FSC certification for wood products represents a real approach to assuring customers that the product they choose come from forest that were managed in a sustainable manner*" (FSC, 2011).

Intent:

To encourage the best forest management practices.

Requirements:

"Use a minimum 50% (based on cost) of wood based materials and products that are certified in accordancewith the Forest Stewardship Council's principles and criteria for wood building components" (USGBC, 2009). "This should include, but not limited to, general dimensional framing, and non-rented temporary construction applications such as bracing, concrete form work and predestrian barriers" (Hunt, 2004). Preservative treated woods also provide environmental, economical, and social benefits for our communities (McConnell and Irby, 2011).

Scoring Criteria:

One point for using certified wood in the project.

Standards/Resources:

- "Designing and Building with FSC", Forest Product Solutions, Forest Stewardship Council.

3.2.3 Category 3-Maintenance

A majority of the bridges built around the 1960's and 1970's need significant repair and maintenance actions (Helms, 2011). Lead and chromate based paints and coatings removal may have significant impacts on the environment, workers, and public. This section outlines the requirements of inspection technologies, bridge painting, cleaning, deck drainage, and impacts to fish and wildlife that should be met in order to reduce associated environmental impacts.

Criteria 3.1: Efficient Inspection Technologies (3 Points)

Description:

Inspection technologies play a very important role in collecting data and reliability indices of various structural and environmental conditions. Use of efficient equipment and processes can help in assessing the conditions of the bridge more efficiently and accurately. Efficient and accurate data is required to make decisions regarding various maintenance actions. Therefore, it is recommended to use efficient inspection technologies and processes for assessing the bridge conditions for proper maintenance action decisions. Taking proper and timely maintenance actions would be cost-effective and ensure a longer service life.

Intent:

To use efficient inspection technologies and processes for proper maintenance action decisions, thus enhancing the service life and reducing associated environmental impacts.

Requirements:

a) Follow Recommended Framework for a Bridge Inspection QA/QC Program of National Bridge Inspection Standards, FHWA. The framework describes the quality control and quality assurance procedures for accuracy and consistency in the bridge inspections. The framework outlines documentation of QA/QC program, Quality Assurance (QA) procedures, and Quality control (QC) procedures.

b) Use of specialized bridge equipment such as under bridge inspection vehicles, mobile inspection platforms, non-destructive evaluation equipment, and data collection and analysis equipment (Lwin, 2005) for efficient data collection and to allow workers to maneuver safely into position, allowing for hands-on inspection and maintenance work.

The office of bridge technology, FHWA, outlines a policy regarding the use of federal-aid funds, specifically highway bridge replacement and rehabilitation programs (HBRRP) funds for the purchase or rent of specialized inspection equipment. Federal HBRRP funds may also be used for the installation of permanent features that facilitate inspection activities on highway bridges as defined in 23 CFR 650.305. Such features as handrails, anchor points for a horizontal lifeline, and catwalks would be a few examples. In addition to HBRRP funds, National Highway System, Surface Transportation Program, and State Planning and Research funds may be used for the development, establishment, and implementation of bridge management systems and associated data collection activities.

Scoring Criteria:

Two points will be awarded for meeting the first requirement only.

One point will be awarded for meeting both requirements.

Standards/ Resources:

- Recommended Framework for a Bridge Inspection QA/QC Program, National Bridge Inspection Standards (NBIS), Bridge Technology, Federal Highway Administration and Funding For Bridge Inspection Equipment And Access Features, National Bridge Inspection Standards (NBIS), Bridge Technology, Federal Highway Administration (FHWA)
- MDOT Bridge Inspection Manuals and MDOT Inspection Manual, Michigan Department of Transportation.

Criteria 3.2: Bridge Painting/Coating (6 Points)

Description:

Bridge painting and cleaning are an important part of the bridge life cycle. Painting enhances the aesthetics and protects the steel bridge elements against corrosion and other weather deterioration (AASHTO, 2012). Paint should be used to slow corrosion cause by moisture, air, and oxidizing chemicals (Chang, Abdelrazig, and Chen., 2000). An effective bridge painting and cleaning plan is required as certain activities can be expected during bridge painting and cleaning, such as traffic lane closures, pedestrian and bicycle detours, moderate construction noise and dust, and normal work hours of 7 a.m. to 4 p.m. with occasional night time and weekend works. Typically, bridge abutments and piers are made of concrete. The beams and diaphragms made of steel are what need to be painted.

Intent:

To prevent bridge components from deterioration due to corrosion thus increasing the life expectancy of bridges and also protect workers and the environment from paint related by-products.

Requirements:

a) Utilize best practices to protect workers and the environment during lead paint removal and remove lead from existing structures; replace with zinc-rich type 4 systems (AASHTO, 2012).
b) Consider applying coating to the structural steel or reinforcement i.e., consider using zinc rich coatings that provide galvanic protection with additional coatings of epoxy and urethane paints (MDOT, 2012). Consider galvanizing, metallizing methods and inorganic zinc-rich paints (Kline, 2009). The concentration of zinc powder in the mixed coating is >80% by weight for the best performing inorganic zinc paints. AASHTO M300 covers zinc-rich coatings for steel (FHWA, 2012).

Scoring Criteria:

Three points will be awarded if zinc rich coatings are used for all the components and six points are awarded for meeting all the requirements.

Standards/Resources:

- Zinc-Rich Bridge Coatings, FHWA Bridge Coatings Technical Note: Zinc-Rich Bridge Coatings
- Clean Air Act Amendments
- Society for Protective Coatings (SACE)
- National Association of Corrosion Engineers (NACE)
- GS11 Green Seal Environmental Standard for Paints and Coatings

Criteria 3.3: Bridge Cleaning (2 Points)

Description:

Bridge cleaning is important in bridge maintenance. It consists of cleaning all bridge components vulnerable to dirt, bird-drop accumulation, accumulation of any chemicals, etc., by using a suitable means or method such as hand tools, air blasting, or water jetting. Bridge cleaning may increase the life of bridge components significantly (AASHTO, 2009).

Intent:

To clean components of bridges vulnerable to dirt, bird drop, accumulation, etc., thus increasing the longevity of the bridge components and lessening future maintenance requirements.

Requirements:

Bridge components subjected to dirt, bird drop accumulation, etc., should be cleaned periodically by using hand tools, air blasting, or preferably water jetting. Specifically,

a) Use proper respirators to avoid inhalation of dust or any other material.
b) Bridge components such as decks, pier caps, abutment seats, select beam flanges, wing walls, bearing systems, and open expansion joints should receive water flush.
c) Use best practices in channel maintenance for cleaning of weeds, float, debris, etc., from the vicinity of the bridge.
d) Develop a management plan for containment of wash water, i.e., to collect, sample, test, monitor, and dispose wash water. Avoid allowing wash water to enter into storm sewers, surface water, wetlands, ditches, floodplains, etc., unless in compliance with the local standards.
e) Determine the pollutant level of the wash water to select suitable disposal method, such as disposing it in surface waters or below the ground surface.
f) Wash water may also be hauled to a licensed treatment or disposal facility, in accordance with the approved wash water sampling and disposal plan (North Carolina Department of Transportation, 2008).

Scoring Criteria:

- One point will be awarded for developing schedule of cleaning operations.
- Two points will be awarded if a wash water management plan is also developed.

Standards/Resources:

- Drainage System cleaning, Pavement Cleaning, MDOT Scoping Manual, Michigan Department of Transportation.
- “Part 7.1.3, Bridge Cleaning; Chapter 7, Bridge Maintenance, Center for Environmental Excellence by AAHSTO” American Association of State and Transportation Officials.
- NCDOT Guidelines for Managing Bridge Wash Water Version 1.0.

Criteria 3.4: Bridge Deck Drainage (2 Points)

Description:

Bridge deck drainage is an important feature and care should be given while designing and maintaining the deck drainage. It should be designed to accommodate runoff. Effective design and maintenance of deck drainage is required to prevent the deck structure and reinforcing steel from corrosion due to deicing salts and moisture (AASHTO, 2009).

Intent:

To avoid impacts on the deck structure and reinforcing bars due to inefficient drainage.

Requirements:

a) Gutter flow from roadways should be intercepted before it reaches a bridge;
b) Avoid zero gradients and sag vertical curves on bridges;
c) Larger grates and inlet structures can be used onto the subsequent roadway sections to collect runoff from bridge decks immediately (AASHTO, 2009).

Scoring Criteria:

One point for meeting any of the two requirements.

Three points for meeting all of the requirements.

Standards/Resources:

- "Proper Drainage Reduces Roadway Problems." Nevada Milepost, Nevada's Technology Transfer Quarterly, Vol. 12, No. 1, (Spring 2002) p. 1.

Criteria 3.5: Avoiding and Minimizing Impacts to Fish and Wildlife (1 Point)

Description:

Bridge maintenance operations can severely disrupt the natural flow of river and stream ecosystems. Road crossings like bridges and culverts are a growing concern in altering habitats and disrupting the river and stream current (Jackson, 2003). Stream crossing methods include bridges, open-bottom or arch culverts, box culverts, and pipe culverts. Depending on the type of crossing, its size, method of installation, and maintenance, a crossing may have many or relatively few adverse impacts on a river or stream ecosystem.

Intent:

To avoid impacts on fish and wildlife due to maintenance activities.

Requirements:

a) Seek ways to build more durable structures, and in an environmentally sound fashion. Identify opportunities to avoid and minimize impacts.

b) Scheduling maintenance and improvements so that minimal time is spent in sensitive environments. Practices may include scheduling bridge maintenance to avoid egg spawning incubation, juvenile rearing and downstream migration periods of fish (AASHTO, 2009).

Scoring Criteria:

- One point is awarded for meeting the requirement.

Standards/Resources:

- Federal Endangered Species Act
- Rivers and Harbor Act
- Clean Water Act

Criteria 3.6: Corrosion Control Materials (3 Points)

Description:

This criterion will address corrosion control materials that can be used during rehabilitation and maintenance of bridges.

Intent:

To prevent or minimize the corrosion of bridge elements due to the penetration of chloride based deicers. This minimizes early deterioration of the structure. Each recommended method would either result in an increased amount of time between maintenance cycles or extend the bridge's service life.

Requirements:

a) Consider using galvanic anodes in all concrete patches that extend below the top layer of reinforcement. Only galvanic anodes listed on MDOT's QPL can be used.
b) Consider using Carbon Fiber Reinforced Polymer (CFRP) wrap. This increases the strength, is lightweight and provides additional corrosion resistance.

Scoring Criteria:

Two points are awarded if any one requirement is met.

Three points are awarded for meeting both requirements.

Standards/Resources:

- MDOT standard specifications for construction section 712.03
- Michigan State University Report, 2000, "Repair of Corrosion Damaged Columns Using FRP Wraps"

Criteria 3.7: Bridge Deck Joints and Deck Joint Seals (4 Points)

Description:

Bridge deck joints are important components for the proper functioning of a structure. Various factors such as temperature change, deflection caused by loads, creep, and shrinkage of concrete, stream or ice flow, and the longitudinal force of vehicles cause bridges to expand and contract. Bridge deck joints allow a bridge to expand and contract while protecting critical elements underneath the joint.

Intent:

To minimize or eliminate poorly maintained bridge deck joints and seals thus maintaining the service life of the bridge

Requirements:

Consider:

a) Eliminating bridge deck joints (when possible) or moving joints off bridge with the use of sleeper slabs.
b) If possible, discontinue the use of compression seals in new construction, replacement, and rehabilitation. Replace existing compression seals and block out style joints in those locations where expansion or rotation is needed with strip seal style expansion devices.
c) Establish a routine maintenance procedure to maintain joints.

Scoring Criteria:

The points are awarded based on the requirement met as shown in Table 3.12.

Table 3.12: Scoring Criteria for Bridge Deck Joints and Seals

Requirement	Points
a	2
b	1
c	1

Standards/Resources:

- “Evaluation of various types of bridge deck joints”, Final Report 510, Baker Engineering and Energy, Arizona Department of Transportation

Criteria 3.8 Snow and Ice Control (1 Point)

Description:

Michigan is one of the states that receive heavy snowfall in the winter. The standard procedure to remove snow or ice is by chemical treatment and plowing. Deicers are applied to roads to break up frozen precipitation, provide traction, and ease cleanup efforts. The most commonly used deicer in Michigan is salt.

Intent:

To implement snow and ice control techniques and to reduce the associated impacts of snow and ice on bridges.

Requirements:

a) Implement a snow and ice control plan including techniques to remove snow and ice from bridges.
b) Implement a management plan to monitor the amount of deicer applied.
c) Applying appropriate treatments or putting sensors on the bridge in order to track weather and bridge conditions. Currently MDOT uses weather stations on some bridges. By monitoring air temperature anti-icing chemicals can be applied prior to storm events or frost. As long as anti-icing agents are applied before the bridge deck freezes, deicing agents (such as salt) will not have to be added immediately and the snow and ice do not bond to the deck surface, making cleanup easier.
d) Anti-icing measures should take place before the snow falls and ice forms on the roadway. Liquid form (brine) is generally used as anti-icing chemicals to road surfaces just before a snow or ice storm. "Liquid sodium chloride (NaCl) is the most effective choice for anti-icing above 15° F (-9.4° C)" (Salt Institute, 2011)
e) Pre-wetting is an effective method of spraying deicing salt as it assists in spreading less salt, saving money, and minimizing the threat to the environment. Also wet salt clings to the road instead of bouncing off or being swept off by traffic thereby saving the amount of salt used.

Sodium chloride (salt) brine is a low-cost, effective alternative to liquid calcium chloride as a pre-wetting agent (Donahey and Burkheimer, 1996).

Scoring Criteria:

One point will be awarded for making a snow and ice control plan and using any one method to implement the plan.

Standards/Resources:

- Operation and Maintenance Criteria 9- Snow and Ice Control, Sustainable Highways Self-Evaluation Tool, FHWA, USDOT

CHAPTER 4

DELPHI SURVEY: METHODOLOGY, DATA COLLECTION AND ANALYSIS

4.1 Overview

This section deals with the adopted research methodology to reach a consensus for establishing weights in the categories design, construction, and maintenance, as well as awarding points to various criteria to rate sustainable bridges. The Delphi approach was chosen for data collection for this study and consisted of two rounds of surveys. The surveys were conducted by professionals and experts working in the Design, Construction, Maintenance, and Environmental sections in MDOT. The overall research study was segmented into four phases. The phases are literature review, development and distribution of survey Round 1, Round 2, and conclusion. The research methodology can be summarized in Figure 4.1.

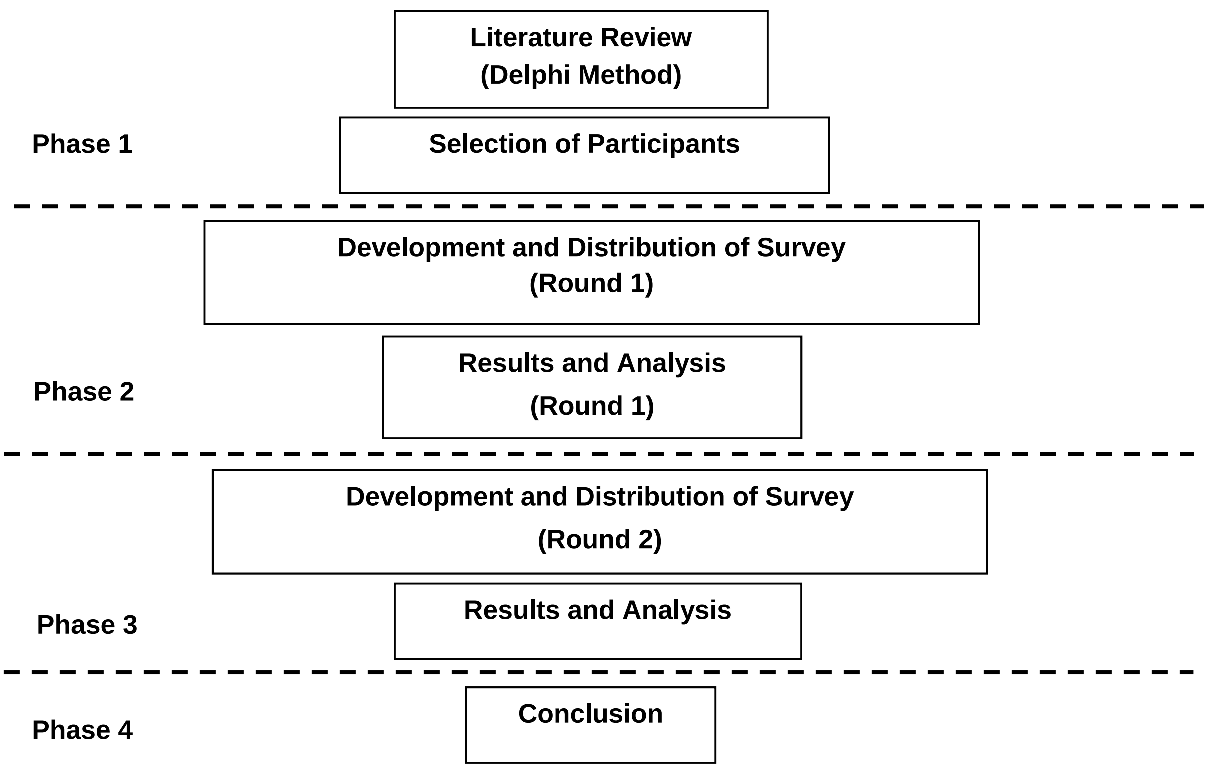


Figure 4.1: Phases of Delphi Survey

4.2 Literature Review and Selection of Participants

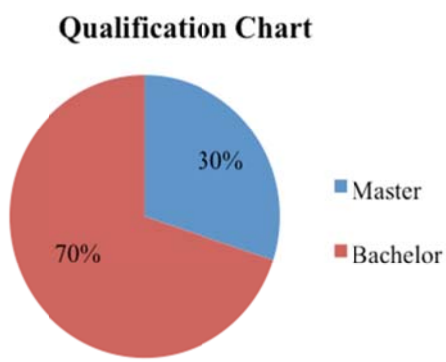
In Phase 1, a comprehensive literature review on the Delphi approach assisted in our selection of participants. This review, already discussed, facilitated in understanding the current practices and analyzing the data obtained from questionnaire. Phase 2 entails the development and distribution of the first questionnaire and completion and return of the 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.

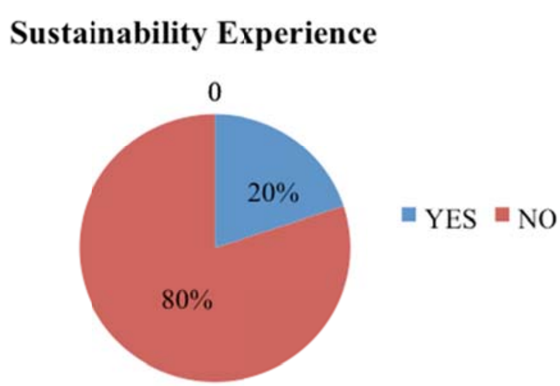
Table 4.1: Characteristics and Requirements of Participants (Hallowell, 2010)

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

After carrying out the comprehensive literature review on Delphi techniques, the following requirements for participants were laid and sent 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.

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 the environmental department. All the participants have over 10 years of experience. The pie chart given in Figure 4.2 shows the qualification of the participants, i.e., only three participants hold a master's degree. As far as sustainability practices are concerned, only two participants out of ten have prior experience in sustainability projects, as seen in Figure 4.3.





4.3 Developments 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.

4.3.1 Round 1 Results and Analysis

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

a) The maximum frequency response, was recorded in Site category under the Design section.
b) The least frequency response, six, was recorded in the overall rating of the framework.
c) The lowest standard deviation was viewed in the “Snow and Ice Control” criteria under the Maintenance section (3.25), indicating all the participants strongly agreed to one value.
d) The standard deviation was high in the Construction section.

Note: 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.

4.3.2 Round 2 Results and Analysis

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, the median, into account. They were free to change their percentage 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.

4.4 Phase 4: 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 the Delphi process was emailed to MDOT. This included a table showing Round 1 and 2 percentages points allocated to each category.

4.4.1 Response Rate

It was observed that the highest response, nine, was recorded in the Site category under the Design section and the least response, six, was recorded in assigning percentages to the overall rating of the Design, Construction, and Maintenance section. Table 4.2 shows the response rate by participants in each section and Table 4.3 shows the overall response rate by 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 a difference is that all the participants did not take part in the complete survey. Rather they participated in the sections in which they currently work or had prior experience. For example, a participant working in the 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: Response Rate of Participants

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: Response Rate of Participants

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

4.4.2 Discussion

The overall consensus was approached after two rounds. The scores did not change in Round 2. Afterward, the raw data from Round 1 and 2 were used to perform a statistical analysis to obtain mean percentages. It was established that the Design section was rated to be the most important and hence, this section was assigned 47 points. The Construction and Maintenance sections received 31 and 22 points respectively. Figure 4.4 shows the overall rating for the framework after percentage point allocation.

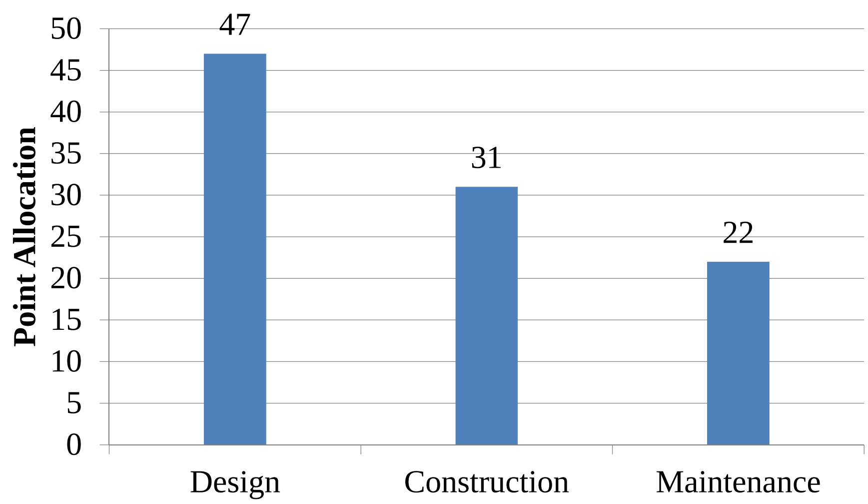


Figure 4.4: Points Distribution for Categories

The Design section entails three sub-categories: Site, Material, and Others. The total score of 47 points assigned to Design section was further subdivided among Site (22 points), Material (16 points), and Others (9 points). The same approach was adopted to allocate points within these three sub-categories. In the Site category, criterion Site Selection and criterion Soil Erosion and Sedimentation were assigned 6 points each, which is the maximum. Figure 4.5 shows the points allocated to each criterion in Design Section.

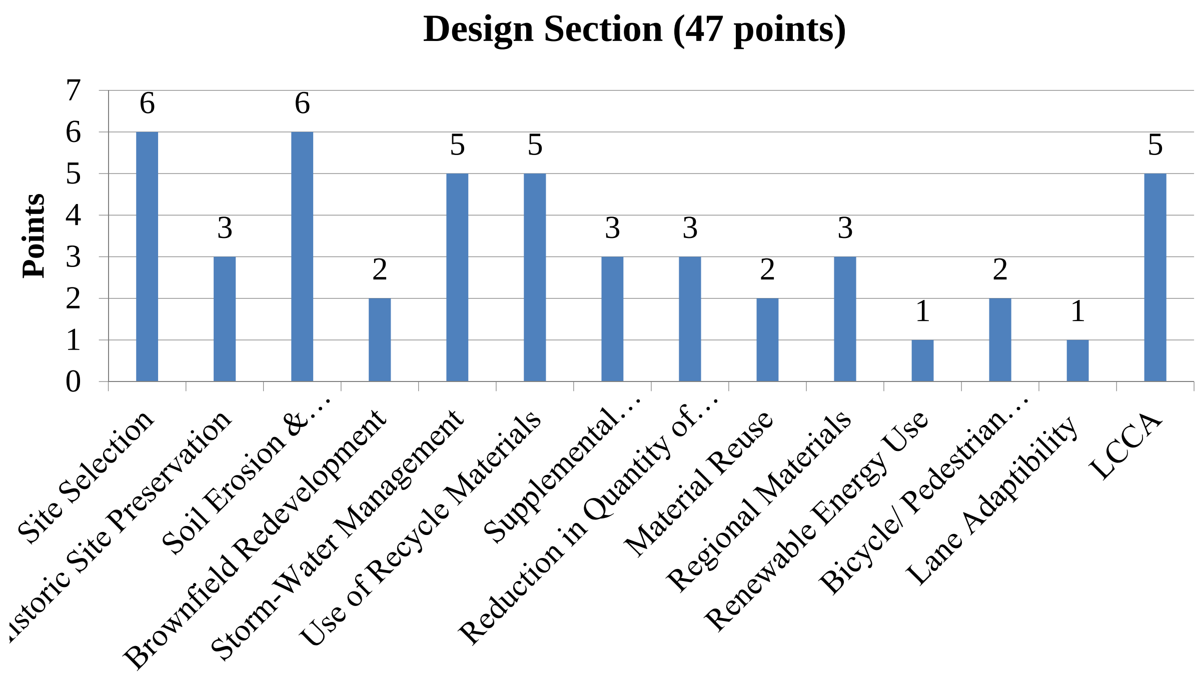


Figure 4.5: Points Distribution for Design Section

The Construction section includes six criteria and was awarded 31 points in the overall framework rating. A total of 14 points were assigned to the Accelerated Bridge Construction Techniques criterion to demonstrate that it had an enormous impact on this section, whereas the Use of Certified Wood criterion received only one point. The Corrosion Resistant Steel Reinforcement criterion collected 8 points and was rated as the second most important criteria in this section. Figure 4.6 shows the Points Allocation in the Construction section.

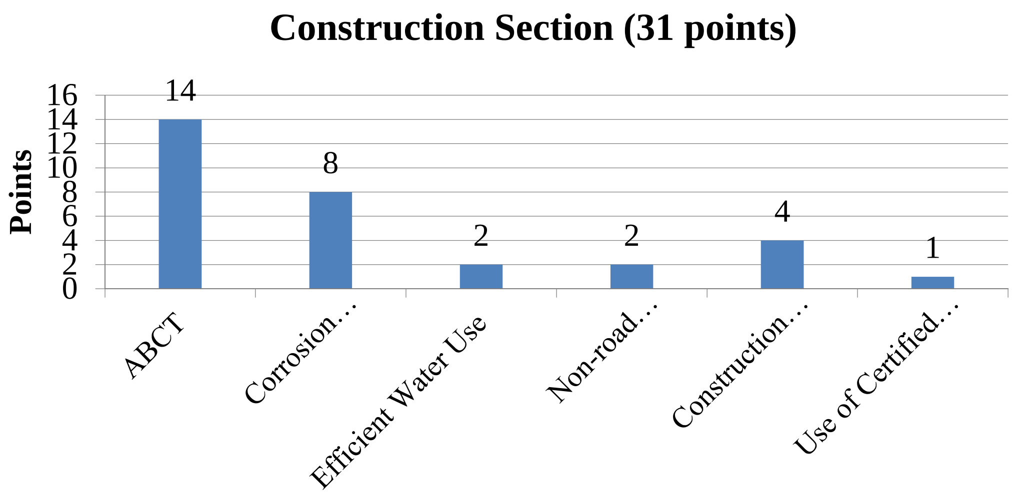


Figure 4.6: Points Distribution for Construction Section

The Maintenance section includes eight criteria and was awarded 22 points in the overall framework rating. A total of 6 points were assigned to the Bridge Painting and Coating criterion to demonstrate its large impact on this section whereas, criteria like Avoiding and Minimizing Impacts to Fish and Wildlife and Snow and Ice Control received only one point. The Bridge Deck Joint and Deck Joint Seals criterion collected 4 points, and were rated as the second most important criteria in this section. Figure 4.7 shows the Points in the Maintenance section.

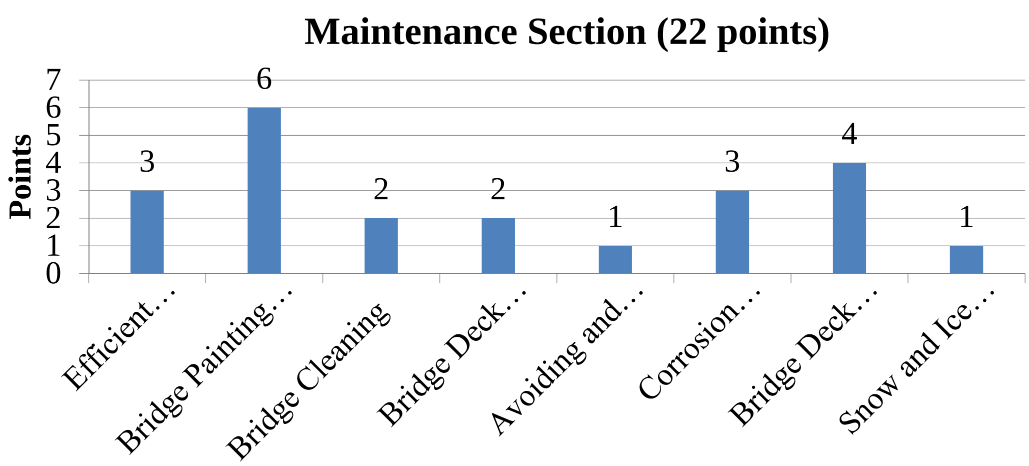


Figure 4.7: Points Distribution for Maintenance Section

4.5 Scorecard of the Green Rating System

Based on the results of the Delphi survey, a scorecard was developed for the rating, which is shown in Table 4.4.

Table 4.4: Scorecard for the Green Rating System

Scorecard		
1. Design (47 Points)		
Criteria	Criteria Name	Maximum Available Points
Criteria 1.1.1	Site Selection	6
Criteria 1.1.2	Historic Site Preservation	3
Criteria 1.1.3	Soil Erosion and Sedimentation Control	6
Criteria 1.1.4	Brownfield Redevelopment	2
Criteria 1.1.5	Storm-Water Management	5
Criteria 1.2.1	Use of Recycle Materials	5
Criteria 1.2.2	Supplemental Cementitious Materials	3
Criteria 1.2.3	Reduction in Quantity of Materials	3
Criteria 1.2.4	Material Reuse	2
Criteria 1.2.5	Regional Materials	3
Criteria 1.3.1	Renewable Energy Use	1
Criteria 1.3.2	Bicycle/ Pedestrian Pathways	2
Criteria 1.3.3	Lane Adaptability	1
Criteria 1.3.4	Life Cycle Cost Analysis	5

Table 4.4 (cont'd)

Scorecard		
2. Construction (31 Points)		
Criteria	Criteria Name	Maximum Available Points
Criteria 2.1	Accelerated Bridge Construction Techniques	14
Criteria 2.2	Corrosion resistant steel reinforcement	8
Criteria 2.3	Efficient Water Use	2
Criteria 2.4	Non-road equipment emission reduction	2
Criteria 2.5	Construction Waste Management	4
Criteria 2.6	Use of Certified Wood	1
3. Maintenance (22 Points)		
Criteria	Criteria Name	Maximum Available Points
Criteria 3.1	Efficient Inspection Technologies	3
Criteria 3.2	Bridge Painting/Coating	6
Criteria 3.3	Bridge Cleaning	2
Criteria 3.4	Bridge Deck Drainage	2
Criteria 3.5	Avoiding and Minimizing Impacts to Fish and Wild Life	1
Criteria 3.6	Corrosion Control Materials	3
Criteria 3.7	Bridge Deck Joints and Deck Joint Seals	4
Criteria 3.8	Snow and Ice Control	1

4.6 Certification Levels

After assigning points to each criterion, the next step is to decide certification levels to categorize sustainable bridges. The methodology for determining certification levels is shown in Table 4.5. Each criterion is determined whether it is easy to implement, difficult to implement, or has a medium level of difficulty in achieving the criteria. This was first determined by the discussion of research panel. It was sent for further review to MDOT experts and the justification for its level of difficulty was then provided by MDOT. The sum of points of easy to implement, medium to achieve, and difficult to achieve were found.

Table 4.5: Certification Levels Determination

Criteria	Criteria Name	Level of Implementation			Available Points	Justification
		Easy	Medium	Difficult		
Criteria 1.1.1	Site Selection			6	6	Bridge designers normally do not have a choice in site selection.
Criteria 1.1.2	Historic Site Preservation	3			3	Required by MDOT
Criteria 1.1.3	Soil Erosion and Sedimentation Control	2	4		6	Requirements “a”, “b” and “c” are required. BMP's are optional
Criteria 1.1.4	Brownfield Redevelopment			2	2	Usually avoided. MDOT does not want to assume liability
Criteria 1.1.5	Storm-Water Management	2	3		5	Requirement “a” is optional
Criteria 1.2.1	Use of Recycle Materials			5	5	FHWA requires new materials to be used in all new constructions. Has been mandated in some pilot projects as backfill
Criteria 1.2.2	Supplemental Cementitious Materials	1		2	3	Dictated by the mix design
Criteria 1.2.3	Reduction in Quantity of Materials			3	3	Deflection req. limit the beam shape so we can choose higher strengths but may not be able to reduce cross section
Criteria 1.2.4	Material Reuse			2	2	Again, FHWA limit materials to new
Criteria 1.2.5	Regional Materials			3	3	Existing supplier may be outside the 500-mile radius. Contractor choice and not MDOT's
Criteria 1.3.1	Renewable Energy Use		1		1	This is considered and applied where feasible

Table 4.5. (cont'd)

Criteria	Criteria Name	Level of Implementation			Available Points	Justification
Criteria 1.3.2	Bicycle/ Pedestrian Pathways		2		2	Mandated to consider this in design but not required to construct
Criteria 1.3.3	Lane Adaptability	1			1	Standard practice now
Criteria 1.3.4	Life Cycle Cost Analysis	5			5	Standard practice now
Criteria 2.1	Accelerated Bridge Construction Techniques	3	5	6	14	SPMT work in Utah but so far unsuccessful in MI. FHWA now mandates that 25% of all bridges use ABCT
Criteria 2.2	Corrosion resistant steel reinforcement	4	4		8	Epoxy coated rebar is required above ground.
Criteria 2.3	Efficient Water Use			2	2	Gray water is not allowed in mix design so this may be impossible to get.
Criteria 2.4	Non-road equipment emission reduction			2	2	Contractors choice
Criteria 2.5	Construction Waste Management		2	2	4	MDOT Spec 205.03P requires us to handle all waste within right of way.
Criteria 2.6	Use of Certified Wood	1			1	Not applicable
Criteria 3.1	Efficient Inspection Technologies		3		3	Standard practice now
Criteria 3.2	Bridge Painting/Coating	3	3		6	Should receive 6 points if concrete beams are used.
Criteria 3.3	Bridge Cleaning		1	1	2	
Criteria 3.4	Bridge Deck Drainage	2			2	Required by MDOT

Table 4.5. (cont'd)

Criteria	Criteria Name	Level of Implementation			Available Points	Justification
Criteria 3.5	Avoiding and Minimizing Impacts to Fish and Wild Life	1			1	Required by MDOT
Criteria 3.6	Corrosion Control Materials	2	1		3	Use of anodes is standard practice
Criteria 3.7	Bridge Deck Joints and Deck Joint Seals	2	2		4	Requirement "a" and "b" are MDOT policy.
Criteria 3.8	Snow and Ice Control	1			1	Standard practice now
Total		33	31	36	100	

The score range is divided into in three major levels: 0-33 representing the lower range, 34-64 representing the middle range, and 65-100 representing the higher range. The lower range and the higher range are further divided into two halves. This is because some of the criteria are easy to achieve and are very basic components of every bridge design and construction project. Those seeking certification are likely to achieve the certified level in any project as they can easily obtain at least 1 or 2 points. The lower range consists of the Non-Green level, followed by Certified. Similarly, the higher range consists of the Total Green level, followed by Evergreen; this raises the bar for an elevated objective for sustainability. The certification levels are shown in the Table 4.6.

Table 4.6: Certification Levels for Bridge Green Rating System

Certification Level	Score Range
Non-Green	0-16
Certified	17-34
Green	35-64
Total Green	65-82
Evergreen	82-100

CHAPTER 5

GHG EMISSION CALCULATION GUIDELINES BASED ON LCA METHODOLOGY

5.1 Introduction

The construction sector accounts for 131 million metric tons of CO_2 equivalents (EPA, 2009). The transportation sector is one of the biggest contributors of Greenhouse Gas (GHG) emissions. According to greenhouse report by the Environmental Protection Agency (EPA), the transportation sector was responsible for 27% of GHG emissions in 2002 and is the second biggest contributor by sector, following the industrial sector, which is responsible for 32% of GHG emissions (EPA, 2008). Therefore, a significant amount of GHG emissions are associated with the construction and use of transportation infrastructure. This has led State Department of Transportation Agencies to take the challenge of global climate change and investigate strategies that reduce the life cycle GHG emissions associated with transportation infrastructure, which involves the design, construction and maintenance of bridges (Mukherjee and Cass, 2012).

The California Environmental Protection Agency has already developed a greenhouse gas emission inventory that estimates the amount of GHG emissions associated with various activities. The inventory includes estimation of various gas pollutants such as carbon-dioxide (CO_2), methane (CH_4), sulfur hexafluoride (SF_6), nitrous oxide (N_2O) etc. (California EPA, 2012). This study proposes guidelines to measure GHG emissions for bridge construction projects with the aim to calculate the carbon footprint, defined as a composite measure of all GHG emissions expressed as equivalents of carbon dioxide emissions, and to develop a tool that can be used to estimate and benchmark carbon footprints for bridge construction projects. The Cradle to Gate LCA approach is taken into account to estimate the emissions from raw material the acquisition, manufacturing, and construction phases of different bridges.

5.2 Goals and Objectives

The goal of this section is to develop an LCA framework that includes guidelines for determining the carbon footprint associated with various items in bridge construction projects. This can enable various transportation agencies to evaluate the framework and investigate various strategies to reduce GHG emissions, thus supporting sustainable decision-making. This would allow them to consider such alternatives that reduce GHG emissions. The guidelines were developed using the following objectives:

Objective 1 – Develop a construction inventory that includes a list of materials and equipment that can be used in bridge projects.

To accomplish this objective, a list of materials and equipment that can be used in bridge projects was collected using MDOT construction plans and specifications and construction inventory developed by Mukherjee and Cass (2011) for computing GHG emissions in highway reconstruction and rehabilitation projects.

Objective 2 - Report estimated emission factors for all the materials and equipment.

Estimated emission factors were found for the products based on literature review, reviewing historical databases and using the software tool "SimaPro".

Objective 3 – Provide a tool to calculate the quantity of GHG emissions due to materials and equipment used in the bridge project.

An Excel based tool was developed to calculate the quantity of GHG emissions from the products. This tool is based on the web-based tool called project estimator developed by Mukherjee and Cass (2011) for calculating GHG emissions in highway reconstruction and rehabilitation projects. This tool can be found at http://www.construction.mtu.edu:8000/cass_reports/webpage/estimator.html.

Objective 4 – Conduct a case study and compare GHG emissions based considering two alternatives.

A case study is conducted which include a MDOT bridge replacement project. This case study is used to compare GHG emissions for two alternative bridge decks – a conventional concrete bridge deck and a Fiber Reinforced Polymer (FRP) bridge deck.

5.3 Building Blocks for Developing GHG Emission Calculation Guidelines

One building block for developing GHG emission calculation guidelines (Figure 5.1) is the research study "Carbon Footprint for HMA and HCC Pavements"; most of the products and emissions factors are obtained from product inventory developed in this study Other building blocks include literature and historical databases, and the software tool "SimaPro" as these are used to obtain emission factors of some of the products.,

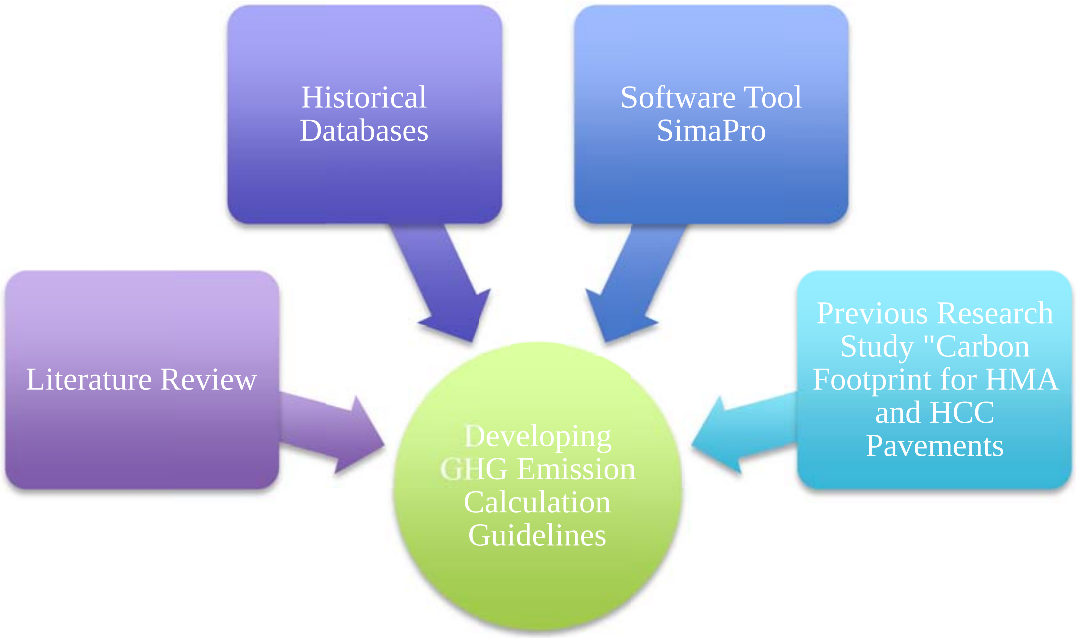


Figure 5.1: Building Blocks for Developing GHG Emission Calculation Guidelines

a) Carbon Footprint for HMA and HCC Pavements

Mukherjee and Cass (2011) conducted this research study and prepared a report for MDOT. Researchers proposed a project based life cycle assessment framework that can be used to estimate GHG emissions of typical highway reconstruction and rehabilitation projects. The aim of the research study is to calculate the carbon footprint of Hot-Mix Asphalt (HMA) and Portland Cement Concrete (PCC) pavements for both reconstruction and rehabilitation projects. The objectives stated in the research study are:

a) Report construction inventories for 14 highway reconstruction, rehabilitation, and Capital Preventive Maintenance (CPM) projects observed over a period of two summers

b) Report estimated emission factors for construction materials and equipment used
c) Report estimated emission factors for use phase of highways
d) Provide contractors a tool to benchmark construction and rehabilitation projects
e) Provide MDOT a tool to assess emissions through the different life cycle stages of a pavement (Mukherjee and Cass, 2012).

State Agencies and contractors can use it to estimate GHG emissions for specific construction operations. These can be used to investigate or identify alternative materials or improvements in construction processes to reduce their emissions. In turn, this will encourage the adoption of low emission products and techniques into practice, thus indirectly including other stakeholders such as material suppliers and equipment manufacturers. The framework was developed using the following steps:

Data Collection Phase:

In this phase, data were collected from 14 different highway construction and maintenance project sites in the state of Michigan to develop a comprehensive project inventory of materials and equipment. These projects included HMA and concrete reconstruction, maintenance, and rehabilitation projects. The data were collected during the construction phase and use phase of the pavement. The collection of this data was very important to know the materials, equipment, and processes involved to develop project inventory. Estimates of GHG emissions from these products were calculated, taking advantage of the existing methods of calculating GHG emissions. It accounts for emissions from the following stages:

a) Extraction of raw materials or mining;
b) Manufacturing and production of the products (materials and equipment used to construct the pavement);
c) Off-road and on-road transportation of products;
d) Processes involved during the construction and maintenance of the pavement
e) Service life (use-phase of the pavement)

Motor Vehicle Emission simulator (MOVES), a traffic simulation environment developed by EPA, is used to estimate the use phase emissions due to on-road vehicular traffic. Excess emissions due to traffic delays and reduced speeds in construction zones are also considered.

Emission factors were collected from existing literature and historical databases to estimate the emissions from these products. EPA defines an emission factor as "a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per mega-gram of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category (i.e., a population average)" (EPA, 2011).

Once the emission factor is developed for a product, emissions due to the product in a life cycle can be calculated by multiplying the emission factor by its quantity. For example, if the emission factor is 0.012 and 100 MT of asphaltic material is used in the project, then emissions due to asphaltic material will be 0.012 X 100 MT = 1.2 MT of $CO_{2,}$ i.e., CO_2 equivalent emissions of asphaltic materials will be 1.2 MT/100 MT of material. Similarly, the emission factor for other products can be developed and emissions can be calculated. Once the emissions from all the products and process are calculated these can be summed up to calculate the total project emissions.

Inventory Development:

The data that were collected through the 14 projects were organized into material and equipment categories to develop a project inventory. The inventory would consist of product and processes, their emission factors, and other details.

Analyzing the inventory and estimating project life cycle GHG emissions:

LCA techniques were used to assess the environmental impacts of the products and processes. Economic Input Output Life-cycle Assessment (EIO-LCA) (Hendrickson et al. 1998, Cicas et al. 2007) is one of the many methods used to assess environmental impacts. The principal investigator in this research study uses this method in his previous work to assess the environmental impact associated with the products and processes.

Hybrid LCA Methodology:

There are two ways to conduct a LCA a) input-output based LCA or b) a process based LCA. Economic input-output based LCAs are based on economic transactions and resource interactions between an exhaustive set of economic sectors. The Economic Input Output-Life Cycle Assessment (EIO-LCA) is also used in the hybrid model. It is a model that defines the scope and number of environmental effects quantified in a LCA, developed at Carnegie Mellon University (Hendrickson , 2006). It estimates the economic contribution, resource requirements, and environmental emissions for a particular product, service, or activity.

In this study, in order to estimate the GHG for all materials and equipment inputs, an input-output and/or process the LCA tool is used to take advantage of the most recent emission factors that have been reported in the process LCA literature, when applicable, as well as maximize the advantages of an input-output LCA. In the model, the GHG emissions are quantified as a function of the construction and vehicle operations in terms of material/fuel usage.

The emission factors used in this study are from process LCAs reported in literature. They have been taken primarily from the Stripple (Stripple, 2011), Athena (AETHNA, 2006) and NREL (NREL) inventories. These emission factors are usually expressed as tons of CO_2 equivalents per unit weight or volume. Therefore, given a bulk volume or weight of a material use on a particular project, the emissions can be calculated using the emission factors. The framework is based on a process, product, service (PPS) method that includes different process and product components. This approach uses existing calculation methods of GHG emissions but uses the data collected through 14 highway construction projects.

Product Components:

All the materials that are listed in department of transportation agency specifications were accounted for. Both virgin materials and recycled materials were taken into consideration and were accounted for during the mining, manufacturing, and transportation of the materials to and from the site phases. All the equipment that are used in highway construction were taken into consideration and accounted for emissions due to manufacturing, transportation, construction, and maintenance operations (Mukherjee and Cass, 2012). For each of these products, emission factors were developed; emissions can be calculated depending on the quantity of these products.

Process Components:

It includes two components - the processes on site that are directly involved in the highway construction and maintenance operations, e.g., construction schedule and operation design; and the processes that directly influence decisions of long-term pavement behavior, e.g., determination of maintenance schedules (Mukherjee and Cass, 2012).

Service life components:

Since it can be difficult to estimate, a traffic simulation environment MOVES was used to estimate use phase emissions due to on-road vehicular traffic.

Implementation of web based tool to calculate GHG emissions of the products:

The Project estimator tool PE-2 was developed which is an easy to use interface to calculate GHG emissions in a project. This tool can be accessed at http://www.construction.mtu.edu:8000/cass_reports/webpage/estimator.html.

The purpose of the tool is

1) Inventory Reporting:

User can query all relevant data collected and creates a report for the project.

2) Benchmarking and Estimating

The PE-2 tool can be used at the project level to estimate and benchmark emissions. To benchmark expected project emissions, use the bill of materials and estimated material and equipment use in the project. At the end of the project, use PE-2 to generate an emissions report using the actual data collected. MDOT should encourage contractors (through direct economic or equivalent incentive) to reduce the actual project emissions when compared to the benchmark for the project. An incentive plan can be generated for the contractor's efforts at reducing GHG emissions during the project construction process. This could be through more efficient project site design and schedule planning or using alternative materials during the construction process.

Literature and Historical Databases:

Various historical databases are available to obtain emission factors for calculating life cycle GHG emissions from products. National Renewable Energy Laboratory (NREL) has developed a life cycle inventory database to assess life cycle impacts. "U.S. Life Cycle Inventory (LCI) database provides individual gate-to-gate, cradle-to-gate and cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly in the U.S" (NREL, 2012). Various other databases such as life cycle inventory of Portland concrete, life cycle inventory of steel and other products were accessed to determine GHG emissions from those products. Most of the emission factors of all the equipments in this study are adopted from the research report "Carbon Footprint for HMA and HCC Pavements" developed by Mukherjee and Cass (2012).

SimaPro:

SimaPro is the LCA tool most widely used in the industry. SimaPro is used in this study to calculate the emission factor of some of the products that can be used on bridge projects. Cradle to Gate LCA is performed using SimaPro according to International Standard ISO 14040 i.e., it includes the four phases that were previously described. They are goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation. Environmental performance is generally measured in terms of a wide range of potential effects, such as (Carmody and Trysty, 2005) Fossil fuel depletion, other non-renewable resource use, water use, global warming potential, stratospheric ozone depletion, ground level ozone (smog) creation, nutrification (excess nutrients)/eutrophication (oxygen deficiency) of water bodies, acidification and acid deposition (dry and wet), and toxic releases to air, water, and land.

All of these measures are indicators of the environmental loadings that can result from the manufacture, use, and disposal of a product. SimaPro is used in this study to calculate total cradle to gate CO_2 equivalent releases of different products. The international standard organization ISO 14040 and ISO 14044 has developed a framework and guideline on how to conduct an LCA. SimaPro is organized according to ISO 14040 and ISO 14044 guidelines for conducting LCA shown in Figure 5.2. The following steps are defined in conducting an LCA (ISO 14040, 2006; ISO 14044, 2006):

a) Defining goal and scope of the study;

b) Development of an exhaustive inventory of all energy and material inputs, and the environmental outputs and emissions associated with each life cycle phase;

c) Analysis of impacts of inputs and outputs identified in the inventory analysis on humans and ecology, and;

d) Appropriate interpretation of the analysis to support policy and decision- making.

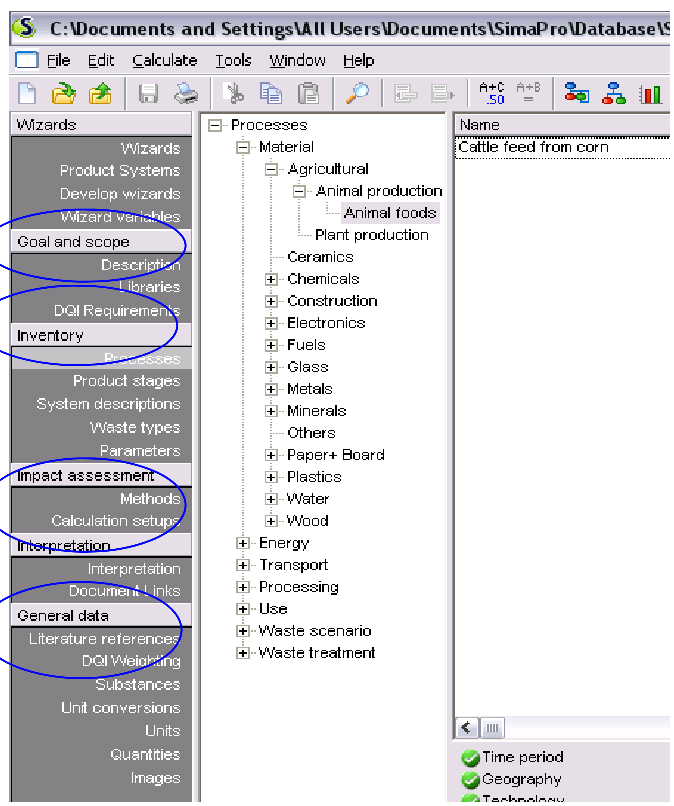
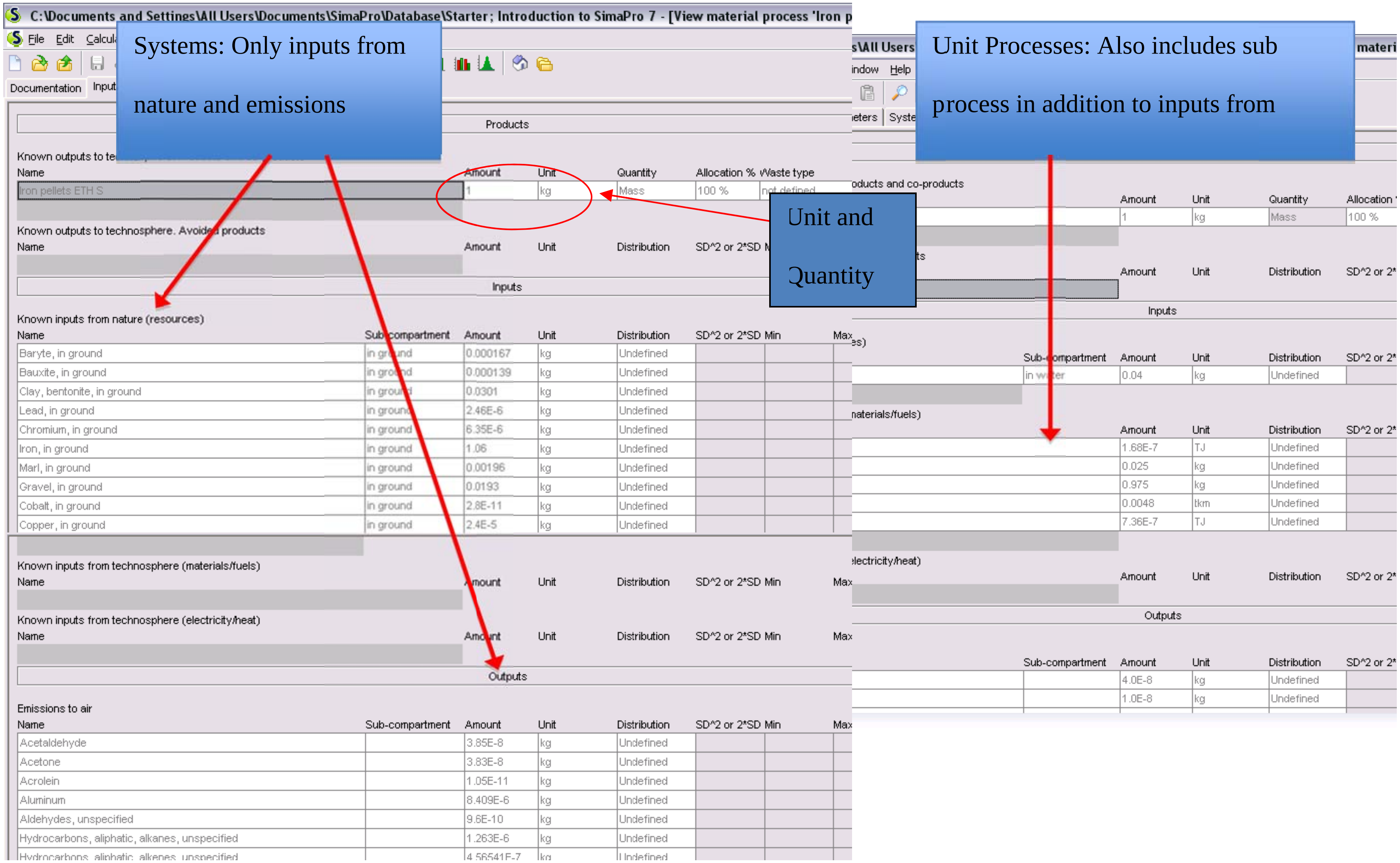


Figure 5.2: SimaPro Organization

All the general decisions regarding the LCA study are defined in the goal and scope phase. The reason for the study and the overall goal of the study is defined in this stage. The product description and all the assumptions are also described. System boundaries, impact categories, data quality, and methodology are also described in the goal and scope definition phase. It needs to be decided what is included and what is excluded from the product system and whether all or part of the product life cycle is taken into account.

In the Life Cycle Inventory (LCI) phase shown in Figure 5.3, all the processes are defined in each life cycle phase and energy, and material inputs and environmental emission outputs are determined and included. The outputs can be air emissions, water pollutants, solid wastes, and other releases. The inputs and outputs can be determined through an exhaustive data collection procedure. Quantitative and qualitative data for every process in the system can be collected through site visits, commercially or publicly available databases or through the collection of secondary data from literature. The LCI database lists all material and energy inputs and outputs. The LCI result allows calculating potential impacts of a product system on humans and ecology. This impact assessment method is known as Life Cycle Impact Assessment (LCIA). There are four steps in calculating LCIA: classification, characterization, normalization, and evaluation. The last two steps are optional. Each output is classified into one or more impact category. Impact categories include global warming potential (GWP), fossil depletion, freshwater eutrophication, ozone depletion, terrestrial acidification, etc. Therefore, the issue of global warming is represented by the GWP category. Any emission to air that contributes to global warming is classified as contributors to GWP. The quantity of each of these pollutants is then converted to quantity of eq. CO2 by multiplying their quantities by a characterization factor to determine their CO2 equivalent if eq. CO2 is the reference unit of the impact category. The characterization factor is determined by different scientific groups and different methodologies, the most commonimpact category methodology is Tools for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) (EPA, 2012) in USA) The total quantity of CO_2 equivalent can be calculated for the impact category. This study is focused on determining the GHG emissions in terms of CO_2 equivalent, thus determining the GWP of product system.


Systems: Only inputs from
nature and emissions
Unit Processes: Also includes sub
process in addition to inputs from
Unit and
Quantity

The last step, which is the interpretation of the results shown in Figure 5.4 and Figure 5.5, has great significance as it can be used to determine the environmental hotspots and conclusions. These can be used to support policy and decision-making. Figure 5.6 to Figure 5.12 and Table 5.1 shows the results obtained from SimaPro. It shows cradle to gate CO_2 eq. emissions from different products. Table 5.2 list emission factors of all the materials.

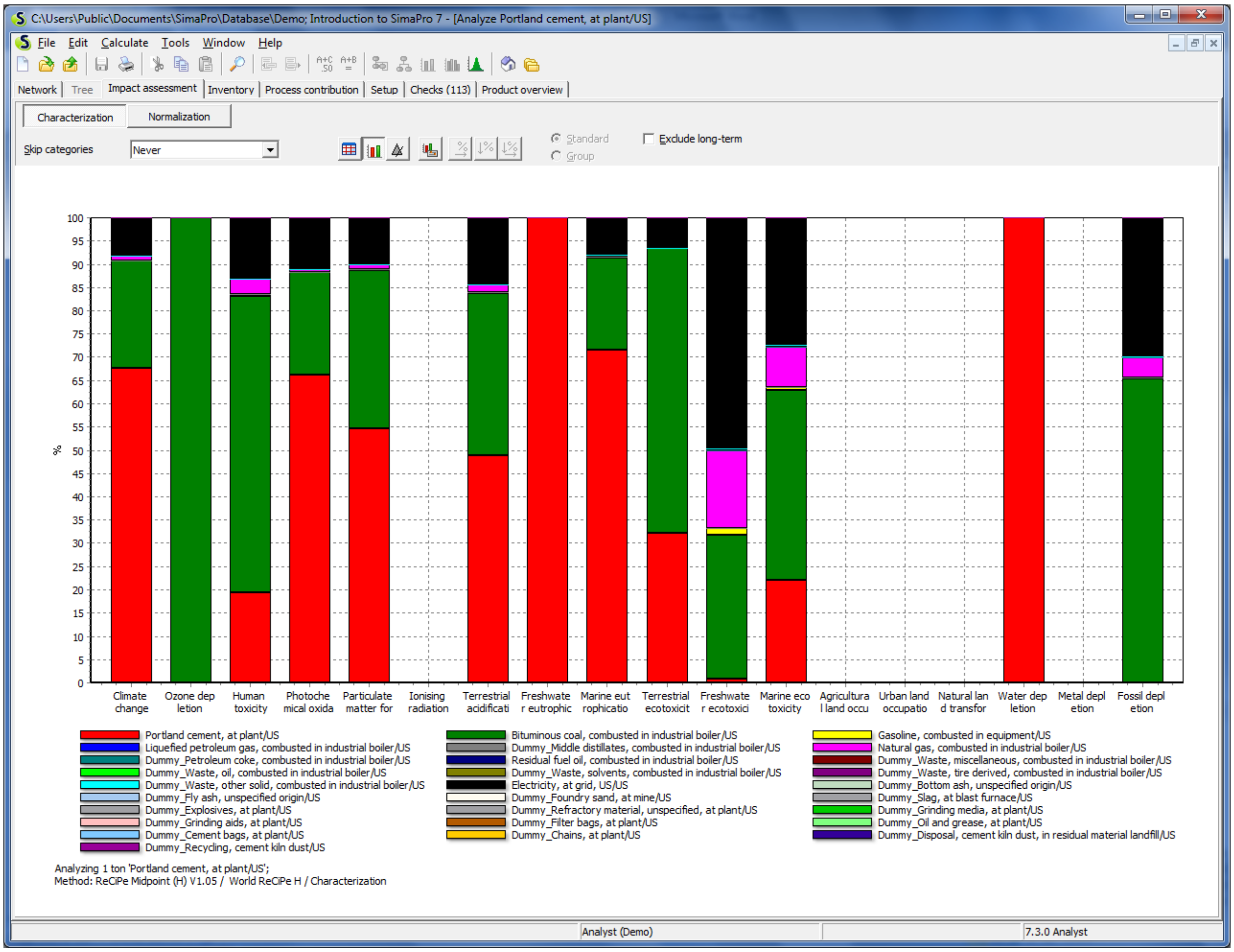
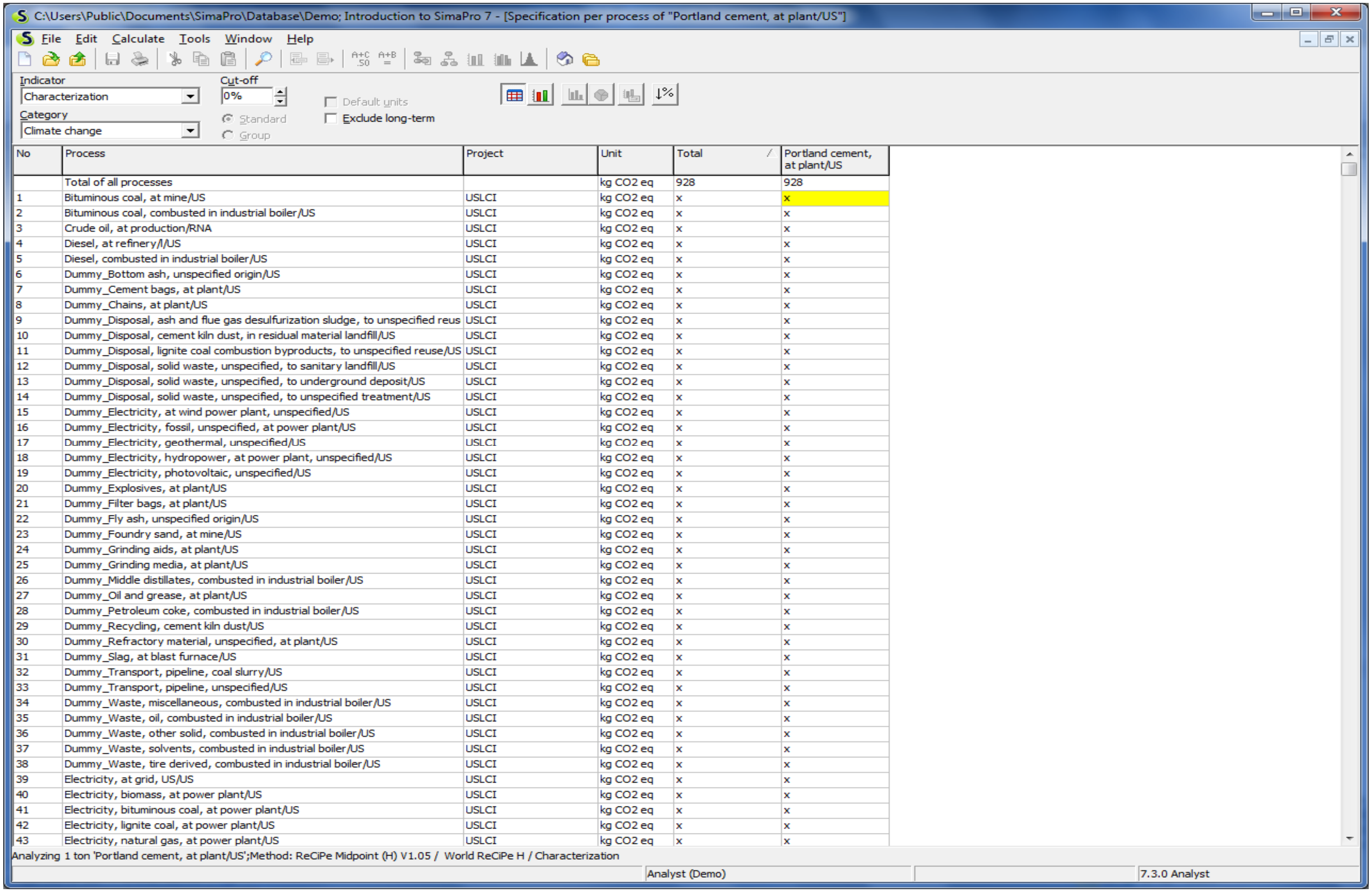
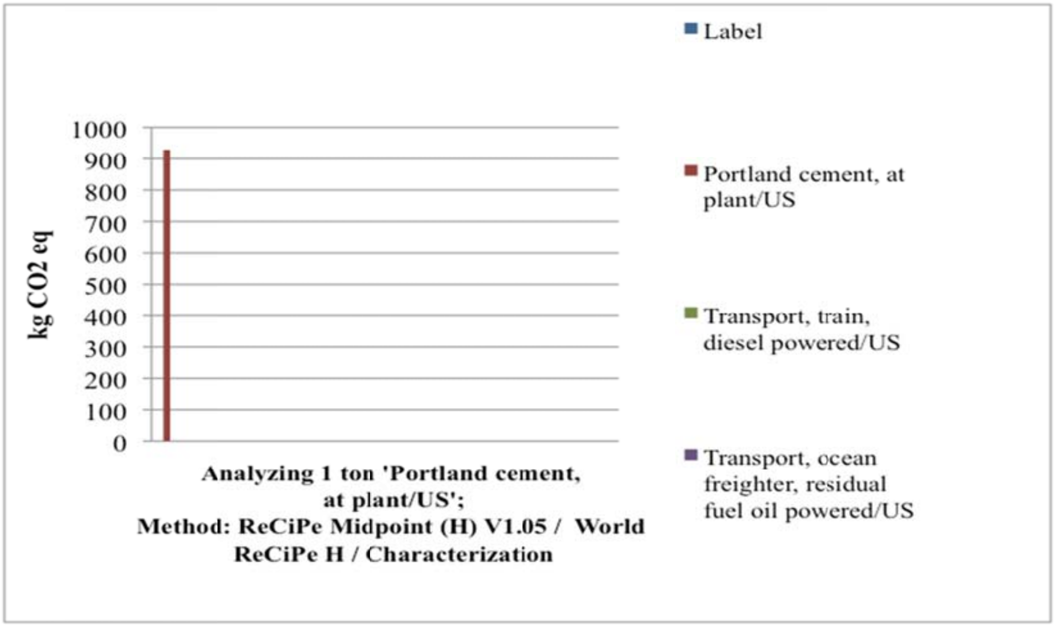


Figure 5.4: Impact Assessment Phase

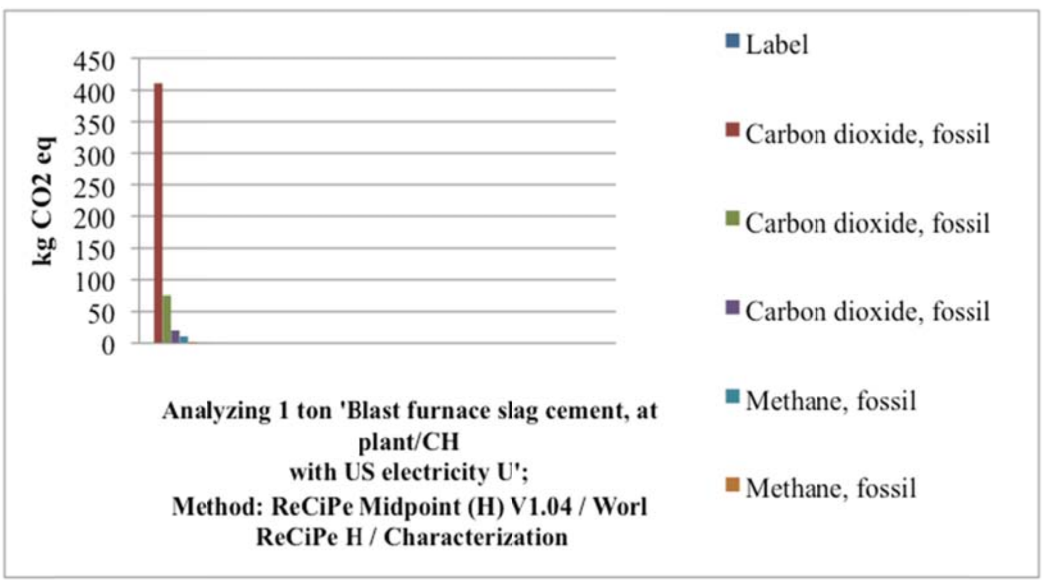


No	Process	Project	Unit	Total	Portland cement, at plant/US
	Total of all processes		kg CO2 eq	928	928
1	Bituminous coal, at mine/US	USLCI	kg CO2 eq	x	x
2	Bituminous coal, combusted in industrial boiler/US	USLCI	kg CO2 eq	x	x
3	Crude oil, at production/RNA	USLCI	kg CO2 eq	x	x
4	Diesel, at refinery/l/US	USLCI	kg CO2 eq	x	x
5	Diesel, combusted in industrial boiler/US	USLCI	kg CO2 eq	x	x
6	Dummy_Bottom ash, unspecified origin/US	USLCI	kg CO2 eq	x	x
7	Dummy_Cement bags, at plant/US	USLCI	kg CO2 eq	x	x
8	Dummy_Chains, at plant/US	USLCI	kg CO2 eq	x	x
9	Dummy_Disposal, ash and flue gas desulfurization sludge, to unspecified reus	USLCI	kg CO2 eq	x	x
10	Dummy_Disposal, cement kiln dust, in residual material landfill/US	USLCI	kg CO2 eq	x	x
11	Dummy_Disposal, lignite coal combustion byproducts, to unspecified reuse/US	USLCI	kg CO2 eq	x	x
12	Dummy_Disposal, solid waste, unspecified, to sanitary landfill/US	USLCI	kg CO2 eq	x	x
13	Dummy_Disposal, solid waste, unspecified, to underground deposit/US	USLCI	kg CO2 eq	x	x
14	Dummy_Disposal, solid waste, unspecified, to unspecified treatment/US	USLCI	kg CO2 eq	x	x
15	Dummy_Electricity, at wind power plant, unspecified/US	USLCI	kg CO2 eq	x	x
16	Dummy_Electricity, fossil, unspecified, at power plant/US	USLCI	kg CO2 eq	x	x
17	Dummy_Electricity, geothermal, unspecified/US	USLCI	kg CO2 eq	x	x
18	Dummy_Electricity, hydropower, at power plant, unspecified/US	USLCI	kg CO2 eq	x	x
19	Dummy_Electricity, photovoltaic, unspecified/US	USLCI	kg CO2 eq	x	x
20	Dummy_Explosives, at plant/US	USLCI	kg CO2 eq	x	x
21	Dummy_Filter bags, at plant/US	USLCI	kg CO2 eq	x	x
22	Dummy_Fly ash, unspecified origin/US	USLCI	kg CO2 eq	x	x
23	Dummy_Foundry sand, at mine/US	USLCI	kg CO2 eq	x	x
24	Dummy_Grinding aids, at plant/US	USLCI	kg CO2 eq	x	x
25	Dummy_Grinding media, at plant/US	USLCI	kg CO2 eq	x	x
26	Dummy_Middle distillates, combusted in industrial boiler/US	USLCI	kg CO2 eq	x	x
27	Dummy_Oil and grease, at plant/US	USLCI	kg CO2 eq	x	x
28	Dummy_Petroleum coke, combusted in industrial boiler/US	USLCI	kg CO2 eq	x	x
29	Dummy_Recycling, cement kiln dust/US	USLCI	kg CO2 eq	x	x
30	Dummy_Refractory material, unspecified, at plant/US	USLCI	kg CO2 eq	x	x
31	Dummy_Slag, at blast furnace/US	USLCI	kg CO2 eq	x	x
32	Dummy_Transport, pipeline, coal slurry/US	USLCI	kg CO2 eq	x	x
33	Dummy_Transport, pipeline, unspecified/US	USLCI	kg CO2 eq	x	x
34	Dummy_Waste, miscellaneous, combusted in industrial boiler/US	USLCI	kg CO2 eq	x	x
35	Dummy_Waste, oil, combusted in industrial boiler/US	USLCI	kg CO2 eq	x	x
36	Dummy_Waste, other solid, combusted in industrial boiler/US	USLCI	kg CO2 eq	x	x
37	Dummy_Waste, solvents, combusted in industrial boiler/US	USLCI	kg CO2 eq	x	x
38	Dummy_Waste, tire derived, combusted in industrial boiler/US	USLCI	kg CO2 eq	x	x
39	Electricity, at grid, US/US	USLCI	kg CO2 eq	x	x
40	Electricity, biomass, at power plant/US	USLCI	kg CO2 eq	x	x
41	Electricity, bituminous coal, at power plant/US	USLCI	kg CO2 eq	x	x
42	Electricity, lignite coal, at power plant/US	USLCI	kg CO2 eq	x	x
43	Electricity, natural gas, at power plant/US	USLCI	kg CO2 eq	x	x

Figure 5.5: Impact Assessment Phase



ants, 2012)



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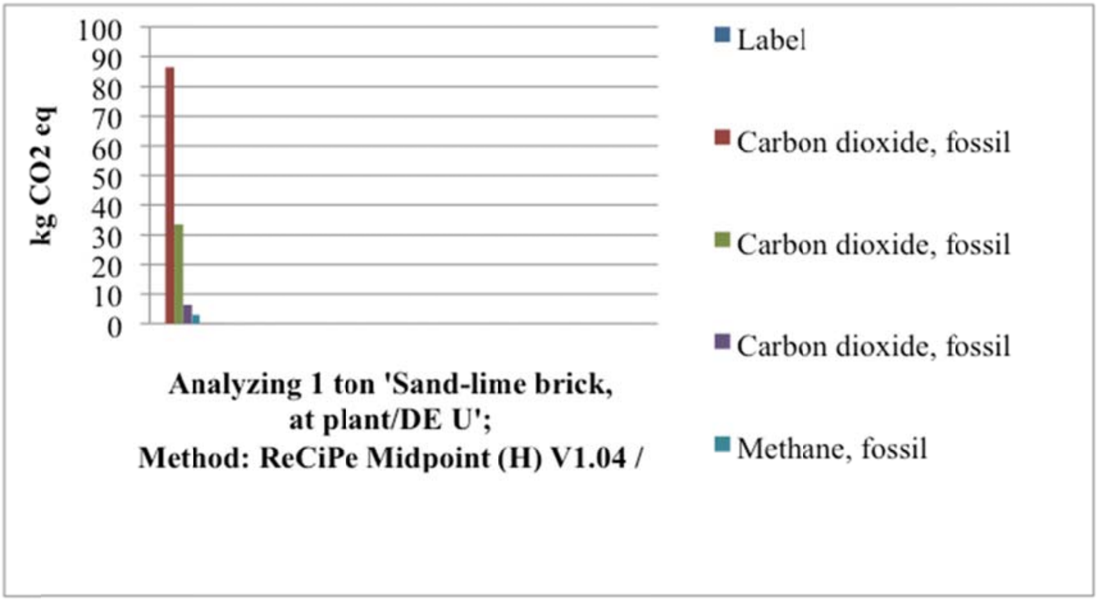
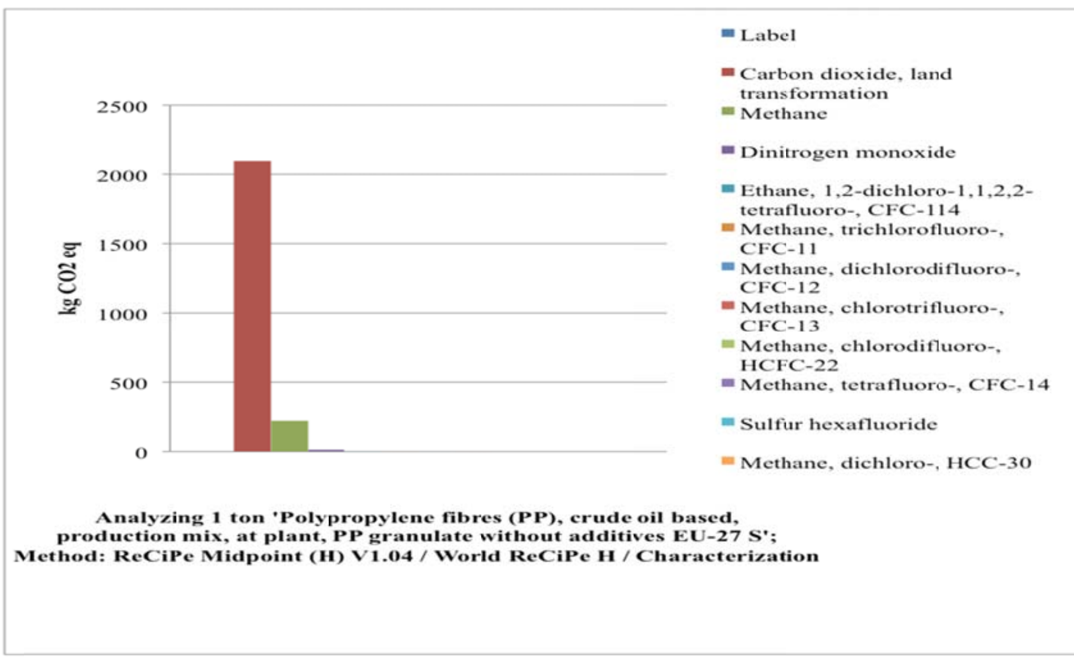
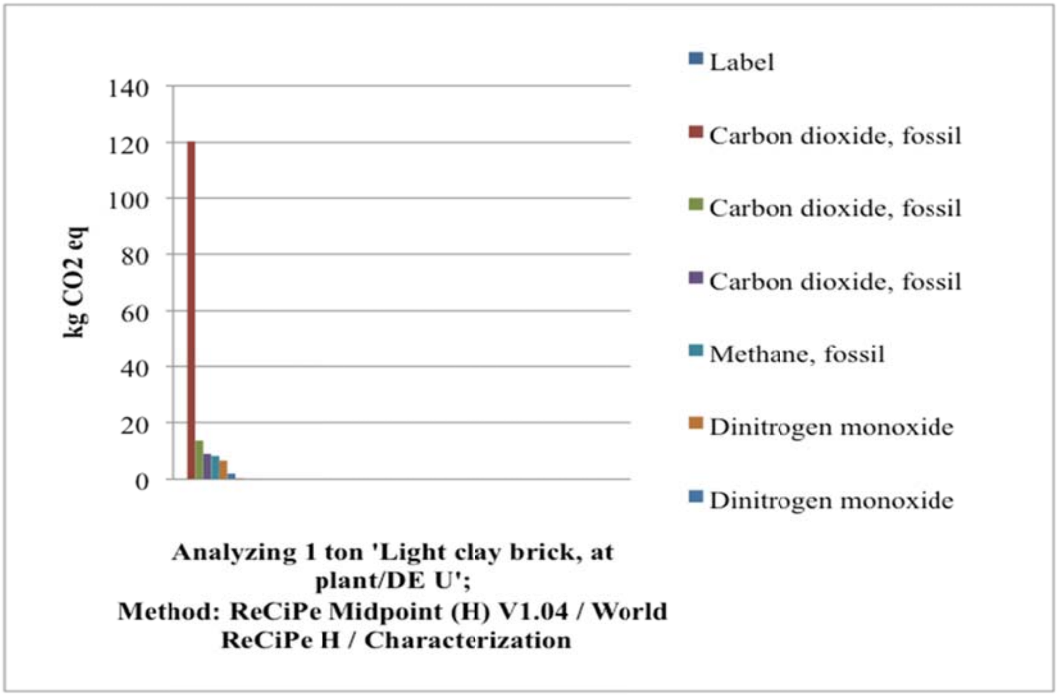

100
90
80
70
60
50
40
30
20
10
0
kg CO2 eq
Label
Carbon dioxide, fossil
Carbon dioxide, fossil
Carbon dioxide, fossil
Methane, fossil
Analyzing 1 ton 'Sand-lime brick, at plant/DE U';
Method: ReCiPe Midpoint (H) V1.04 /

2)


2500
2000
1500
1000
500
0
kg CO2 eq
Label
Carbon dioxide, land transformation
Methane
Dinitrogen monoxide
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114
Methane, trichlorofluoro-, CFC-11
Methane, dichlorodifluoro-, CFC-12
Methane, chlorotrifluoro-, CFC-13
Methane, chlorodifluoro-, HCFC-22
Methane, tetrafluoro-, CFC-14
Sulfur hexafluoride
Methane, dichloro-, HCC-30
Analyzing 1 ton 'Polypropylene fibres (PP), crude oil based, production mix, at plant, PP granulate without additives EU-27 S';
Method: ReCiPe Midpoint (H) V1.04 / World ReCiPe H / Characterization

12)



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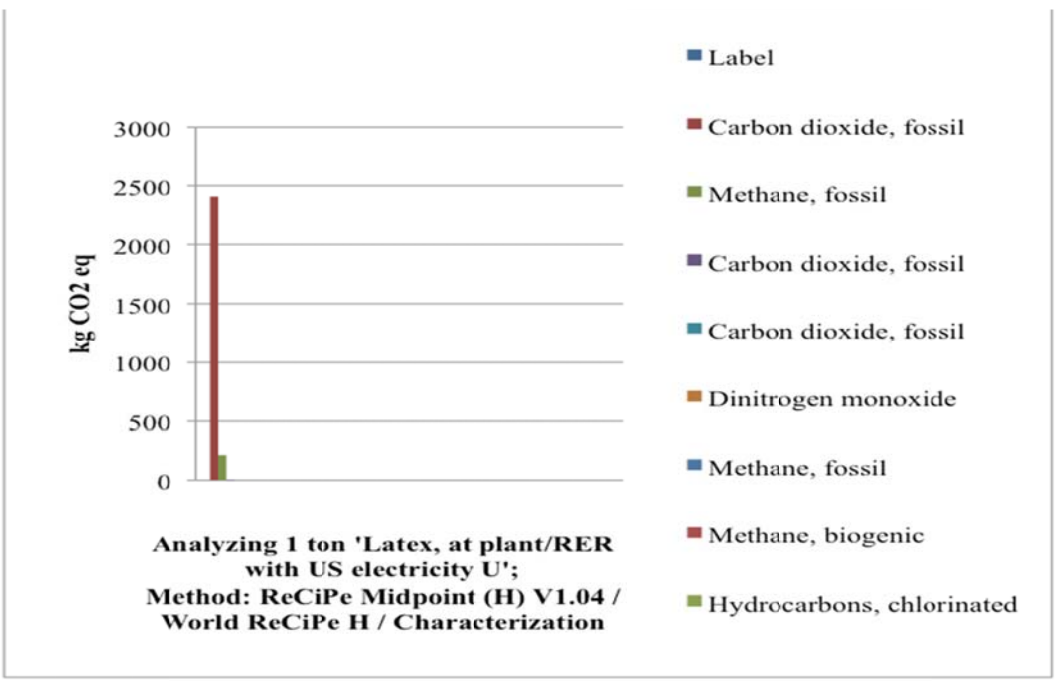
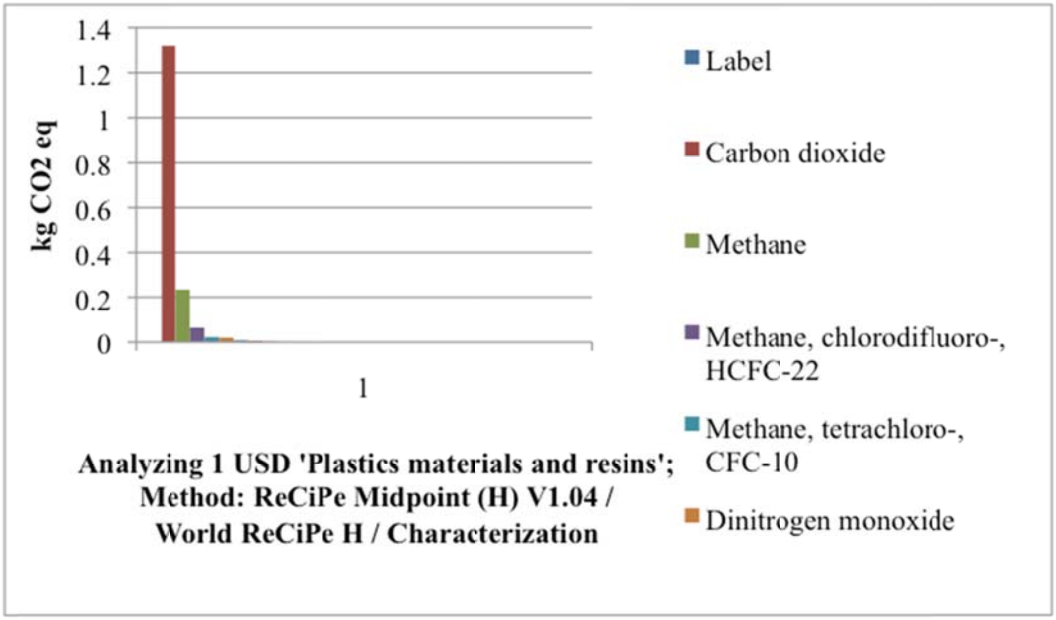


, 2012)



sins (Pre-

Table 5.1: Emission Factors Obtained Using SimaPro (Pre-Consultants, 2012)

Product	Unit	Emission Factor (MT eq. CO_2)
Portland Cement	Ton	0.928
Blast Furnace Slag Cement	Ton	0.522
Concrete Block	Ton	0.121
Sand Lime Brick	Ton	0.13
Polypropylene Fibers	Ton	2.33
Light Clay Bricks	Ton	0.161
Latex	Ton	2.63
Plastics and Resins	Ton	0.00168
Portland Slag Cement	Ton	0.776

5.4 GHG Emissions Calculation Guidelines

In order to develop LCA guidelines for bridges, the framework described above can directly be used. The following steps can be followed for conducting LCA of bridges and determining the carbon footprint:

a) Use bill of materials to determine all the materials to be used on the project. Also determine all the construction equipment to be used, their number and estimated hours of usage.

b) Use the emissions estimating tool to calculate the emission from the products. This tool is based on Project Estimator Tool PE-2, which can be found at http://www.construction.mtu.edu:8000/cass_reports/webpage/estimator.html (Mukherjee and Cass, 2012) to determine life cycle GHG emissions (Cradle to Gate) associated with the materials and equipment to create benchmark emissions of the project.

The Excel file has two sheets. The material emission estimator calculates the emission from materials and equipment emission estimator calculates the emissions from the equipment. The material and equipment categories were organized according to MDOT pay-item specifications. A separate category "Other" is also included in the material emissions estimator, which lists the recommended sustainable products from the framework. Use the material estimator shown in Table 5.2 for calculating GHG emissions from various materials. Input the quantity of materials corresponding to the material selected to determine emissions.

Use the equipment estimator from the project estimator tool developed by Mukherjee and Cass (2011) for calculating GHG emissions from various equipments. It is required to enter the equipment amount and the estimated hours of equipment use corresponding to the equipment selected to calculate GHG emissions. The sum of all these emissions will be the benchmark emissions for the project. At the end of the project, use the emission estimator tool to generate an emissions report using the actual data collected. MDOT should encourage contractors (through direct economic or equivalent incentive) to reduce the actual project emissions when compared to the benchmark for the project (Mukherjee and Cass, 2012). Investigate strategies to identify alternative products and processes to reduce GHG emissions of products that have higher GHG emissions. Determine all the recommended solution and alternative products that can be used on the project. Calculate the GHG emissions of all the final products that will be used and know the carbon footprint of the sustainable bridge project. Table 5.3 is a material estimator which calculates the cradle to gate emissions from materials. The sum of emissions in the last row is the emission due to unit quantity of all the materials.

Table 5.2: Material Estimator

Cradle to Gate Emissions					
Material	**Unit**	**Quantity**	**Emission Factor**	**Emissions (MT CO_2 Eq.)**	**Remarks/Details**
Section 901 (Cement and Lime)					
Portland Cement	Ton	1	0.928	0.928	(Pre-Consultants, 2012)
Fly Ash	Ton	1	0.0177	0.0177	(Mukherjee and Cass, 2011)
Blast Furnace Slag Cement	Ton	1	0.522	0.522	(Pre-Consultants, 2012)
Section 902 (Aggregates)					
Natural Aggregates	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 21A	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 21AA	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 21AA Crushed Concrete	Ton	1	0.0021	0.0021	(Mukherjee and Cass, 2011)
Aggregates 22A	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 22A Crushed Concrete	Ton	1	0.0021	0.0021	(Mukherjee and Cass, 2011)
Aggregates 22A (For Temp Use Only)	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)

Table 5.2 (cont'd)

Material	Unit	Quantity	Emission Factor	Emissions (MT CO_2 Eq.)	Remarks/Details
Aggregates 23A	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 23A Carol Pit 11-077	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 23A (For Temp Use Only)	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 23A (Reed Pit A 11-085)	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 25A	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 29A	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 2FA	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 34R	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 3FA	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 4G	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregates 4G Modified Crushed Concrete	Ton	1	0.0021	0.0021	(Mukherjee and Cass, 2011)
Aggregates 4G Modified Limestone	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregate 6A	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Aggregate Coarse CS-2	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)

Table 5.2 (cont'd)

Material	Unit	Quantity	Emission Factor	Emissions (MT CO_2 Eq.)	Remarks/Details
Fine Aggregate 2fa	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Fine Aggregate 2FA	Ton	1	0.0061	0.0061	(Mukherjee and Cass, 2011)
Flowable Fill	Cyd	1	0.0001	0.0001	(Mukherjee and Cass, 2011)
Granular Material	Cyd	1	0.0001	0.0001	(Mukherjee and Cass, 2011)
Granular Material CL II	Cyd	1	0.0001	0.0001	(Mukherjee and Cass, 2011)
Granular Material CL III	Cyd	1	0.0001	0.0001	(Mukherjee and Cass, 2011)
Granular Material CL IIIA	Cyd	1	0.0001	0.0001	(Mukherjee and Cass, 2011)
Granular Material CL II Modified	Cyd	1	0.0001	0.0001	(Mukherjee and Cass, 2011)
Granular Material CL II Newark	Cyd	1	0.0001	0.0001	(Mukherjee and Cass, 2011)
Granular Material CL Tri City	Cyd	1	0.0001	0.0001	(Mukherjee and Cass, 2011)
Granular Material CL (Ton)	Ton	1	0.00006	0.00006	(Mukherjee and Cass, 2011)
Pulverized HMA	Ton	1	0.0049	0.0049	(Mukherjee and Cass, 2011)
Sound Class II (D) for Underdrain	Cyd	1	0.0001	0.0001	(Mukherjee and Cass, 2011)
Sound earth	Cyd	1	0.0001	0.0001	(Mukherjee and Cass, 2011)

Table 5.2 (cont'd)

Material	Unit	Quantity	Emission Factor	Emissions (MT CO_2 Eq.)	Remarks/Details
Section 903 (Admixtures and Curing Materials for Concrete)					
White Membrane Curing Compound for Bridge Decks	Gal	1	0.01255	0.01255	(Mukherjee and Cass, 2011)
Non-Chloride Accelerator	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Latex Admixtures	Ton	1	2.63	2.63	(Pre-Consultants, 2012)
Polypropylene Fibers	Ton	1	2.33	2.33	(Pre-Consultants, 2012)
Section 904 (Asphaltic Materials)					
Asphalt Binder PG 58-28	Ton	1	0.1569	0.1569	(Mukherjee and Cass, 2011)
Emulsified Asphalt	Gal	1	0.0071	0.0071	(Mukherjee and Cass, 2011)
Emulsified Asphalt CSS-1hM	Gal	1	0.0071	0.0071	(Mukherjee and Cass, 2011)
Ashpalt emulsion Chip Seal	Gal	1	0.0071	0.0071	(Mukherjee and Cass, 2011)
Asphalt Emulsion CSS-1hM	Gal	1	0.0071	0.0071	(Mukherjee and Cass, 2011)
Asphalt Emulsion CSS-1mM	Gal	1	0.0071	0.0071	(Mukherjee and Cass, 2011)
Asphalt Emulsion HFRS-2M	Gal	1	0.0071	0.0071	(Mukherjee and Cass, 2011)
Asphalt Emulsion RC-250	Gal	1	0.0071	0.0071	(Mukherjee and Cass, 2011)
Section 905 (Steel Reinforcement)					
Dowel Bar	Ea	1	0.001627	0.001627	(Mukherjee and Cass, 2011)

Table 5.2 (cont'd)

Material	Unit	Quantity	Emission Factor	Emissions (MT CO_2 Eq.)	Remarks/Details
Dowel Bar Epoxy Coated	Ea	1	0.001627	0.001627	(Mukherjee and Cass, 2011)
Steel Reinforcement	Lbs	1	0.0003	0.0003	(Mukherjee and Cass, 2011)
Steel Reinforcement Epoxy Coated	Lbs	1	0.0003	0.0003	(Mukherjee and Cass, 2011)
Lane Ties Epoxy Coated	Ea	1	0.01512	0.01512	(Mukherjee and Cass, 2011)
Load Transfer Device	Ft	1	0.006	0.006	(Mukherjee and Cass, 2011)
Steel Reinforcement Cable Barrier-C Slagter	Lbs	1	0.003	0.003	(Mukherjee and Cass, 2011)
Section 906 (Structural Steel)					
Steel Sections	Ton	1	0.0016	0.0016	(Mukherjee and Cass, 2011)
Hot Rolled-Coil Steel	Ton	1	0.002	0.002	(Mukherjee and Cass, 2011)
Hot-Dip Galvanized Steel	Ton	1	0.0025	0.0025	(Mukherjee and Cass, 2011)
Steel Sheet Piling	Sft	1	0.0589	0.0589	(Mukherjee and Cass, 2011)
Beam Plate Sealant Sherwin Wili 1550A	Tube	1	0	0	(Mukherjee and Cass, 2011)
Guardrail Anchorage Bridge	Ea	1	0	0	(Mukherjee and Cass, 2011)
Structural Steel	Cft	1	NanoMT	1	(Mukherjee and Cass, 2011)

Table 5.2 (cont'd)

Material	Unit	Quantity	Emission Factor	Emissions (MT CO_2 Eq.)	Remarks/Details
Structural Steel Pin and Hangers	Cft	1	0	0	(Mukherjee and Cass, 2011)
Section 907 (Fencing Materials)					
Barbed Wire	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Fence Chain Link (ft)	Ft	1	0.0092	0.0092	(Mukherjee and Cass, 2011)
Fence Gate Chain Link	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Fence Post Chain Link Corner	Ea	1	0.0722	0.0722	(Mukherjee and Cass, 2011)
Fence Post Chain Link Line	Ea	1	0.0722	0.0722	(Mukherjee and Cass, 2011)
Fence Post Steel	Ea	1	0.0722	0.0722	(Mukherjee and Cass, 2011)
Fence Post Steel Woven Wire	Ea	1	0.0722	0.0722	(Mukherjee and Cass, 2011)
Fence Post Wood	Ea	1	0.0066	0.0066	(Mukherjee and Cass, 2011)
Protective Fence	Ft	1	0	0	(Mukherjee and Cass, 2011)
Fence Woven Wire	Ft	1	0.0092	0.0092	(Mukherjee and Cass, 2011)

Table 5.2 (cont'd)

Material	Unit	Quantity	Emission Factor	Emissions (MT CO_2 Eq.)	Remarks/Details
Section 908 (Miscellaneous Metal Products)					
Anchor Bolts	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Bushings	Ea	1	0	0	(Mukherjee and Cass, 2011)
Steel Beam Guardrail	Ft	1	0.0656	0.0656	(Mukherjee and Cass, 2011)
Gaurdrail Approach Terminal 1 B	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Gaurdrail Approach Terminal 1 T	Ea	1	0	0	(Mukherjee and Cass, 2011)
Gaurdrail Approach Terminal 2 B	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Gaurdrail Approach Terminal 2 T	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Gaurdrail Reflectorized Washers	Ea	1	0	0	(Mukherjee and Cass, 2011)
Sleeve Steel	Ea	1	0	0	(Mukherjee and Cass, 2011)
Section 909 (Drainage Products)					
End Section Concrete	Ea	1	0.802	0.802	(Mukherjee and Cass, 2011)
End Section Metal	Ea	1	1.1995	1.1995	(Mukherjee and Cass, 2011)
End Section Grate	Lbs	1	0.0003	0.0003	(Mukherjee and Cass, 2011)
Pipe Cl A	Ft	1	0.1464	0.1464	(Mukherjee and Cass, 2011)

Table 5.2 (cont'd)

Material	Unit	Quantity	Emission Factor	Emissions (MT CO_2 Eq.)	Remarks/Details
Pipe Cl E	Ft	1	0.1464	0.1464	(Mukherjee and Cass, 2011)
Pipe Concrete	Ft	1	0.0663	0.0663	(Mukherjee and Cass, 2011)
Pipe Steel	Ft	1	0.1464	0.1464	(Mukherjee and Cass, 2011)
Pipe Plastic	Ft	1	0.0259	0.0259	(Mukherjee and Cass, 2011)
Pipe RCP	Ft	1	0.0663	0.0663	(Mukherjee and Cass, 2011)
Pipe Perforated Underdrain	Ft	1	0.0004	0.0004	(Mukherjee and Cass, 2011)
Pipe Non-Perforated Underdrain	Ft	1	0.0004	0.0004	(Mukherjee and Cass, 2011)
Pipe Corrugated	Ft	1	0.0259	0.0259	(Mukherjee and Cass, 2011)
Expansion Joint Device	Ea	1	0	0	(Mukherjee and Cass, 2011)
Section 910 (Geo-synthetics)					
Biaxial Geogrid	Syd	1	0.0013	0.0013	(Mukherjee and Cass, 2011)
Geotextile Blanket	Syd	1	0.0013	0.0013	(Mukherjee and Cass, 2011)
Geotextile Liner	Syd	1	0.0013	0.0013	(Mukherjee and Cass, 2011)
Geotextile Separator	Syd	1	0.0013	0.0013	(Mukherjee and Cass, 2011)
Section 912 (Timber and Lumber)					

Table 5.2 (cont'd)

Material	Unit	Quantity	Emission Factor	Emissions (MT CO_2 Eq.)	Remarks/Details
Guardrail Post Wood	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Wood Post	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Post Wood Guard	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Section 913 (Masonry Units)					
Clay Brick	Ton	1	0.161	0.161	(Pre-Consultants, 2012)
Concrete Brick	Ea	1	0.0014	0.0014	(Mukherjee and Cass, 2011)
Concrete Block	Ton	1	0.121	0.121	(Pre-Consultants, 2012)
Sand Lime Brick	Ton	1	0.13	0.13	(Pre-Consultants, 2012)
Section 914 (Joint and Waterproofing Materials)					
Fiber Joint Filler	Sft	1	0.0015	0.0015	(Mukherjee and Cass, 2011)
Hot Poured Joint Sealant	Lbs	1	0.0006	0.0006	(Mukherjee and Cass, 2011)
Foam Backer Road	Ft	1	0.0001	0.0001	(Mukherjee and Cass, 2011)
Epoxy Resin Adhesive		1		1	(Mukherjee and Cass, 2011)
Waterproofing Membrane Preformed	Syd	1	0.0094	0.0094	(Mukherjee and Cass, 2011)
Section 916 (Erosion and Sedimentation Control Materials)					
Cobblestone	Syd	1	0.0172	0.0172	(Mukherjee and Cass, 2011)
Fabric	Cft	1	NanoMT	1	(Mukherjee and Cass, 2011)

Table 5.2 (cont'd)

Material	Unit	Quantity	Emission Factor	Emissions (MT CO_2 Eq.)	Remarks/Details
Plain Rip Rap	Syd	1	0.0172	0.0172	(Mukherjee and Cass, 2011)
Silt Fence	Ft	1	0.0008	0.0008	(Mukherjee and Cass, 2011)
Section 917 (Turf and Landscaping Materials)					
Fertilizer Chemical Nutrient	Lbs	1	0.0008	0.0008	(Mukherjee and Cass, 2011)
Mulch	Ton	1	0	0	(Mukherjee and Cass, 2011)
Mulch Blanket	Syd	1	0.0008	0.0008	(Mukherjee and Cass, 2011)
Mulch Tackifier	Gal	1	0	0	(Mukherjee and Cass, 2011)
Seeding	Lbs	1	0.001	0.001	(Mukherjee and Cass, 2011)
Seeding Mixture	Lbs	1	0.001	0.001	(Mukherjee and Cass, 2011)
Sod	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Tack	Gal	1	0	0	(Mukherjee and Cass, 2011)
Tackifier	Gal	1	0	0	(Mukherjee and Cass, 2011)
Topsoil 4in.	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Turf Reinforcement Mat	Syd	1	0.0008	0.0008	(Mukherjee and Cass, 2011)
Section 918 (Electrical and Lighting Materials)					

Table 5.2 (cont'd)

Material	Unit	Quantity	Emission Factor	Emissions (MT CO_2 Eq.)	Remarks/Details
Conduit	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
High Intensity Light	Ea	1	0	0	(Mukherjee and Cass, 2011)
Section 919 (Permanent Traffic Sign and Support Materials)					
Reflective Sheeting Material	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Dileneator Reflector	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Temporary sign	Sft	1	0	0	(Mukherjee and Cass, 2011)
Sign Cover	Ea	1	0	0	(Mukherjee and Cass, 2011)
Section 920 (Permanent Pavement Marking Materials)					
Pavement Marking Glass Beads	Lbs	1	0.0004	0.0004	(Mukherjee and Cass, 2011)
Pavement Marking Poly Blend-Glass Beads	Lbs	1	0.0004	0.0004	(Mukherjee and Cass, 2011)
Pavement Marking Polyurea	Gal	1	0.059	0.059	(Mukherjee and Cass, 2011)
Pavement Marking Polyurea White	Lbs	1	0.0071	0.0071	(Mukherjee and Cass, 2011)
Pavement Marking Polyurea Yellow	Lbs	1	0.0071	0.0071	(Mukherjee and Cass, 2011)
Reflective Marker	Cft	1	NanoMT	NanoMT	(Mukherjee and Cass, 2011)
Thermoplastic	Lbs	1	0.0071	0.0071	(Mukherjee and Cass, 2011)

Table 5.2 (cont'd)

Material	Unit	Quantity	Emission Factor	Emissions (MT CO_2 Eq.)	Remarks/Details
Concrete Barrier Temporary	Ea	1	0	0	(Mukherjee and Cass, 2011)
Drum Plastic	Ea	1	0	0	(Mukherjee and Cass, 2011)
Other Products					
Stainless Steel	Ton	1	0.00151	0.00151	(ISSF, 2010)
Plastic Materials and Resins	USD	1	0.00168	0.00168	(Pre-Consultants, 2012)
Portland Slag Cement	Ton	1	0.776	0.776	(Pre-Consultants, 2012)
Precast Concrete (Mix 1)	Ton	1	0.49	0.49	(Marceau et. al., 2007)
Precast Concrete (Mix 2)	Ton	1	0.43	0.43	(Marceau et. al., 2007)
Sum of Emissions					

5.5 Case Study

5.5.1 Overview

The GHG emission tool developed in the study can be used to compare different alternatives and choose the best one with the lowest GHG emissions. MDOT provided the research team with bidding documents and data on different bridges in Michigan, to calculate GHG emissions from the products and find out the best alternative for the bridge superstructure. These bridges either require repair/rehabilitation or replacement. GHG emissions were calculated from alternatives on a concrete bridge to evaluate the sustainability of a superstructure. This case study compares two bridge decks: one using a conventional concrete bridge deck and the other using a Fiber Reinforced Polymer (FRP) bridge deck.

5.5.2 Structure Description

The structure considered is located on I-96 EB over Grange Road in Clinton County, 3.5 miles southeast 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 5.3 using National Bridge Inventory (NBI) website (NBI, 2012).

Table 5.3: Case Study-Bridge Structure Details

Description	Details
NBI Structure Number	0000000000001789
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 %

5.5.3 Design Alternatives

This case study considered two alternatives: Table 5.4 below shows a comparison between conventional concrete mix and alternative blast furnace slag cement concrete mix.

Table 5.4: Case Study-Design Alternatives

Alternatives	Details
Base Case: Conventional Concrete Mix Bridge Deck	Concrete Bridge Deck
	Concrete Mix Ratio 1:2:4
Alternative Case: Fiber Reinforced Polymer (FRP) Bridge Deck	FRP Bridge Deck
	Composition: Glass Fibers Epoxy Resins

5.5.4 Methodology

Two stages are considered in the study:

(a) Demolition of the existing bridge superstructure

(b) Construction

Within each stage, three sources of carbon emissions are considered:

(a) Embodied carbon of any new materials/products

(b) Transportation of waste to landfills and transportation of products to site

(c) Traffic diversions

5.5.5 GHG Emission Calculation

1. Cradle to Gate GHG Emission due to Materials/Products

Table 5.5: Case Study: GHG Emission from Materials

(Conventional Concrete Bridge Deck)				
Material	**Unit**	**Quantity**	**Emission Factor (MT CO_2 Eq./Unit)**	**Emissions (MT CO_2 Eq.)**
Portland Cement	Ton		.928	
Aggregates	Ton		.0061	
Reinforcement	Lbs.		.0003	
(FRP Bridge Deck)				
Epoxy Resin				
GRP				
Asphalt				

2. Emissions due to transportation of waste to landfills and transportation of new products

a) Emissions due to transportation of waste to landfills

Table 5.6: Case Study: GHG Emissions from Transportation

Material	Unit	Type of Transport	Transportation Distance	Emissions

b) Emissions due to transportation of products to site

Table 5.7: Case Study: GHG Emissions from Transportation

Material	Unit	Type of Transport	Transportation Distance	Emissions
Concrete Bridge Deck				
Cement				
Aggregates				
Reinforcement steel				
FRP Bridge Deck				
FRP Deck Panel				

3. Emissions due to traffic diversions

Table 5.8: Case Study: GHG Emissions from Diversion

Type of Construction	Period of Disruption	Length of Diversion	Average Daily Traffic Volume	Emissions
Convention Concrete Bridge Deck			19469	
FRP Bridge Deck Construction			19469	

5.5.6 Results

The emissions due to material are calculated based on the emission factor method as shown in Table 5.5. The emissions can be obtained by multiplying the quantity of materials by the emission factor. The emissions due to transportation can be calculated by knowing the transportation distance from landfill to site, the type of transport, and the total distance travelled. It is required to determine the emissions due to vehicle traveling unit distance. The emissions due to transportation can then be calculated by multiplying the total distance traveled by unit value of carbon emissions. Emissions due to diversion of traffic can be calculated as Length of diversion X Avg. daily traffic volume X Unit value of carbon emissions X Period of disruption from vehicles. EPA's MOVES (Motor Vehicle Emission Simulator) (EPA, 2012) can be used to estimate unit value of carbon emissions from vehicles.

5.6 LCA Matrix for the Framework

The LCA matrix shown Figure 5.13 to 5.17 shows which criteria in the framework is impacted by LCA and which tools or metrics can be used to assess the environmental impacts due to that criteria. The criteria of the framework can be evaluated using the LCA matrix to determine the impact of each criteria. The factor that each value represents is shown in Table 5.9.

Table 5.9: LCA Matrix Legend

	5	10	15
Impacted by LCA	Not impacted by LCA	Impacted by LCA	NA
Metrics/Tools	NA	SimaPro	Excel based tool
Sustainability Criteria	Economic	Social	Environmental

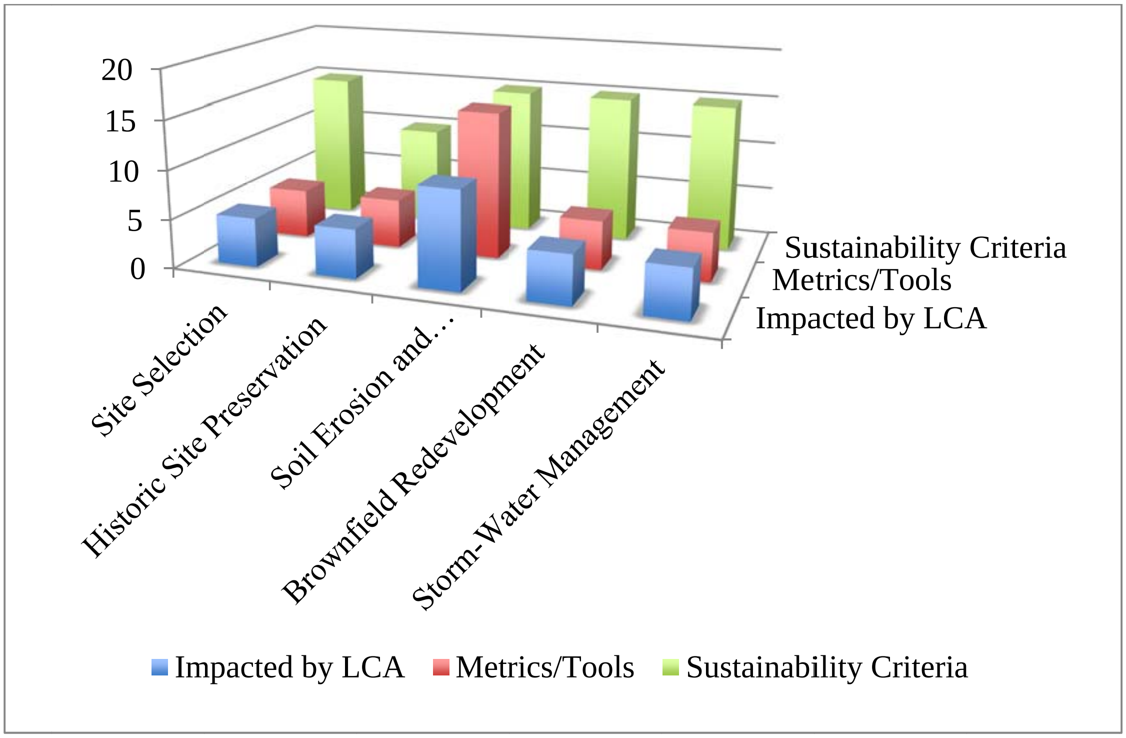


Figure 5.13: Design-Sites Category LCA Matrix

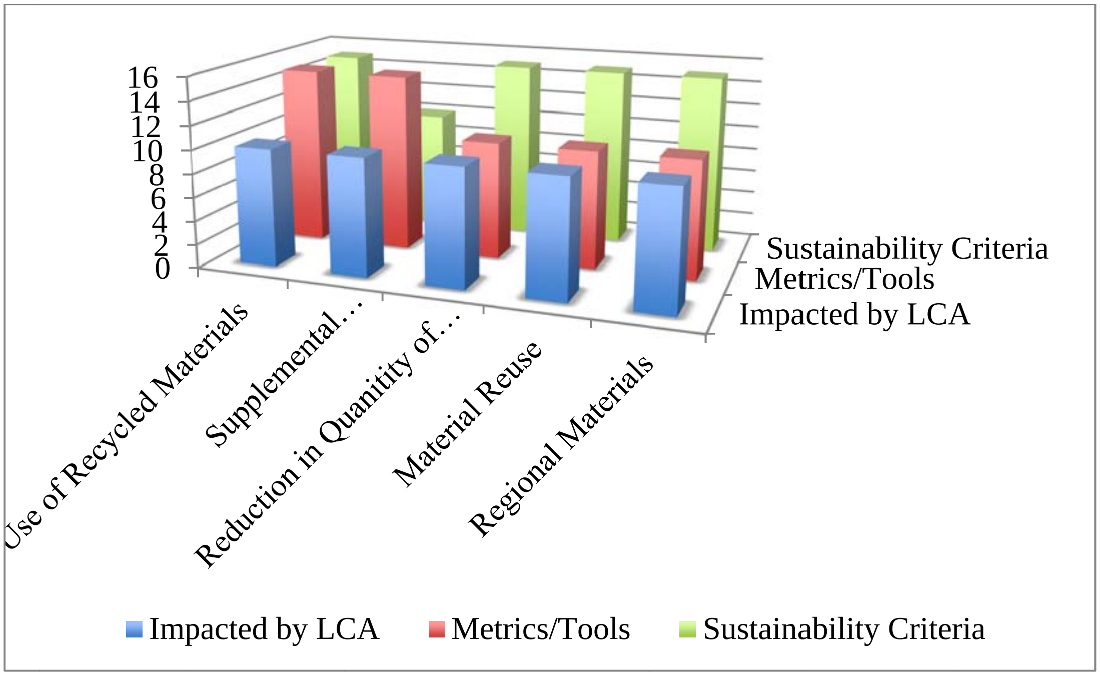


Figure 5.14: Design-Materials Category LCA Matrix

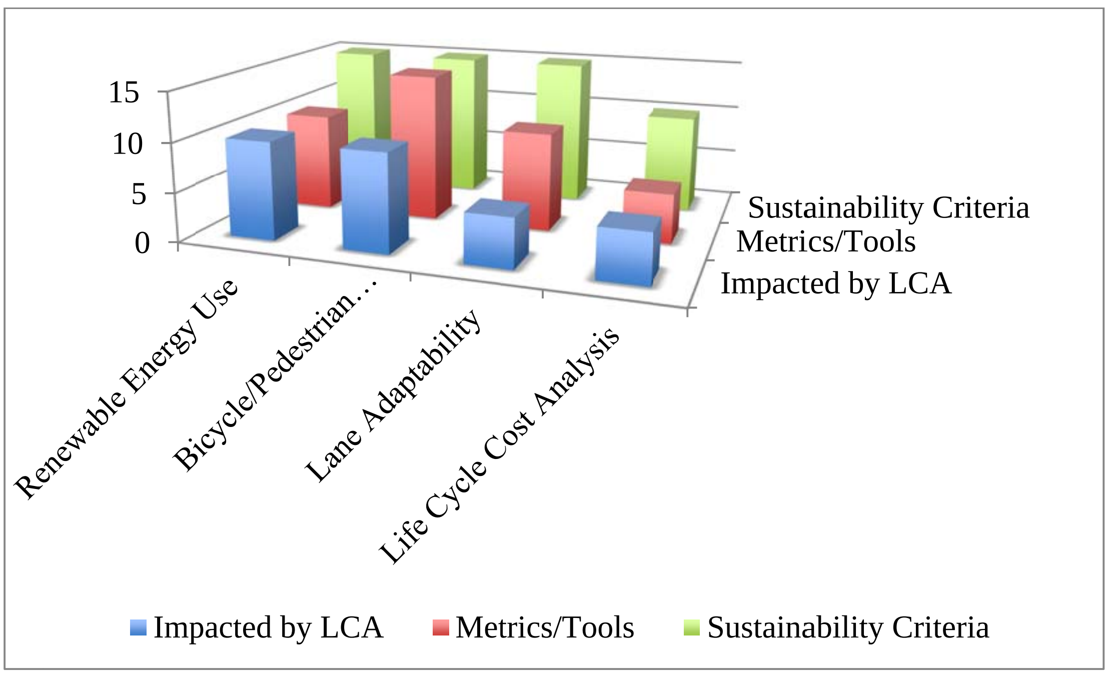


Figure 5.15: Design-Other Category LCA Matrix

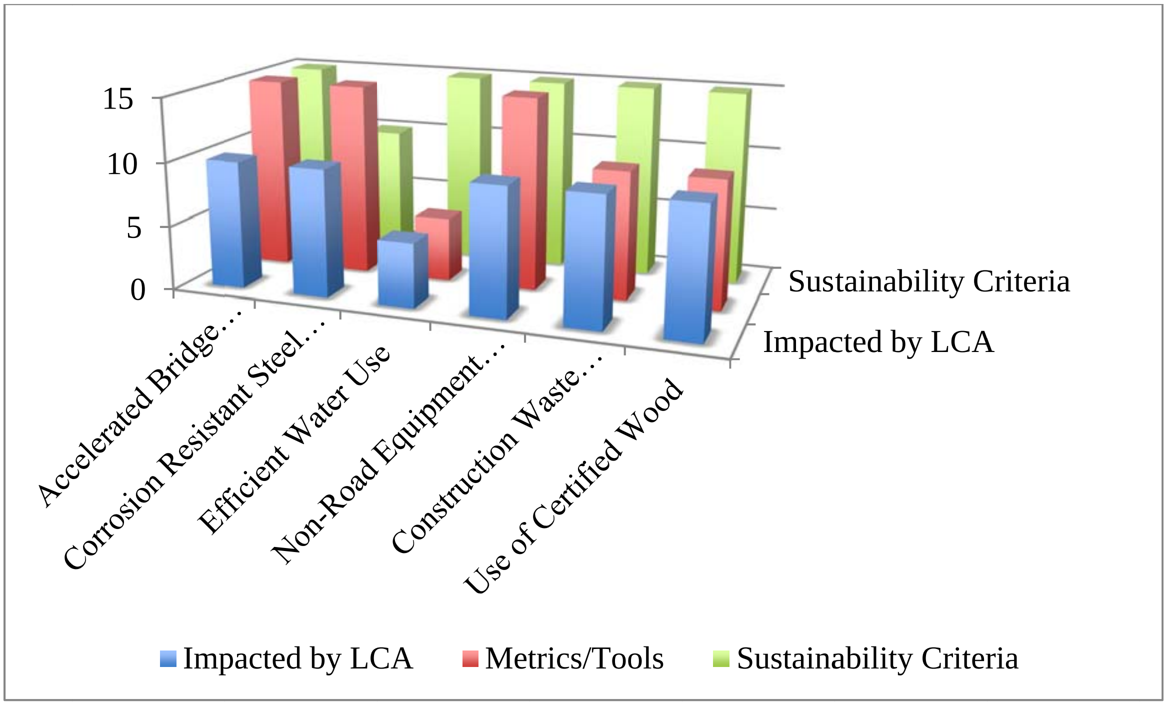


Figure 5.16: Construction Category LCA Matrix

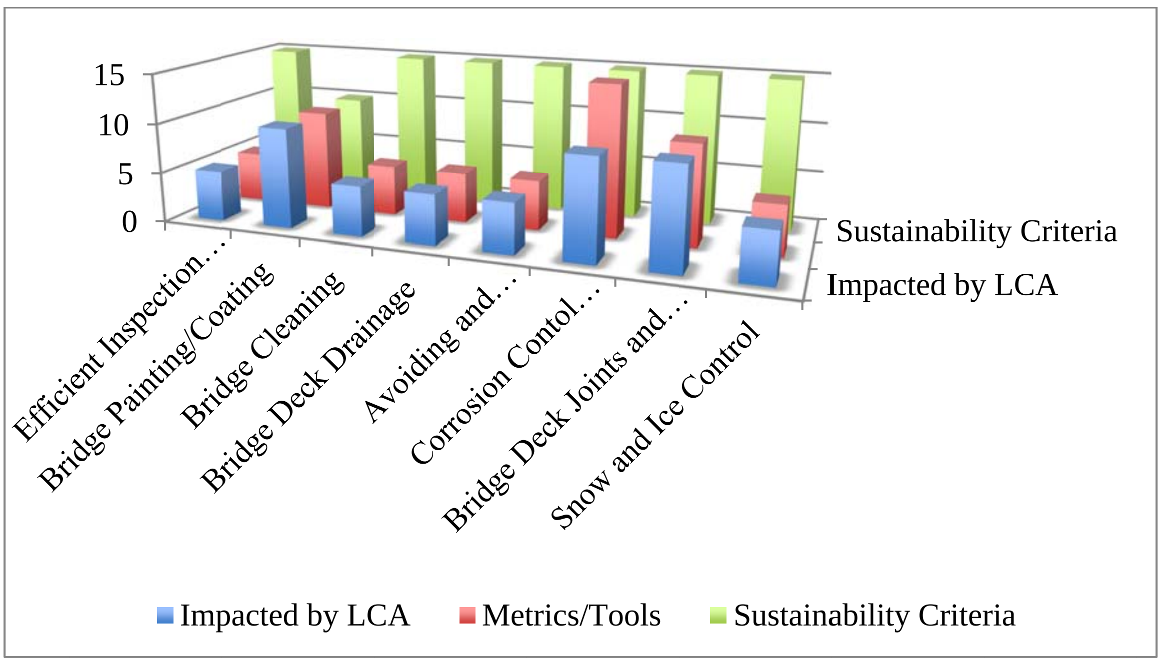


Figure 5.17: Maintenance Category LCA Matrix

CHAPTER 6
LIFE CYCLE COST ANALYSIS GUIDELINES FOR BRIDGES

6.1 Overview

Life-Cycle Cost Analysis (LCCA) is "an engineering economic analysis tool useful in comparing the relative merit of competing project implementation alternatives" (FHWA, 2002). It helps transportation agencies consider different alternatives costs incurred during the service life of a project and opt for the best performance option with the lowest cost. For example, LCCA will help decipher 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.

Michigan Department of Transportation (MDOT) has been dynamically involved in pursuing sustainable techniques in most of the projects and has an impressive record of designing and constructing sustainable bridges. In Michigan, the state enacted PA 79, a bill that mandates 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. This report summarizes a thorough research that establishes guidelines for conducting LCCA on bridges in Michigan.

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

6.2 LCCA Methodologies and Procedure

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

- Determine performance periods and activity timing.
- Establish alternative bridge design strategies for the analysis period.
- Estimate agency costs.
- Estimate user costs.
- Develop expenditure stream diagrams.
- Compute net present value.
- Analyze results.

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

6.2.1 Determine Performance Periods and Activity Timing

The initial bridge design and subsequent rehabilitation/replacement activities has a major impact on LCCA results. It directly affects the frequency of agency intervention on the project, which in turn affects the agency cost as well as user costs during periods of construction and maintenance activities.

The planning horizon or analysis period is a key variable. The time period should be selected on the basis of both the physical elements to be analyzed and the type of decision to be made. Generally the planning horizon should be at least as long as the best-estimate service life of the element (under normal maintenance) that is the primary focus of analysis; this element then has a very low expected residual value in the base case at the end of the analysis period. 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). NBI systems can provide the data and analysis techniques to evaluate bridge condition and performance to identify cost effective strategies for short and long-term capital projects.

Table 6.1: Rating for a Bridge Superstructure (NBI, 2010)

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. It may be necessary to close the bridge until corrective action is taken.
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

Table 6.2 provides 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 6.2: Bridge Preservation Activities (MDOT, 2010)

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 and 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

6.2.2 Establish Alternative Bridge Design Strategies For The Analysis Period

The second step in conducting the LCCA of bridges is to define the alternative design for the analysis period under consideration and evaluate the alternative against the base case. The alternatives must be developed in adequate detail to derive good cost estimates, which are required to run the life cycle cost calculations and to capture the incremental cost differences of the options. Any number of alternatives can be developed for a project. The goal should be to develop roughly two to three alternatives for a project.

Typically, each design alternative has 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 by the University of Michigan, titled "*Life-Cycle Cost Model for Evaluating the Sustainability of Bridges Decks*". In this report, 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 the bridge deck was assumed to be 30 years when constructed with CC and 60 years when ECC was used. The costs were estimated over a 60-year analysis period (Forsberg and Malmborg, 2004). The rehabilitation and replacement activities and their timings identified at the beginning of the analysis are listed below.

Table 6.3: Overview of construction activities (Source: 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

6.2.3 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 the following:

- 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 needed 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. Rehabilitation and maintenance costs depend not only on the types and quantities of materials and work items, but also on the traffic control plan (detours, lane closures, work hours, etc.) selected for each alternative. Different traffic control plans may have different risks of accident costs, including costs to the agency.

6.2.4 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.

A 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.

6.2.5 Develop Expenditure Stream 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.

Figure 6.1 shows a typical expenditure stream 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.

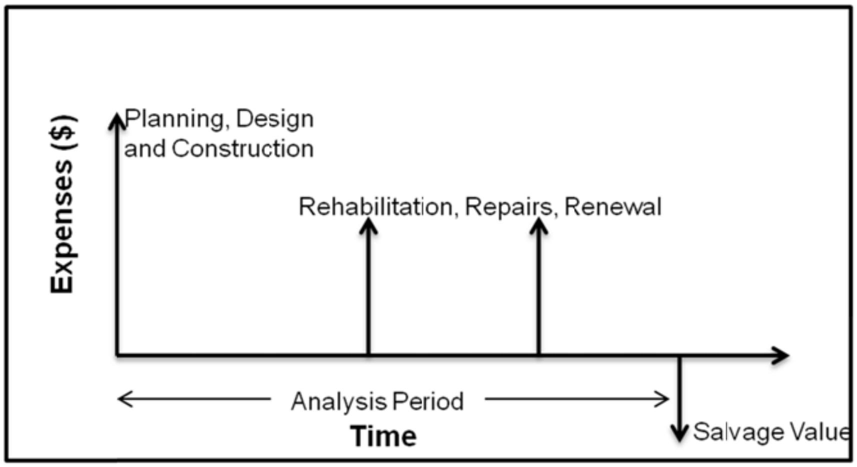


Figure 6.1: Expenditure Stream Diagram

6.2.6 Compute 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 Net Present Value.

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 is the rate used to discount future cash flows to the present value, a key variable of this process. The discount rates are used to determine discount factors. A discount factor is the present value of $1 received at a stated future date. To calculate a discount factor, the following formula may be used: Discount Factor = $[1 / (1+DR)^N)$], For example, the value of $1 two years from now at a discount rate of 4% yields a discount factor of 0.9246. All modules of the LCC used discount factors to determine present values. MDOT uses a 4% discount rate for its construction projects, as per the federal government's recommendation for long-term discount rates (MDOT, 2000).

6.2.7 Result Analysis

Once completed, all LCCA should, at minimum, be subjected to a sensitivity analysis. Sensitivity analysis is a technique used to determine the influence of major LCCA input assumptions, projections, and estimates on LCCA results. In a sensitivity analysis, major input values are varied (either within some percentage of the initial value or over a range of values) while all other input values remain constant and the amount of change in results is noted. The input variables may then be ranked according to their effect on results. Sensitivity analysis allows the analyst to subjectively get a feel for the impact of the variability of individual inputs on overall LCCA results. Often times a sensitivity analysis focuses on best case/worst case scenarios in an attempt to bracket outcomes. Most LCC sensitivity analysis, as a minimum, evaluates the influence of the discount rate used on LCCA results.

6.3 Case Study

6.3.1 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 the superstructure. This research compares the agency cost of two superstructures: one using conventional concrete mix and the other using high performance concrete mix. The agency cost includes initial construction cost, repair, maintenance, and disposal cost. These costs were estimated over an analysis period of 75 years.

6.3.2 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 a 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 using National Bridge Inventory (NBI) website.

Table 6.4: Bridge Details

Description	Details
NBI Structure Number	0000000000001789
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 %

6.3.3 Design Alternatives

In this case study, the research team, worked on a concrete superstructure, considering two alternatives: Table 6.5 shows a comparison between conventional concrete mix and high performance concrete mix.

Table 6.5: 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 every 25 years. Therefore, in its lifespan of 75 years, a bridge using conventional concrete requires two repairs. The work details like quantities and unit prices are extracted from bidding documents provided by MDOT. Table 6.6 shows the breakdown of agency costs. It includes initial construction cost, repair, maintenance, and disposal cost.

Description	Unit	Quantity	Unit Cost	Total 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	
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	

Table 6.7: Operation, Repair and Maintenance Cost of Conventional Concrete

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

Table 6.8: Bridge Disposal Cost

Disposal Cost					
Disposal of Bridge	Sft	5407.2	50	270360	**270360**

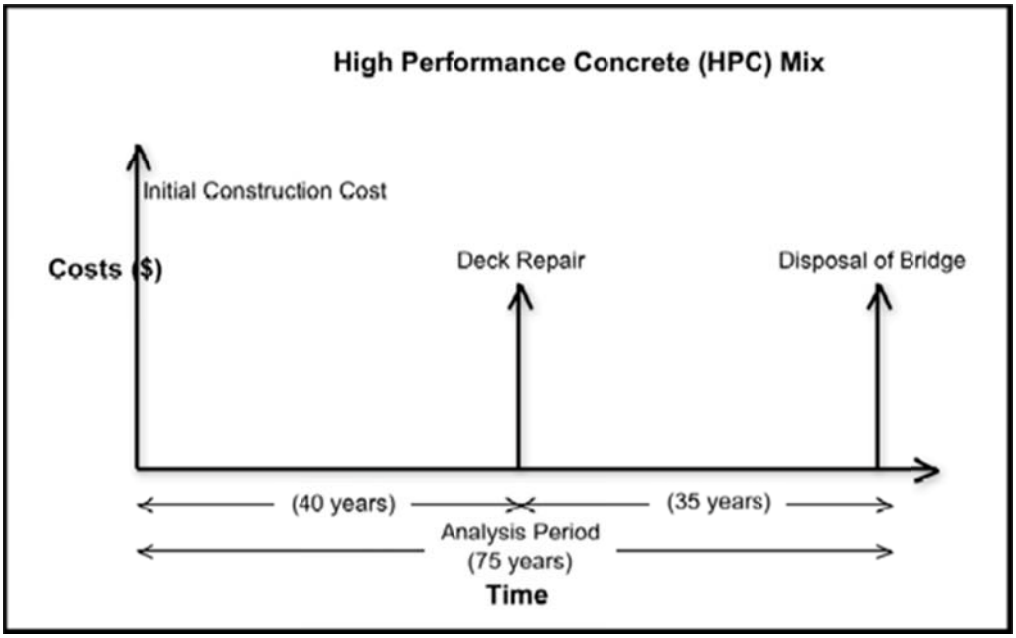
A Life Cycle Cost Analysis (LCCA) is undertaken to evaluate the total performance of construction, repair, maintenance, and disposal activities for conventional concrete mix. The use of LCCA enabled the research team to assess the total life cycle cost of a bridge deck. In Table 6.7, Operation, Repair and Maintenance Cost of Conventional Concrete is given. Table 6.8 depict Bridge Disposal Cost, and Table 6.9 explains the total life cycle cost associated with Conventional Concrete Mix when different repair and maintenance activities are incurred at different points in time.

Table 6.9: Total Life Cycle Cost of Conventional Concrete

Event	Description	Year	Cost	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 CO_2 emissions. HPC requires only one time repair after 40 years. The Figure 6.2 explains the events associated with HPC during its entire life.



During a life cycle of 75 years, it is assumed that a conventional concrete mix deck will be replaced with a similar type of deck. 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. Table 6.10 gives details about the agency cost associated with 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	
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	

Table 6.11: Operation, Repair and Maintenance Cost of HPC Mix

Operation Repair and Maintenance					
Thin Epoxy Overlays	Syd	600.8	60	36048	**36048**

Table 6.12: Disposal Cost of Bridge

Bridge Disposal 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, repair, maintenance, and disposal to the owner, users, and third parties.

Table 6.13: Life Cycle Cost of HPC Mix

Event	Description	Year	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 clear from the chart that the initial construction cost of HPC Mix ($1,680,602.09) is more than the Conventional Concrete Mix ($1,662,013.97). The difference between their initial construction cost is $18,500.12.

In Table 6.11, Operation, Repair and Maintenance Cost of HPC Mix is given. Table 6-12 show the Disposal Cost of Bridge and Table 6.13 depicts Life Cycle Cost of HPC Mix while Figure 6.3 show comparison of individual costs, in Figure 6.4 Total Life Cycle Cost is given.

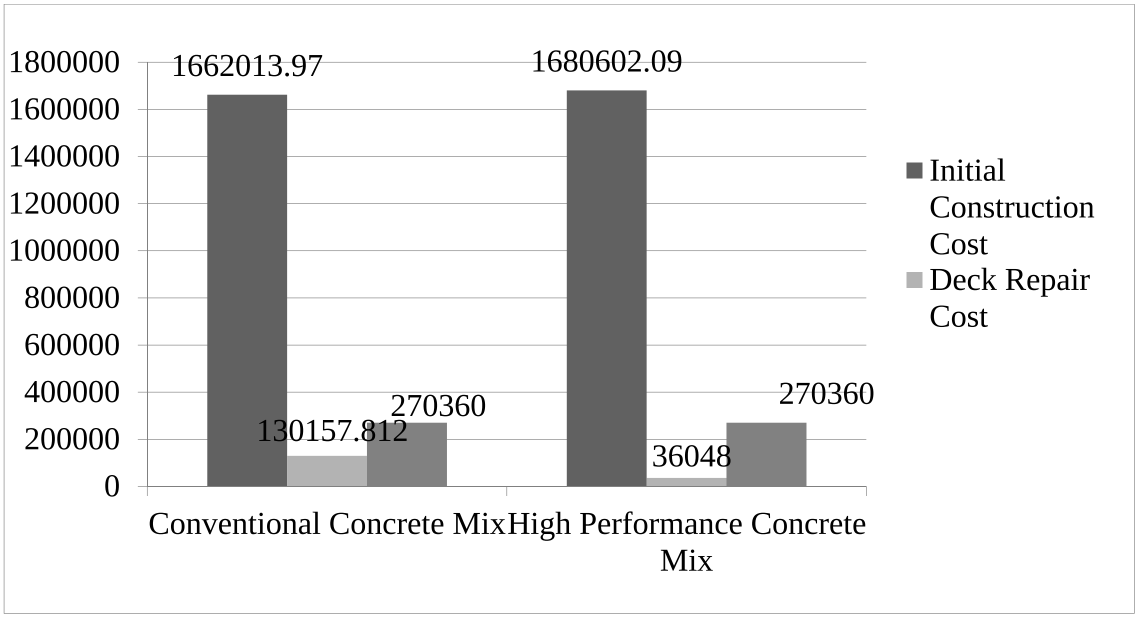


Figure 6.3: Comparison of Life Cycle Costs

However, 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 compared to conventional concrete mix. Therefore, the cost effectiveness of HPC and reduction in number of repairs needed makes this the best option towards building a sustainable environment and promoting green bridges concept.

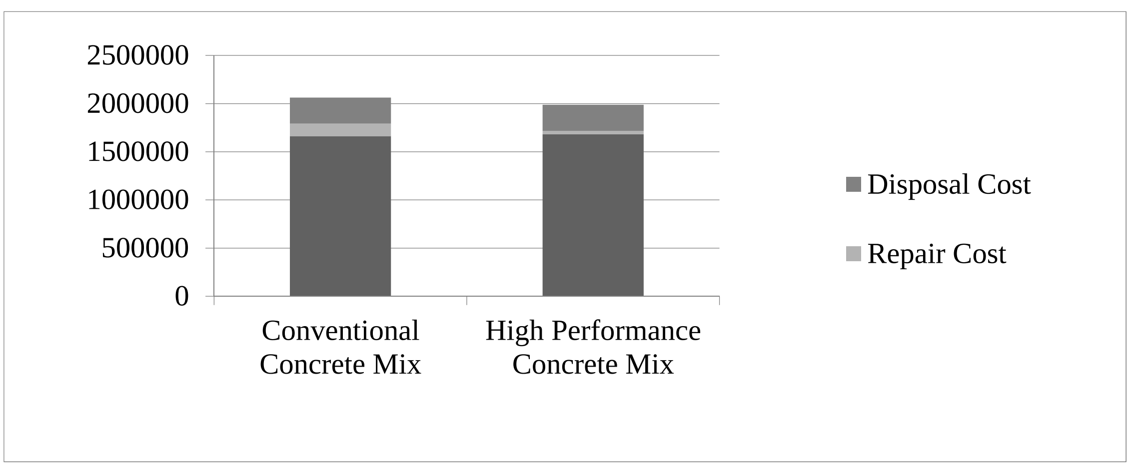


Figure 6.4: Comparison of Total Life Cycle Costs

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 study should be performed on the LCCA results to assess the impact of the discount rate on life cycle cost.

6.4 Conclusion

The section provides in-depth discussion on the step-by-step procedure to conduct LCCA for bridges. The key steps in LCCA of bridges include establishment of bridge alternatives, defining a suitable analysis period, selection of an appropriate discount rate, precise estimation of agency and user costs, and the different economic measures by which alternatives may be compared. The LCCA of bridge alternatives allows the identification of economical approaches, by providing the maximum performance at the lowest cost over the analysis period, resulting in the best decision. Ideally, a comprehensive LCCA would consider quantitatively all of the costs incurred by both the agency and the users over the analysis period. However, some of these costs are difficult to quantify, necessitating some simplifications to the LCCA.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Results and Conclusions

The focus of this project is to develop a framework that assists transportation engineers and managers develop more sustainable design and construction processes for new bridges, and sustainable maintenance practices for existing bridges. As a result of the study, following results were obtained:

a) Sustainable practices were synthesized that can be used in bridge construction projects.
b) A framework was developed to implement sustainable strategies in bridge projects. The framework includes a green rating system, which is divided into three major categories, Design, Construction, and Maintenance. Design, construction and maintenance sections are further divided into various criteria. For each criterion the description, intent, and requirements have been established.
c) A scorecard for the rating system is developed based on the results of the Delphi Survey.
d) Certification levels are developed to categorize sustainable bridges. The certification levels are Non-Green, Certified, Green, Total Green, and Evergreen. The score range for these certification levels are 0-16, 17-34, 35-64, 65-82, and 83-100 respectively.
e) Guidelines were developed to estimate cradle to gate GHG emissions from materials and GHG emissions from construction equipment in the use phase and can be used to evaluate the framework.
f) A design tool is developed that consists of a material estimator to compute GHG emissions from materials and equipment.
g) LCCA Guidelines were developed to estimate life cycle cost of the alternatives.

7.2 Research Limitations

a) The research uses the term green and sustainable interchangeably.
b) The research study mainly focuses on environmental sustainability.
c) The framework developed is mostly related to the bridges in Michigan as feedback is taken only from Michigan Department of Transportation. However, the framework can also be used by other DOT by modifying the framework or requirements of the criteria to meet their own conditions and needs.
d) The Life Cycle Assessment methodology is focused to assess the potential impact of global warming and ignores other impact categories.
e) Survey results are used to quantify the rating system.
f) Estimated emission factors may have been taken using old databases and records.

7.3 Recommendations for Future Work

1. Framework can be updated based on different requirements:

This framework has been developed based on feedback from MDOT. Some of the criteria, such as snow and ice control, may not be required for other DOTs; therefore that criteria can be excluded from the framework. Similarly, other criteria may be included in the framework. Requirements of criteria can also be modified by other DOTs to meet their conditions and needs.

2. Quantify the rating system using the scientific LCA approach:

In this study, the survey results were used to quantify the rating system, i.e., assigning point values to all the criteria. In this study, case studies were not used to perform complete LCA of bridges due to lack of time and data availability constraints. With the use of LCA software, it is required to add each process associated with each life cycle stage. It is also required to enter inputs and outputs for each process. This requires a large collection of data. It is recommended to use the LCA approach to quantify the rating system. For this, it is required to conduct 3-4 bridge case studies and perform a complete LCA of those bridges. Then, it is required to assess the overall relative environmental impact of each criterion of the framework**.** This will help in assessing the overall impact of each criterion across all impact categories. Then the points should be distributed to the criteria according to the overall impact they have on the environment.

3. Apply the rating system on 20-30 bridges and adjust the certification levels:

It is possible that most of the bridges may easily achieve the green certification level or most of the bridges may not achieve it. Therefore it is recommended to apply the rating system on 20-30 different bridges and adjust the certification levels. In this study, the rating system was not applied on 20-30 different bridge case studies due lack of time and data availability constraints. Methodology for determining certification levels used in the GreenLITES rating system for highways developed by NYSDOT can be used. In order to set a baseline, statistical thresholds can established for each certification level (by standard deviation from the mean). Certification levels can be determined by dividing all project scores into thirds representing low, middle, and high levels of environmental sustainability. The lower third of all projects did not receive certification, the middle third are *Certified*, and the upper third can be further subdivided into *Green*, *Total Green*, and *Evergreen*, with progressively increasing requirements to attain each successive level (NYSDOT, 2008).

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APPENDICES

APPENDIX A: TERMINOLOGY

Some of the general definitions used in this report are listed below. Other definitions are provided in the sections where they are addressed.

Agency Cost (AC)

It is the cost incurred by an agency responsible for bridge management; typically it includes: Inspections, Maintenance, Construction, Repairs, and Land acquisition.

Analysis Period

The time period, usually measured in years, over which costs of a bridge-management strategy are evaluated; same as time horizon and planning horizon, but not necessarily the same as service life.

Asphalt stabilized base course

Asphalt concrete used as a base course.

Base Case

The management strategy assumed to apply in the absence of any particular agency initiative, sometimes termed the do-nothing alternative, although the base case will generally include at least normal maintenance at historical levels.

Construction Waste

Construction and Demolition Waste means waste derived from the construction or demolition of buildings, roadways, or structures, including but not limited to clean wood, treated or painted wood, plaster, sheetrock, roofing paper and shingles, insulation, glass, stone, soil, flooring materials, brick, masonry, mortar, incidental metal, furniture, and mattresses.

Direct Cost

A cost incurred explicitly for and as a consequence of a bridge-management action.

Discount Rate (DR)

The exponent value used to compute the equivalent present value of a future cost; the effective discount rate accounts for inflation, the relative financial risk of an investment, and the time value of money; compare interest rate, inflation rate and real discount rate.

Embodied Energy:

The sum of energy inputs (fuels/ power, materials, human resources, etc.) that was used in the work to make any product, from the point of extraction and refining materials, bringing it to market, and its disposal / re-purposing.

Indirect Cost

A cost associated with bridge-management action, either an agency cost or user cost.

Interest Rate

The cost of funds used by an agency or enterprise, typically representing the current financial-markets' assessment of the opportunity cost of capital; not necessarily the same as the discount rate used in Bridge LCCA.

Internal Rate of Return

The discount rate such that the net present value of a stream of present and discounted future costs and savings or revenues of exactly zero.

Gray Water

The wastewater generated from domestic activities such as laundry, dishwashing, and bathing, which can be recycled on-site for uses such as landscape irrigation and constructed wetlands.

Green Vehicles

A green vehicle or environmentally friendly vehicle is a road motor vehicle that produces less harmful impacts to the environment than comparable conventional internal combustion engine vehicles running on gasoline or diesel, or one that uses alternative fuels.

High performance buildings

High Performance Buildings are energy efficient, have limited environmental impact, and operate with the lowest possible life-cycle costs.

HMA

Hot mix asphalt concrete (commonly abbreviated as HMAC or HMA) is produced by heating the asphalt binder to decrease its viscosity, and drying the aggregate to remove moisture from it prior to mixing.

Infiltration

The process of water entering soil. Infiltration capacity is the maximum rate at which water can infiltrate the soil.

Impervious surface

Impervious surfaces are mainly artificial structures--such as pavements (roads, sidewalks, driveways, and parking lots) that are covered by impenetrable materials such as asphalt, concrete, brick, stone, and rooftops. Soils compacted by urban development are also highly impervious.

Management Strategy

A set of actions and their timing for developing, deploying, operating, and possibly disposing of a bridge or other major asset; typically stated within the context of certain experience-based rules or standards of professional practice.

Permeability

The state or quality of a material or membrane that causes it to allow liquids or gases to pass through it.

Photosynthesis

The process by which green plants and some other organisms use sunlight to synthesize foods from carbon dioxide and water. Photosynthesis in plants generally involves the green pigment chlorophyll and generates oxygen as a byproduct.

Planning Horizon

The Bridge LCCA analysis period.

Present Value (PV)

The value of a cost incurred at some future time expressed as the amount that would be equivalent if that cost were incurred now, computed as a function of the discount rate and time period between now and the anticipated time when the cost will be incurred.

Real Discount Rate

The value discount rate excluding inflation but allowing for anticipated financial risk and time value of money; compare interest rate, inflation rate.

Residual Value

The present value of the total bridge life-cycle cost computed for an analysis period equal to the service life, less the present value of the bridge for an analysis period shorter than the service life, under the same management strategy; the value of the bridge's remaining lifetime at the end of the Bridge LCCA analysis period. Where appropriate the present values should include the costs of decommissioning the bridge.

Routine Cost

A cost incurred as a consequence of normal activities of a bridge's use.

Ready mix concrete

Ready-mix concrete is a type of concrete that is manufactured in a factory or batching plant, according to a set recipe, and then delivered to a work site by truck mounted transit mixers.

Recycled material

Recycling is processing used materials into new products to prevent waste of potentially useful materials, thereby reducing the consumption of fresh raw materials, energy usage, air pollution (from incineration) and water pollution (from landfilling), the need for "conventional" waste disposal, and lower greenhouse gas emissions as compared to virgin production. Recycling is a key component of modern waste reduction and is the third component of the "Reduce, Reuse, Recycle" waste hierarchy.

Renewable energy

Renewable energy is energy that comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished).

Salvaged materials

Discarded or unused material that has market value and can be sold.

Soil erosion

Erosion is a process that removes soil layers and carries them away to other land. Erosion results in the loss of valuable soil. There are three primary kinds of erosion: wind, water, and tillage. In areas where the land is especially flat or dry, wind erosion is a problem. As wind blows, soil particles spread across the land.

Sedimentation

Sedimentation is the tendency for particles in suspension to settle out of the fluid in which they are entrained, and come to rest against a barrier. This is due to their motion through fluid in response to the forces acting on them: these forces can be due to gravity, centrifugal acceleration, or electromagnetism.

Storm-water runoff

Storm-water is water that originates during precipitation events. It may also be used to apply to water that originates with snowmelt that enters the storm-water system. Storm-water that does not soak into the ground becomes surface runoff, which either flows directly into surface waterways or is channeled into storm sewers, eventually discharging into surface waters.

Sensitivity Analysis

A computational technique for considering the significance of uncertainty in assumptions underlying the Bridge LCCA by systematically varying one or another of these assumptions by a predetermined amount and calculating the outcome, e.g., total bridge life-cycle cost; changes in the outcome that are proportionately larger than changes in assumptions indicate that assumptions to which the outcome–and hence the decision to be made–are relatively sensitive.

Service Life (SL)

The period of time from a defined instant, typically the end of construction or the beginning of the analysis period, until a bridge's service condition declines to an unacceptable level; AASHTO recommends that new bridges be designed for a 75-year service life; specific values of service life depend on specification of a management strategy.

Total Bridge Life-Cycle Cost (TLCC)

The sum of all costs anticipated during the service life, discounted to their equivalent present value at the beginning of the analysis period; as presented in this guidance manual, the sum of all routine agency costs, routine user costs, and the vulnerability cost.

Turbidity

Turbidity is the cloudiness or haziness of a fluid caused by individual particles (suspended solids) that are generally invisible to the naked eye, similar to smoke in air. The measurement of turbidity is a key test of water quality.

User Cost (UC)

A cost borne by bridge users, for example, increased fuel consumption and time lost due to congestion during repairs.

Vulnerability Cost (VC)

An amount representing the expected value of annual extraordinary costs anticipated under a particular bridge-management strategy, typically including both agency costs and user costs.

APPENDIX B: SURVEY

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.

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 Redevelopment	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	

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	

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?

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.			
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?

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.			
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 C: SURVEY RESULTS

DESIGN		ROUND 1			
Site		Results			
Criteria	Title	Frequency	Mean	Median	Std Dev
1.1.1	Site Selection	9	25	25	8.660254
1.1.2	Historic Site Preservation	9	13.77778	14	8.197222
1.1.3	Soil Erosion & Sedimentation Control	9	26.77778	25	4.146618
1.1.4	Brownfield Redevelopment	9	11	10	7.26292
1.1.5	Storm-Water management	9	23.44444	25	3.431877
Total			100	99	
Materials					
Criteria	Title	Frequency	Mean	Median	Std Dev
1.2.1	Use of Recycle Materials	7	30	25	14.7196
1.2.2	Supplemental Cementitious Material	7	16.42857	20	10.29332
1.2.3	Reduction in Quantity of Materials	7	19.28571	20	7.319251
1.2.4	Material Reuse	7	12.85714	10	10.74598
1.2.5	Regional Material	8	19.375	19.375	12.08231
Total			97.94643	94.375	
Others					
Criteria	Title	Frequency	Mean	Median	Std Dev
1.3.1	Renewable Energy Use	7	10.875	5	14.12866
1.3.2	Bicycle/Pedestrain Pathways	7	15.71429	15	7.867958
1.3.3	Lane Adaptability	7	13.28571	10	8.199884
1.3.4	Life Cycle Cost Analysis	7	58.57143	70	22.86086
Total			98.44643	100	
Title		Frequency	Mean	Median	Std Dev
Site		7	46.42857	50	13.75811
Material		7	34.28571	30	19.24157
Others		7	19.28571	20	13.67131
CONSTRUCTION					
Criteria	Title	Frequency	Mean	Median	Std Dev
2.1	ABCT	7	45	30	24.83277
2.2	Corrosion Resistant Steel Reinforcement	7	26.42857	20	23.0424
2.3	Efficient Water Use	7	8.142857	5	8.802056
2.4	Fuel Efficient Vehicles	7	5.285714	5	4.715728
2.5	Construction Waste Management	7	12	5	11.6046
2.6	Use of Certified Wood	7	3.857143	2	4.561746
Total					
MAINTENANCE					
Criteria	Title	Frequency	Mean	Median	Std Dev
3.1	Efficient Inspection Tech	7	14	18	9.146948
3.2	Bridge Painting/Coating/Sealing	7	25	20	18.25742
3.3	Bridge Cleaning	7	7.714286	10	4.990467
3.4	Bridge Deck Drainage	7	8	8	6.191392
3.5	Avoiding and Minimizing Impacts to Fish and Wild Life	7	5.857143	5	4.180453
3.6	Corrosion Control Materials	7	16	20	7.302967
3.7	Bridge Deck Joints and Deck Joint Seals	7	17.85714	20	6.841749
3.8	Snow and Ice Control	7	5.571429	5	3.258688
Total					
OVERALL RATING					
	Title	Frequency	Mean	Median	Std Dev
	Design	6	47.21667	45	11.24641
	Construction	6	30.55	31.65	14.20616
	Maintenance	6	22.21667	25	10.46335