DEVELOPMENT OF FRAMEWORK FOR IMPLEMENTING SUSTAINABILITY IN BRIDGE PROJECTS WITH GREENHOUSE GAS (GHG) EMISSIONS CALCULATION GUIDELINES BASED ON LCA METHODOLOGY IMPLEMENTATIONS

By

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ABSTRACT

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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. Application of sustainable practices for 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 will assist 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 discussion and interview 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, guidelines were developed to estimate GHG emissions in bridge projects based on LCA methodology to evaluate the framework.

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CHAPTER 1

INTRODUCTION

1.1 Overview

Sustainable practices are a key component 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). The U.S. transportation system involves a substantial investment on behalf of the government and taxpayers, and widespread concern is growing over the critical state of infrastructure (Mistry, 2005). 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 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 environmental sustainable alternatives (ASBI 2007, Hong et. al., 2006). The U.S. department of transportation states: “DOT is committed to become leader in sustainability. The U.S. department of transportation incorporating sustainable practices in department’s mission helps to promote energy and natural resource conservation, decrease Greenhouse Gas (GHG) emissions, reduces pollution and contamination releases, enhances the workplace by minimizing hazardous materials and chemicals and strengthens 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 step in implementing sustainability practices in 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, involving the application of sustainable materials, standards that aim at reducing environmental pollution, and other concepts that contribute towards sustainability.

Feedback in this study is taken from MDOT and the framework is developed based on MDOT requirements, therefore, this study mostly relates to the bridges in Michigan. This framework can assist MDOT in implementing sustainable approaches in bridge projects. However, these concepts can also be used as a guideline for other transportation agencies by modifying the framework or requirements of some of the criteria used to meet their own local conditions and needs.

Chapter 1, “Introduction” discusses importance of sustainability, 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 United States and LCA applications to compute GHG emissions in construction projects. Chapter 3, “Framework for Assessing Sustainability in Bridge Design, Construction and Maintenance” includes the development of framework for to implement sustainability in bridge projects. This includes development of green rating system for the bridges, quantifying green rating system, determining certification levels for the green rating system to categorize sustainable bridges. Chapter 4, “GHG Emission Calculation Guidelines Based on LCA Methodology” to evaluate the framework and support sustainable decision-making. This includes the development of excel based tool, which can be used to compute estimated GHG emissions due to materials and equipment that can be used in bridge projects. Chapter 5, “Results and Conclusions” discuss the summary of results and provides recommendations for future work.

1.2 Need Statement

The built environment has great impact on the natural environment, human health, and economy (EPA, 2010). Incorporating green strategies has seen a large number of environmental, economic, and social benefits. 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, i.e., 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% (more than 1400) of Michigan bridges are considered structurally deficient under the federal rating system and thus 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 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 recent need to adopt methodologies that aim at reducing such impacts and contribute to sustainability. Therefore, this study is necessary for developing a framework for bridges that can be used as a guideline to achieve sustainability.

1.3 Research Goal and Objectives

The overall research goal is to develop a framework, which can be used as a guideline to achieve environmental sustainability in bridge projects and enable various transportation agencies and organizations to be leading states for the green design, construction, and maintenance of bridges. The goal was achieved by meeting the following objectives:

1. Summarize the current sustainable practices followed in building projects, bridge projects and other sectors.
2. Develop a framework that can be used to implement sustainability in bridges. This will include the development of a green rating system for bridges and determination of certification levels to categorize sustainable bridges.
3. Develop GHG emissions calculation guidelines for bridges based on LCA methodology to determine the carbon footprint associated with various items in bridge construction projects that can enable transportation agencies that can be used to evaluate the framework and investigate various strategies to reduce GHG emissions, thus supporting sustainable decision-making.

1.3.1 Objective 1

Summarize the current sustainable practices followed in building projects, bridge projects and other sectors.

To achieve this objective, a theoretical analysis of journals, articles, research papers, and theses was done. In this objective, literature is reviewed related to sustainable practices followed in building construction and infrastructure. Various green rating systems such as LEED V.3 by USGBC, Envision Rating System by Institute of Sustainable Infrastructure (ISI), INVEST rating system developed by FHWA etc. were reviewed. Sustainable practices followed by various U.S. transportation agencies were also studied in detail. Application of sustainable materials in bridge design, construction, and maintenance and LCA applications were studied and construction standards described by EPA, AASHTO, and FHWA etc., were reviewed to establish requirements in the framework, which is described in detail in Chapter 3.

1.3.2 Objective 2

> Develop a framework that can be used to implement sustainability in bridges. This will include the development of a green rating system for bridges and determination of certification levels to categorize sustainable bridges.

Based on the detailed content analysis discussed in the Objective 1, the framework consisting of a rating system was developed. The rating is divided into three categories as follows: 1) Design, 2) Construction, and 3) Maintenance. The details of the design category can be found in MS thesis "Life Cycle Cost Analysis and Delphi Survey to Assist Sustainable Bridge Design, Construction and Maintenance" developed by Awan (2012), which is based on MDOT research project work titled as "Implementation of Sustainability in Bridge Design, Construction and Maintenance". The description, intent, requirements, and standards have been established for each criterion under Construction and Maintenance category by consulting various references such as the American Association of State Highway and Transportation Officials (AASHTO), American Standard for Testing Materials (ASTM), Environmental Protection Agency (EPA), Leadership in Energy and Environmental Design (LEED®V.3) construction standards. In order to quantify the rating system, point values are assigned to each criterion and weights are assigned to all three categories. The weights are assigned based on the results of the Delphi survey conducted at MDOT divisions, which were taken from thesis "Life Cycle Cost Analysis and Delphi Survey to Assist Sustainable Bridge Design, Construction and Maintenance (Awan, 2012). The certification levels were developed based on research panel discussion and interviews with MDOT experts to categorize sustainable bridges. The methodology is described in detail in the relevant section.

1.3.3 Objective 3

> Develop GHG emissions calculation guidelines for bridges based on LCA methodology to determine the carbon footprint associated with various items in bridge construction projects that can enable transportation agencies that can be used to evaluate the framework and investigate various strategies to reduce GHG emissions, thus supporting sustainable decision-making.

Transportation sector is the second biggest contributor of GHG emissions followed by the industrial sector, which is the biggest contributor of GHG emissions. In 2002, it is estimated that transportation sectors is responsible for 1908 MMT CO_2 Eq., which is 29% of all the key sectors (EPA, 2008). Figure 1.1 shows estimates of GHG emissions from various sectors in United States.

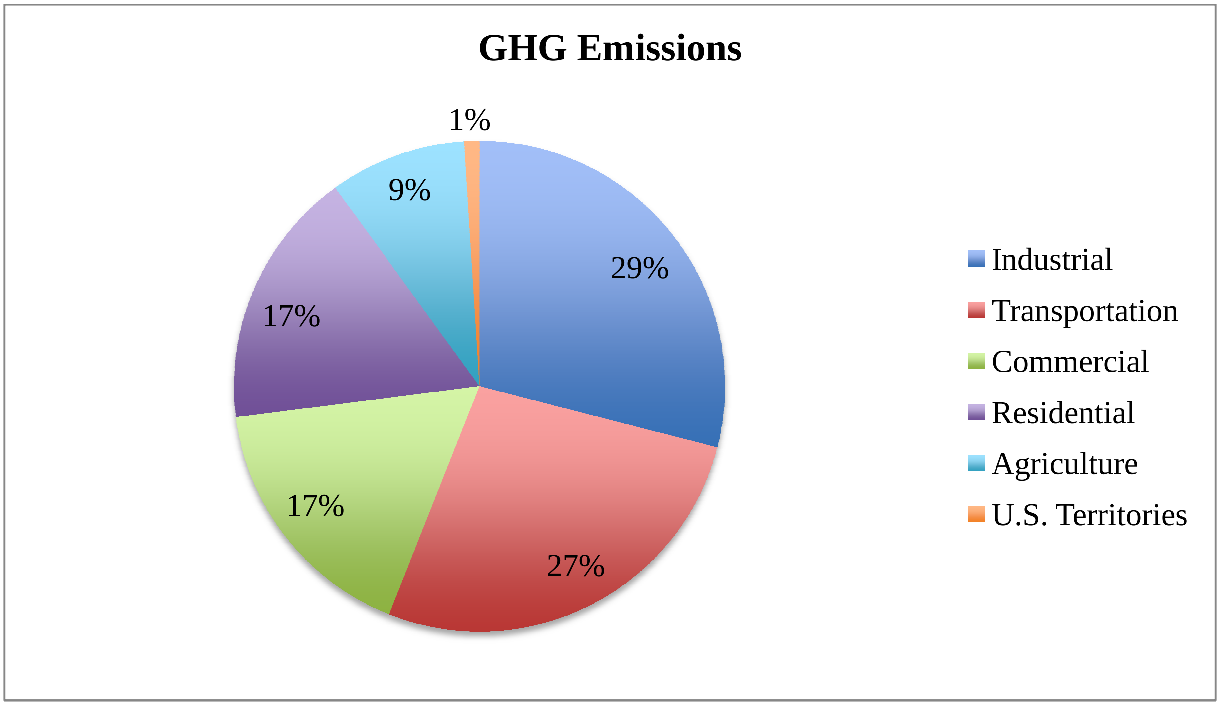


Figure 1.1: Total 2002 GHG Emissions By Sector (MMT CO_2 Eq.), Factoring in Purchased Electricity (Source: EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks) (For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis)

The guidelines include developed of excel based tool that can be used to compute GHG emissions from materials and equipment that can be used in bridge construction projects. GHG emission calculation can be used to evaluate the framework.

1.4 Research Methodology

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

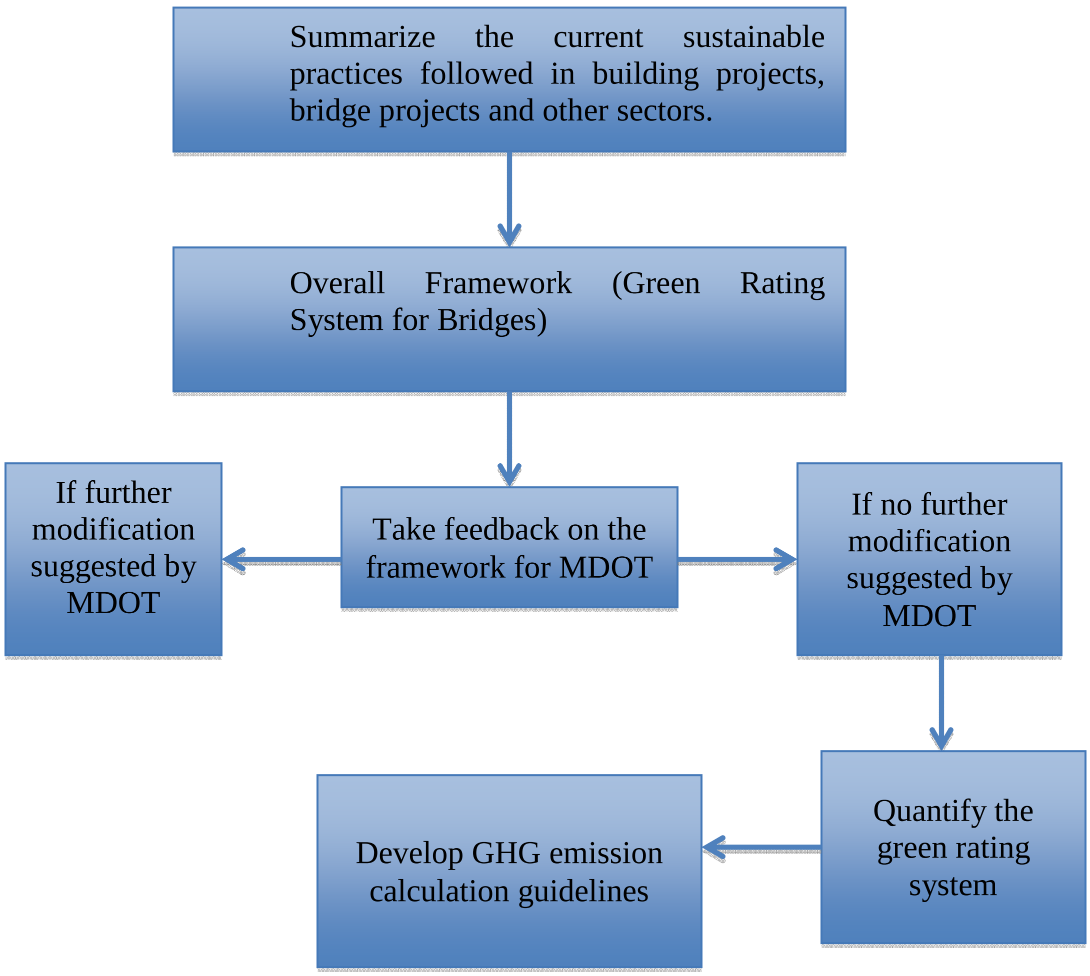


Figure 1.2: Research Methodology

1.5 Deliverables and Research Contribution

This research aims to provide a framework to organizations to implement green practices in bridge design, construction, and maintenance. This will be used to categorize sustainable bridges and contribute to sustainable environment. These outputs were provided in the following chapters and the relevant appendix.

1.6 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 excel in certain and 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 will assist transportation engineers and managers develop more environmentally sustainable design and construction processes for new bridges, and sustainable maintenance practices for existing bridges. Figure 1.3 shows the steps in the research study, which include the development of a green rating system for the bridges, quantifying the green rating system, developing GHG emission calculation guidelines, and recommendations for the future work.

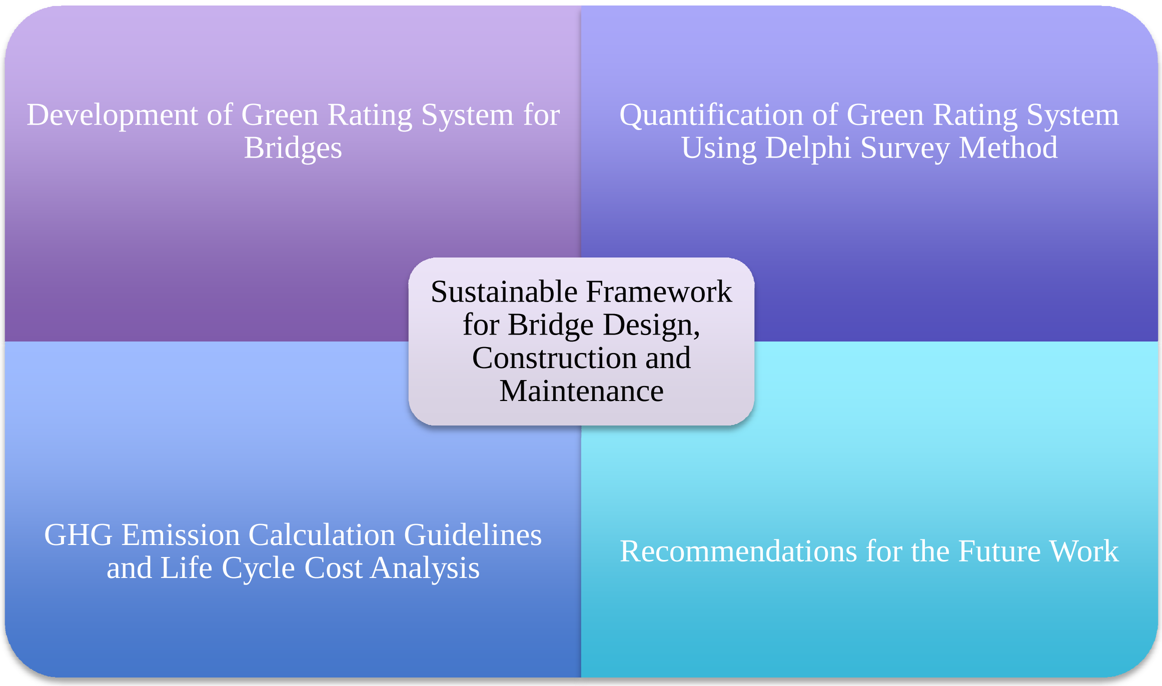


Figure 1.3: Steps in the Research Study

CHAPTER 2

LITERATURE REVIEW

2.1 Literature Review Categories

In this chapter, literature is reviewed to form three categories as shown in Figure 2.1. The first category reviews literature about current sustainable practices in bridge design, construction and maintenance by consulting articles, theses, books, journals and magazines. The second category reviews literature about major existing Green Rating Systems in United States such as LEED V.3 (USGBC, 2009); Envision™ Rating System (ISI, 2012), GreenLITES Certification System (NYSDOT, 2008), Sustainable Self-Highway Evaluation Tool (FHWA, 2012). Other 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 applications. It includes the concept of LCA, its applications, use of LCA software and estimating GHG emissions.

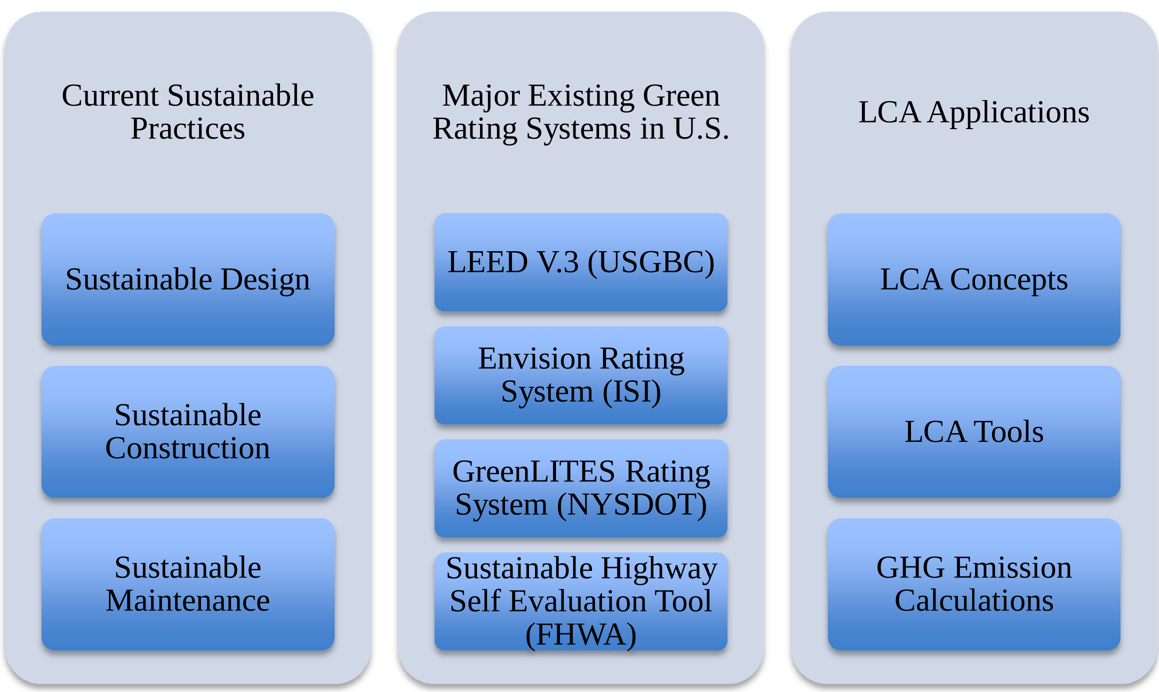


Figure 2.1: Categories of Literature Review

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 US contribute 39% of all carbon dioxide (CO_2) emissions and 40% of raw material use, 72% of the total electricity consumption, (EPA, 2009); sustainability is increasingly adopted by the US building industry with the 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). 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 but 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 and 2) Environmental Sustainability in the context of bridges. The structural sustainability, in American Concrete Institution (ACI) fall 2010 Convention, states "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 use saturated lightweight aggregates for internal curing for the promotion of hydration to minimize shrinkage and cracking. HPC should have other optimum concrete characteristics such as low water/cement ratio, 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 will be on environmental sustainability of the bridges. Environmental sustainability deals with the environmental impacts of the products or the process in all life cycle stages of the bridge, i.e. to measure the environmental impacts and performance of the products 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

Design of the bridges is an important phase where most of the decision taken can have impacts on 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, foundation types are some of the factors that should be taken into consideration during the design stage and alternative ways are usually considered to achieve sustainability.

Lounis & Daigle (2007) compared the environmental benefits of High Performance Concrete Decks (HPC) and Normal Performance Concrete (NPC) bridge decks. It was found that construction of HPC structures results in reduction in the number of maintenance and repair actions that 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 the 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 the 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 normal concrete deck having the same water-to-cementitious materials ratio (Lounis & 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, requiring 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 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 ingression of chlorides and due to carbonation. Chloride ingression has been formulated on the assumption that it would occur by ionic diffusion. Based on it concrete mix, cementitious content were determined and the additional materials such as fly ash and slag has been used to reduce the heat of hydration and greenhouse gas emission thereby increasing the durability.

Another factor, which decreases the durability of the structure, is carbonation. The primary concern is for superstructure elements. It decreases the PH value of concrete due to which the passive iron oxide layer, which protects reinforcement from corrosion, is not maintained. 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 long life of a bridge, selection of good quality of concrete; selection of greater cover to 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 are considered important factors (Connal, 2009).

Materials play an important role in sustainability and number of research studies has 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 safe environment. A single clear span for the bridge is one of the best environmental solutions, avoiding permanent piers in the river. Steel is recyclable material and it can be recycled and reused multiple numbers of times without affecting its structure or properties. It promotes management of sustainable resources. It minimizes the effect on local community, as steel components are manufactured offsite. Selection of 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 & 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 to corrosion. Since copper is used as an alloy, it provides a mechanism, which provides prevention from atmospheric corrosion. FHWA is emphasizing on using weathering steel for bridge construction as it improves the performance and research and studies are underway of weathering steel bridge performance in macro and microenvironments. (Kozy & Triandafilou, 2011).

TxDOT has built over 100 weathering steel bridges since 1970. A research study was conducted for TxDOT, which includes field visits where different samples where collected 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. And it was found that uncoated weathering steel is a very good 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 sustainability of bridges. It is a composite steel hybrid structure, which has requires minimal maintenance and is much economical. In the longer 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: higher strength to weight ratio; high degree of pre-fabrication possible; faster installation; and corrosion resistance (Jacob, 2008).

Transportation industry uses alternative materials in the construction of pavements as 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 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, 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 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”. For the evaluation of energy releases during transportation, average distance travelled and fuel efficiency of the vehicles which travels to and from the site are considered (Pacheo & Campos, 2010). Energy consumption during construction operations is an important factor that should be considered. Energy consumption is found considering the weight of equipment, energy it consumes per hour of operation and the duration of a construction of a typical bridge deck (Pacheo & 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 such type of equipment, which produces lesser 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.

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 as 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 contributes to 12.66 lbs. CO_2/gallon and 11.7 lbs. CO_2/1000 cu.ft. These show that 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).

Accelerated bridge construction technique is an innovative approach greatly contributing towards sustainability. Accelerated construction is used to achieve the construction of structures in a 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). Using precast bent caps, precast columns, precast deck panels, precast barriers, prefabricated trusses, precast abutments, retaining walls and footings allows manufacturing to take place in a controlled environment thereby reducing impacts to traffic and reducing environmental impacts. The main reason for using such techniques is to reduce on-site construction time and mobility impact time (FHWA, 2012).

2.3.3 Sustainable Bridge Maintenance

Bridge maintenance is major part of a bridge life cycle. There are number of activities involved in bridge maintenance which may have significant impacts on 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 improves the roadway or overlaying a bridge deck and superstructure repair to improve a bridge. Long-term fixes include reconstruction/replacement. Reconstruction is the entire building of the roadway. Replacement refers to replacement of the bridge deck, super structure replacement or replacement of whole bridge (MDOT, 2011).

Many attempts have been made to reduce number of maintenance activities to reduce environment impacts associated with them. Use of durable materials prolong service life of bridge components and thus reduce future maintenance activities. High performance structural materials and FRP can be used to design bridges for more durability thus reducing future maintenance activities (Tang, 2004). Efficient inspection technologies should be used to properly assess the condition of bridges timely so that proper actions can be taken regarding maintenance actions. Use of efficient inspection technologies can ensures 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 eligible 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 comprehensive management of bridge system and provides improvement in the type and quality of data is collected, stored, managed and used in a bridge system analysis; realistic and reliable forecast of future needs and; a logical methods for setting priorities for current needs (WSDOT, 2010).

The focus should be more on quantitative assessment of performance of bridge performance rather than visual inspections and condition ratings. A variety of permanent sensors can be installed on bridges, which 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 can report to wireless networks and data can be analyzed and 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 the bridges, which can be used to define and measure sustainability in bridges, various major green rating systems currently used in the United States shown in Figure 2.2 were reviewed. These green rating systems are developed mostly for buildings and highways. Brief overviews of the existing green rating systems are as follow.

2.4.1 LEED (2009)-New Construction

Leadership in Energy and Environmental Design (LEED®) is a rating system for 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 developed five versions i.e. version 1.0 in 1998, version 2.0 in 2000, version2.1 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 countries covering over 1.627 billion square feet of development area which shows the impact and wide recognition for LEED® in US 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: 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. The Figure 2.3 shows the categories and credits of LEED® 2009. 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 are developed in LEED 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 LEED® 2009 rating system to develop the rating system for bridges. The factors considered in analyzing the sustainability of buildings are materials, water, energy, location and indoor air quality while the critical factors that apply to bridges are location, materials, water and traffic impacts. Whittemore (2010) explained the equivalent goals for sustainable bridges by comparing them with the sustainable goals for buildings. His analysis explained the useful metrics from LEED® 2009 that can be taken to define and measure sustainability in bridges. So, 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 what systems are in place, ensures that the consumption of the potable water is the least and the runoff from the structure is of the highest quality (Whittemore, 2010). Therefore, such requirements are to be established after reviewing the standards, which ensures the optimum use of water and its quality. Likewise, certain other credits and prerequisites from LEED® can also 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, 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 the sustainable infrastructure projects. This rating system evaluates the sustainability for 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 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, which can influence the project elements, and processes, which 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, to 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 are 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, Access and mobility. These are the ten 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 (**L**eadership in **T**ransportation and **E**nvironmental **S**ustainability) certification program for implementing sustainability in transportation projects. GreenLITES project design certification program developed by NYSDOT in 2008 includes the development of a green rating system to define and measure sustainability of highways. It shows their commitment in improving the quality of transportation infrastructures by minimizing environmental impacts and reducing 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 i.e. certified, silver, gold and evergreen. The project rating may fall into any of the category based on the cumulative score obtained. The cumulative score is obtained by summing points of each criterion. It was formed after the US 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 for the 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 is a web-based collection of criteria, 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. This tool can be accessed at https://www.sustainablehighways.org/All_Pilot_Criteria_11_1_2011.pdf

FHWA's INVEST can help transportation agencies and organizations integrate sustainability practices in transportation projects and provide practitioners 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 the 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 bridge. The design stage of the bridge commences with the selection of materials, span arrangements, girder spacing, bearing types, substructure type and geometry, and foundation types. Design of 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. As, preservation treatments over time can reduce the overall cost of bridge maintenance. All decisions made in the life cycle of a bridge, especially the ones 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 design, construction and maintenance of the bridges. MDOT current practices were established by studying 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 a soil erosion and sedimentation control program, consists of commitment to environmental stewardship responsibilities;

appropriate staff training; specifications and project plans that address erosion control issues (MDOT, 2006). The development of the program is divided into three phases which planning, design and construction phase.

b) Maintenance Activities and Projects

Since maintenance activities also have potential impacts on lakes, streams and wetlands, MDOT also conduct 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 large amount of contaminants. These contaminants may be washed away by the rain, snow melts and may enter streams, rivers and lakes. Excess contaminants may cause public health concerns, 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 mix of fixes strategy for the maintenance of bridges. This strategy uses combination of long-term fixes, medium term fixes and short term fixes. Long-term fixes include reconstruction/replacement. Reconstruction is the entire building of the roadway. Replacement refers to replacement of the bridge deck, super structure replacement or replacement of whole bridge. Medium term fixes includes rehabilitation. Rehabilitation is the application of structural enhancements, such as multiple course resurfacing or concrete pavement repairs, that improves the roadway or overlaying a bridge deck and superstructure repair to improve a bridge. 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 increasing the service life of the 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, which is used to analyze environmental impacts of products through its all life cycle stages. An ideal life cycle would account for all the phases of the product. This is called Cradle to Grave approach. Similarly, LCA has different stages, which are Cradle to Gate, which includes raw material acquisition to production stage and Gate to Gate stage, which includes only 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

The life cycle of the bridges play 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, weather 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, which are measured to assess the environmental performance of the product (Trusty, 2006) are Toxic releases to air, water and land; Fossil fuel depletion, CO_2 emissions, Non-renewable energy use, Global warming potential, Acidification and Acid Deposition, Nutriphication/Eutrophication of water bodies, Stratospheric ozone depletion.

GHG emissions are one of the major contributors to the negative impacts to the environment and, the main focus of this study developing guidelines for determining GHG emissions or the carbon footprint of the bridges. Guidelines for calculation of GHG emissions are based on LCA methodology. It is well known that bridge construction project involves large number of products and processes. Cement is the most common material used in large quantity in construction. Cement is highly energy intensive material (Worrell et. al., 2001). It consumes as well as release high amount of energy into the surroundings during all life cycle stages like 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 CO_2 emissions (Worrell et. al., 2001) and significant levels of SO_2, NO_x, particulate matter and other pollutants. Similarly, different products and products release 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 therefore it is important to review the LCA concepts and applications. A number of LCA studies had been made and extensive literature is published recently. Singh, Berghorn, Joshi and Syal (2011) had made a systematic compilation of all the Construction-LCA related literature and presented its structured review. These 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 a good idea of the LCA methodologies and databases for LCA.

An integrated LCA-LCCA model was developed and applied on 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 the sustainability such as life cycle energy, greenhouse gas emissions, agency, rehabilitation, social, construction-related user delay costs and environmental pollutant damage costs 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 total 60-year service life with a traffic flow rate of 35,000 cars per day in each direction. Study shows that ECC link slab system has a 37% cost advantage over the conventional system, 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 research study conducted, individual credits within the LEED program were critically analyzed using life cycle approach. A case study of building was conducted to measure life cycle energy consumption and solid waste generation to analyze the impacts of implementation of LEED requirements (Scheuer & 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) which is an LCA software tool developed by National Standards of Intitute and Technology takes a life cycle approach to building materials and focus on both life cycle environmental and cost data. It was shown that BEES can be used to integrate LCA itno 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 our economy. 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”.

EPA has developed a report, which gives an overview of sources and 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 the construction activities that results in GHG emissions and have the most influence on contractors potential ability to affect emissions. Similarly, material selection, employee commuting, materials shipment and vegetation removal have some influence and site selection and structural design and performance have little influence (EPA, 2009).

Emphasis on recycling and reusing of materials is placed as GHG emissions released during the manufacturing and transportation of the construction materials are avoided. Therefore, recycled materials should be used on the project like 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 type of blended cement is greatly reduced. Table 2.3 shows the environmental impact score of the traditional Portland cement and the blended cement (Huntzinger & 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 & Eatmon, 2009).

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

Environmental Impact Category	Traditional Portland Cement	Blended Cement
Greenhouse	.088	.069
Acidification	.043	.034

Also, recycling steel reduces GHG emissions and save energy by 56%. Also recycling 1 ton of steel conserves 2500 pounds of iron ore, 1400 pounds of coal and 120 pounds of limestone (West, 2012).

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 widely be used for environmental labeling, product environmental improvement, ecodesign and policy evaluation (Menke et. al., 1996). Menke, Davis and Vigon (1996) identified comprehensive list of 37 LCA tools and the related literature was reviewed.

LCA tools measures the environmental impacts primarily across a five set of environmental indicators which are 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 according to the institution type such as Academic tools, Government and Industry.

Table 2.4: GHG Impact Tools (Adopted from (Mukherjee & 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™

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 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 & 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	**Title**	**Intent**	**Standards**
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 (R&D), 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	**Title**	**Intent**	**Standards**
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 3.5	Avoiding and Minimizing Impacts to Fish and Wild Life	To avoid impacts on fish and wild life due to maintenance activities	Federal Endangered Species Act; Rivers and Harbor Act; Clean Water Act; Michigan Department of Environmental Quality (MDEQ).
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 the Bridges

An extensive content analysis of MDOT's current practices as well as existing sustainability and bridge related sources was carried out to develop the framework. After going through a significant research session by consulting different journals, articles, books and websites, MDOT's design and construction manuals, New York State Department of Transportation (NYSDOT) Leadership In Transportation and Environmental Sustainability Project Design Certification Program (NYSDOT, 2008), LEED®, 2009 and a master's thesis on "development of a rating system for sustainable bridges" provided significant guidance in selecting and defining categories and credits for the framework to assess in this work. Current sustainable practices in design, construction and maintenance followed by MDOT have also been reviewed. For this purpose MDOT manuals such as MDOT scoping manual, MDOT design manual, MDOT drainage manual and MDOT bridge preservation matrix have been reviewed.

MDOT follows best management practices for storm water management (Quality and Quantity Control), measures to avoid soil erosion and sedimentation control, 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 such as 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 than other material 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 will be the intent of this category. The design principles will be consistent with MDOT policy and standards. MDOT has already been practicing several sustainable techniques and has incorporated these criteria in their design strategies, which are environmentally responsible. The design section is divided into sites, materials and other which are further subdivided into various criteria. Guidance is given under each criterion for assigning points to the particular category. This study describes in detail the construction and maintenance category while details on design category can be found in MS thesis completed by Awan (2012), which is based on the research work for MDOT titled as "Implementation of Sustainability in Bridge Design, Construction and Maintenance (MDOT, 2012).

3.2.2 Category 2-Construction

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

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

Description:

Accelerated construction is used to achieve the construction of structures in a 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, bridge is prefabricated in 50-100 feet long units under factory conditions behind an abutment and bridge is launched by sliding it on bearings into the final position without the aid of scaffolding. The advantages are less first cost due to less equipment and less labor and less maintenance cost (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 3.2. The points will be awarded based on the time reduced due to the application of accelerated bridge construction techniques. The points will be awarded based on the following criteria:

Table 3.2: 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, US 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 in winter. Sodium chloride can penetrate through cracks and over time through diffusion and acts as catalyst for reinforcement corrosion. This is one of the primary reasons of 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, stainless steel clad reinforcement.

b) Stainless steel industry share of CO_2 emissions could be around 12% of global emissions. Stainless steel contributes greatly towards sustainability and it leaves reduced carbon footprint (Gopal, 2006).

Scoring Criteria:

4 Points will be awarded if epoxy coated reinforcement are used on the project and 8 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 around 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 the bridge construction and incorporate water efficiency and conservation in equipment washing. It entails considerable reduction in use of potable water and employs on-site resources in order to lessen demand on municipal water supply.

Requirements:

Consider use of 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 3.3 using any of the outlined or other techniques.

Table 3.3: 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 type of equipment, which produces lesser 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 identify, collect and remove the 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 contractors to 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 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 3.4. An example for calculations is shown in Table 3.5.

Table 3.4: Scoring Criteria for Construction Waste Management

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

Table 3.5: 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 has 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 & Irby, 2011).

Scoring Criteria:

1 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

Majority of the bridges built in around 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 wild life that should be met in order to reduce environmental impacts associated with these.

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 ensure increasing service life and be cost-effective.

Intent:

To use efficient inspection technologies and processes for proper maintenance action decision 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 the 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 development, establishment, and implementation of bridge management systems and associated data collection activities.

Scoring Criteria:

2 points for meeting the first requirement only.

2 points 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 important part of the bridge life cycle. The painting enhances the aesthetics and protects the steel bridge elements against corrosion and other weather deterioration (AASHTO, 2012).Paints should be used to slow corrosion cause by moisture, air, and oxidizing chemicals (Chang, Abdelrazig, & 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 AM to 4 PM with occasional night time and weekend works. Paint should be used to slow corrosion cause by moisture, air, and oxidizing chemicals. Typically, bridge abutments and piers are made of concrete. The beams and diaphragms made of steel are what needs to be painted.

Intent:

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

Requirements:

a) Utilize best practices to protect workers and environment during lead paint removal and remove lead from existing structures and 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:

3 points are awarded, if zinc rich coatings are used for all the components and 6 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 of 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, 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 disposal of wash water. Avoid entering wash water 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 off in surface waters or below the ground surface.

f) The 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:

- 1 point will be awarded for developing schedule of cleaning operations.
- 2 points will be awarded if 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:

1 point for meeting any of the two requirements.

3 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 Wild Life (1 Point)

Description:

Bridge maintenance operations can severely disrupt the natural flow of river and stream ecosystems. The road crossings like bridges and culverts have 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 wild life 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 to spend minimal time 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:

- 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:

2 points are awarded, if any one requirement is met.

3 points are awarded for meeting both the 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 proper functioning of the structure. Various factors such as temperature change, deflection caused by loads, creep and shrinkage of concrete, stream or ice flow and longitudinal force of vehicles causes bridge to expand and contract. Bridge deck joints allow the 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) Discontinue to the extent possible 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 3.6

Table 3.6: 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 get heavy snow in winters. The standard procedure to remove snow or ice is by chemical treatment and plowing. Deicers are applied to roadway 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 to reduce associated impacts of snow and ice on the bridge.

Requirements:

a) Implement snow and ice control plan including techniques to remove snow and ice from bridges.
b) Implement management plan to monitor the quantity 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 effective method of spraying deicing salt as it assist 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. Sodium chloride (salt) brine is a low-cost, effective alternative to liquid calcium chloride as a pre-wetting agent (Donahey & Burkheimer, 1996).

Scoring Criteria:

1 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

3.3 Quantifying the Green Rating System

A Delphi Survey conducted by another member of the research group is used to assign weights to category and point values to the criteria. The details of the survey can be found in the thesis "Life Cycle Costs Analysis and Delphi Survey to Assist Sustainable Framework for Bridges in Michigan" developed by Awan (2012). Based on the results of Delphi survey, scorecard for the rating is developed which is shown in Table 3.7

Table 3.7: 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 & 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 3.7 (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

3.4 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 3.8. Each criterion is determined whether it is easy to implement, difficult to implement or has 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 to achieve has been then provided by MDOT. The sum of points of easy to implement, medium to achieve and difficult to achieve were found.

Table 3.8: 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 & Sedimentation Control	2	4		6	Requirements "a", "b" & "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 3.8 (cont'd)

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
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.

Table 3.8 (cont’d)

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 are divided into in three major levels which are 0-33 which represents the lower range, 34-64 which represents the middle range and 65-100 which represents the higher range. The lower range and the higher range is further divided into two halves since some of the criteria are easy to achieve and very basic component of every bridge design and construction project and they are likely to achieve Certified level in every project as any project can easily obtain at least 1 or 2 points therefore, the certified level is further relegated to non-green level. Similarly, in order to achieve complete sustainability in bridge project, the total green level to further upgraded to Evergreen level. The certification levels are shown in the Table 3.9.

Table 3.9: 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 4

GHG EMISSIONS CALCULATION GUIDELINES BASED ON LCA METHODOLOGY

4.1 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 Environmental Protection Agency (EPA), transportation sector is responsible for 27% of GHG emissions in 2002 and is the second biggest contributor by sector followed by Industrial sector, which is responsible for 32% of GHG emissions (EPA, 2008). Therefore, significant amount of GHG emissions are associated with the construction and use of transportation infrastructure and 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 & Cass, 2012).

California Environmental Protection Agency has already developed a greenhouse gas emission inventory that provides the estimate of the amount of GHG emissions associated with the various activities. The inventory includes estimation of various gas pollutants such as Carbon-dioxide (CO_2), Methane (CH_4), Sulphur hexafluoride (SF_6), Nitrous oxide (N_2O) etc. (California EPA, 2012). This study propose 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. Cradle to

Gate LCA approach is taken into account to estimate the emissions from raw material acquisition, manufacturing and construction phase of different bridges.

4.2 Goals and Objectives

The goal of this section is to develop an LCA framework, which include guidelines for determining carbon footprint associated with various items in bridge construction projects that 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, which includes list of materials and equipment that can be used in bridge projects.

To accomplish this objective, list of materials and equipment that can be used in bridge project were collected using MDOT construction plans and specifications and from construction inventory developed by Mukherjee & 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 out for the products based on literature review, reviewing historical databases and using 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.

Excel based tool is developed to calculate the quantities of GHG emission from the products. This tool is based on the web-based tool called project estimator developed by Mukherjee & Cass (2011) for calculating GHG emission 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 emission for two alternative bridge decks – conventional concrete bridge deck and the Fiber Reinforced Polymer (FRP) bridge deck.

4.3 Building Blocks for Developing GHG Emission Calculation Guidelines

The building blocks for developing GHG emission calculation guidelines shown in Figure 4.1 are 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; literature and historical databases as these are used to obtain emission factors of some of the products and software tool "SimaPro" as emission factors are also obtained using this tool.

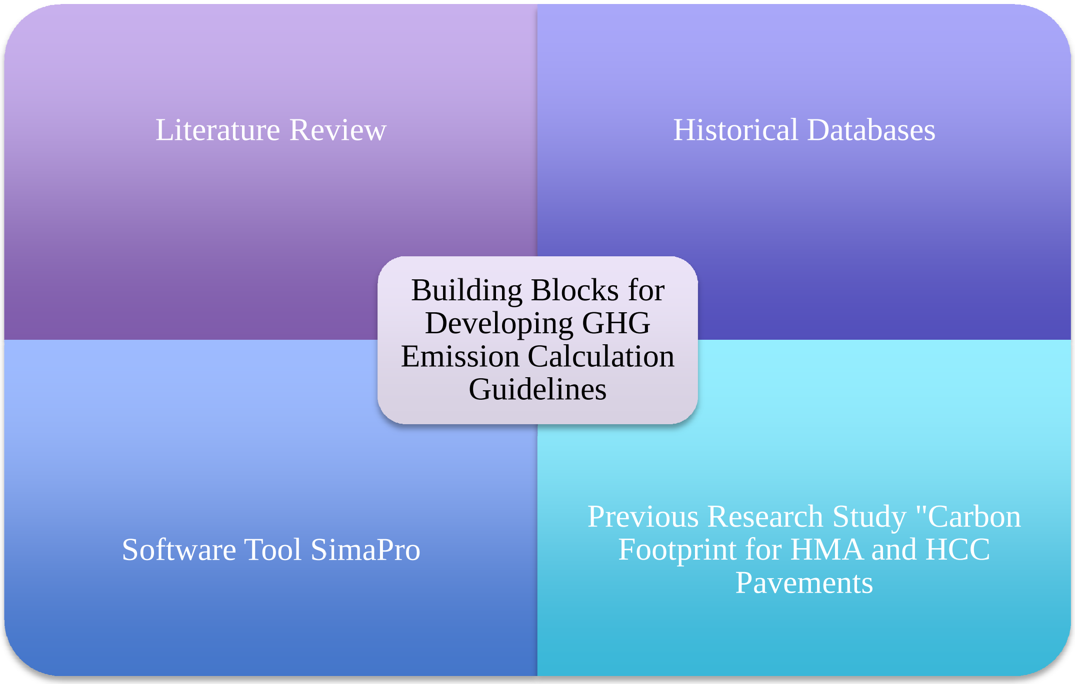


Figure 4.1: Building Blocks for Developing GHG Emission Calculation Guidelines

a) Carbon Footprint for HMA and HCC Pavements

Mukherjee and Cass (2011) conducted this research study and prepared a report for MDOT. They 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 & 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 fourteen 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 the 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), which is 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, historical databases to estimate the emissions from these products. EPA defines emission factor as: “An emissions factor is 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 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 .012 and 100 MT of asphaltic material is used in the project. Then emissions due to asphaltic material will be .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, 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 fourteen 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 an 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 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 by using the emission factors.

The proposed framework is based on process, product, service (PPS) method which includes different process and product components. This approach uses existing calculation methods of GHG emissions but uses the data collected through fourteen highway construction projects.

Product Components:

All the materials that are listed in department of transportation agency specification 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 & 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 & Cass, 2012).

Service life components:

Since, it can be difficult to estimate, a traffic simulation environment MOVES [35] 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 is 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:

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. 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.

b) Literature and Historical Databases

Various historical databases are available to get 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. NREL and its partners created the "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 in this study are adopted from the research report "Carbon Footprint for HMA and HCC Pavements" developed by Amlan Mukherjee and Darrell Cass. Emission factors of all the equipment are adopted from this report.

c) SimaPro

SimaPro is one of the LCA tool and is most widely used in the industry. SimaPro is used in this study to calculate 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 all the four phases, which are described before. These 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 & 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) , 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 4.2. 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.

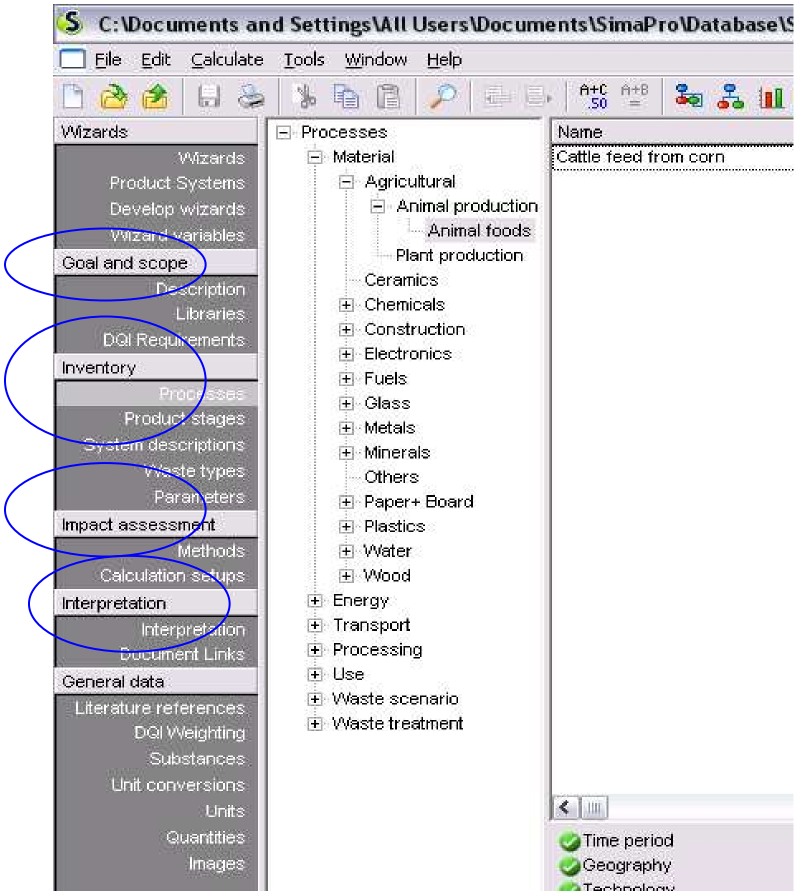


Figure 4.2: SimaPro Organization (The text is not meant to be readable, but for visual reference only)

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, methodology are also described in the goal and scope definition phase. It also needs to be decided that what is included and what is excluded from the product system and whether all or part of the product life cycle is taken into the account.

In the Life Cycle Inventory (LCI) phase shown in Figure 4.3, 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 list all the 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, which are Classification, Characterization, Normalization and Evaluation. The last two steps are optional. Each output is classified into one or more impact categories. Impact categories can be Global Warming Potential (GWP), Fossil Depletion, Freshwater Eutrophication, Ozone Depletion, and 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. CO_2 by multiplying their quantities by a characterization factor (these factors are determined by different scientific groups and different methodologies, most commonly impact category methodology is Tools for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) (EPA, 2012) in USA) to determine their CO_2 equivalent if eq. CO_2 is the reference unit of the impact category. 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 the product system.

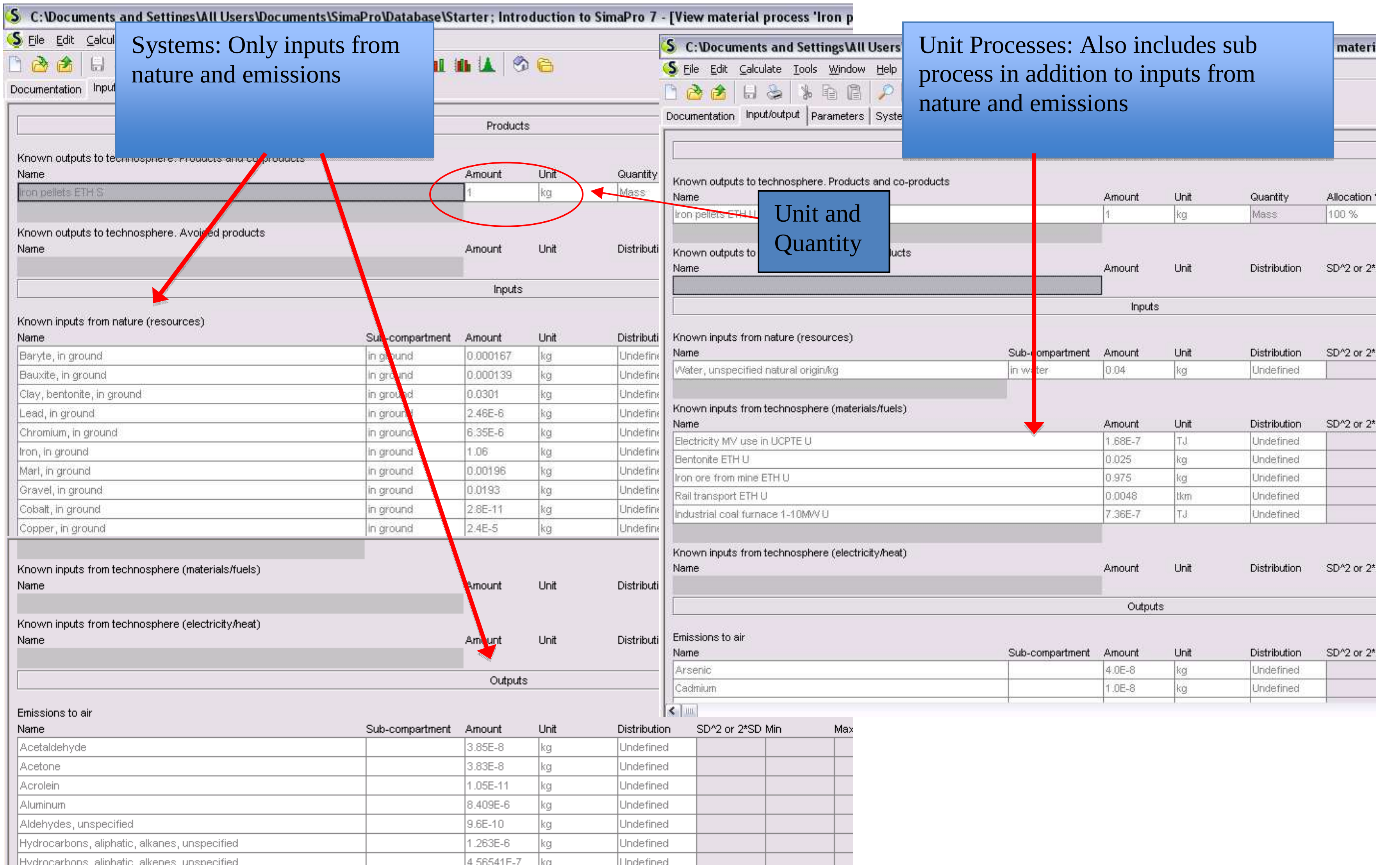


Figure 4.3: LCI Phase (The text is not meant to be readable, but for visual reference only)

The last step, which is interpretation of the results shown in Figure 4.4 and Figure 4.5, 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 4.6 to Figure 4.13 and Table 4.1 shows the results obtained from SimaPro. It shows cradle to gate CO_2 eq. emissions from different products. Table 4.2 list emission factors of all the materials.

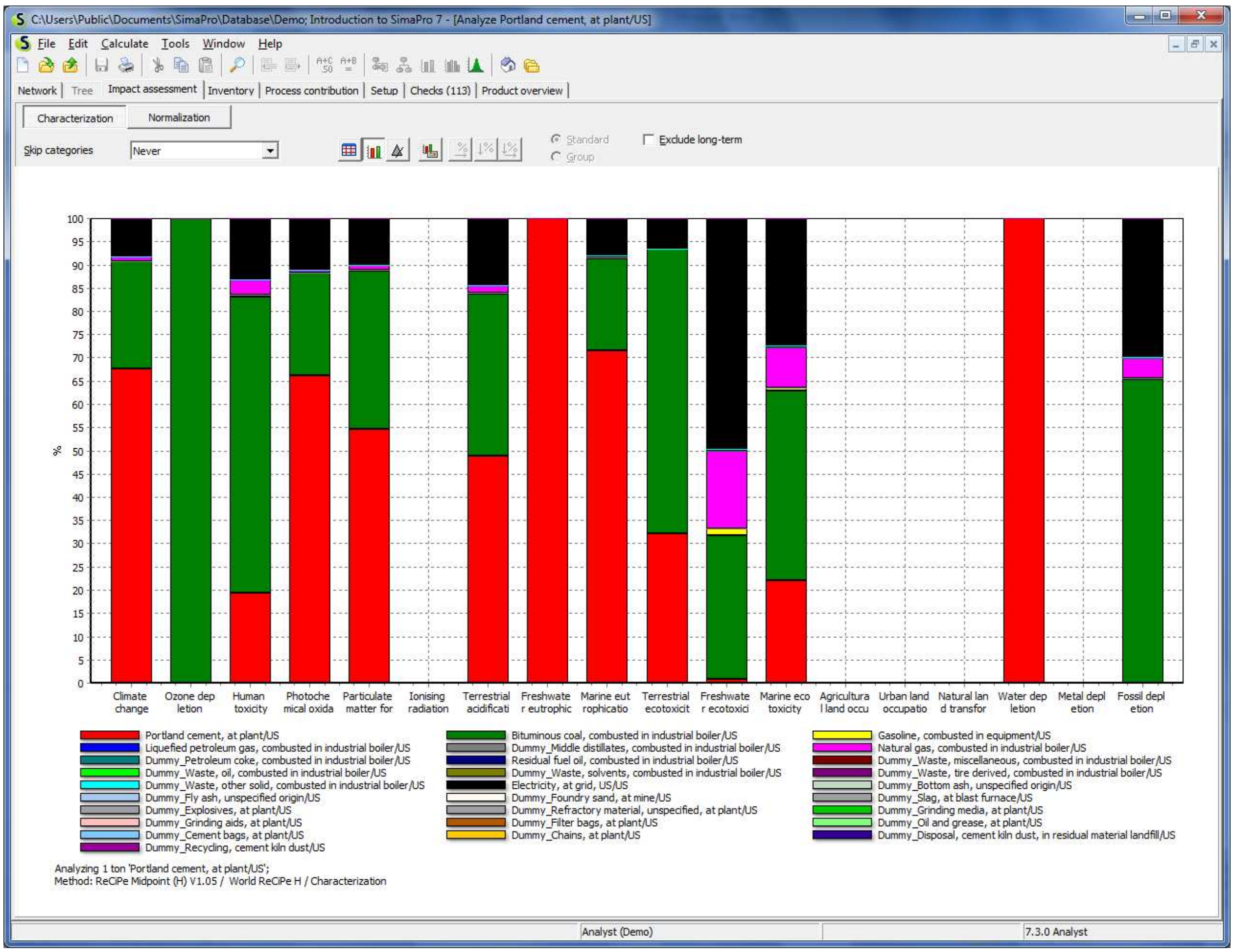
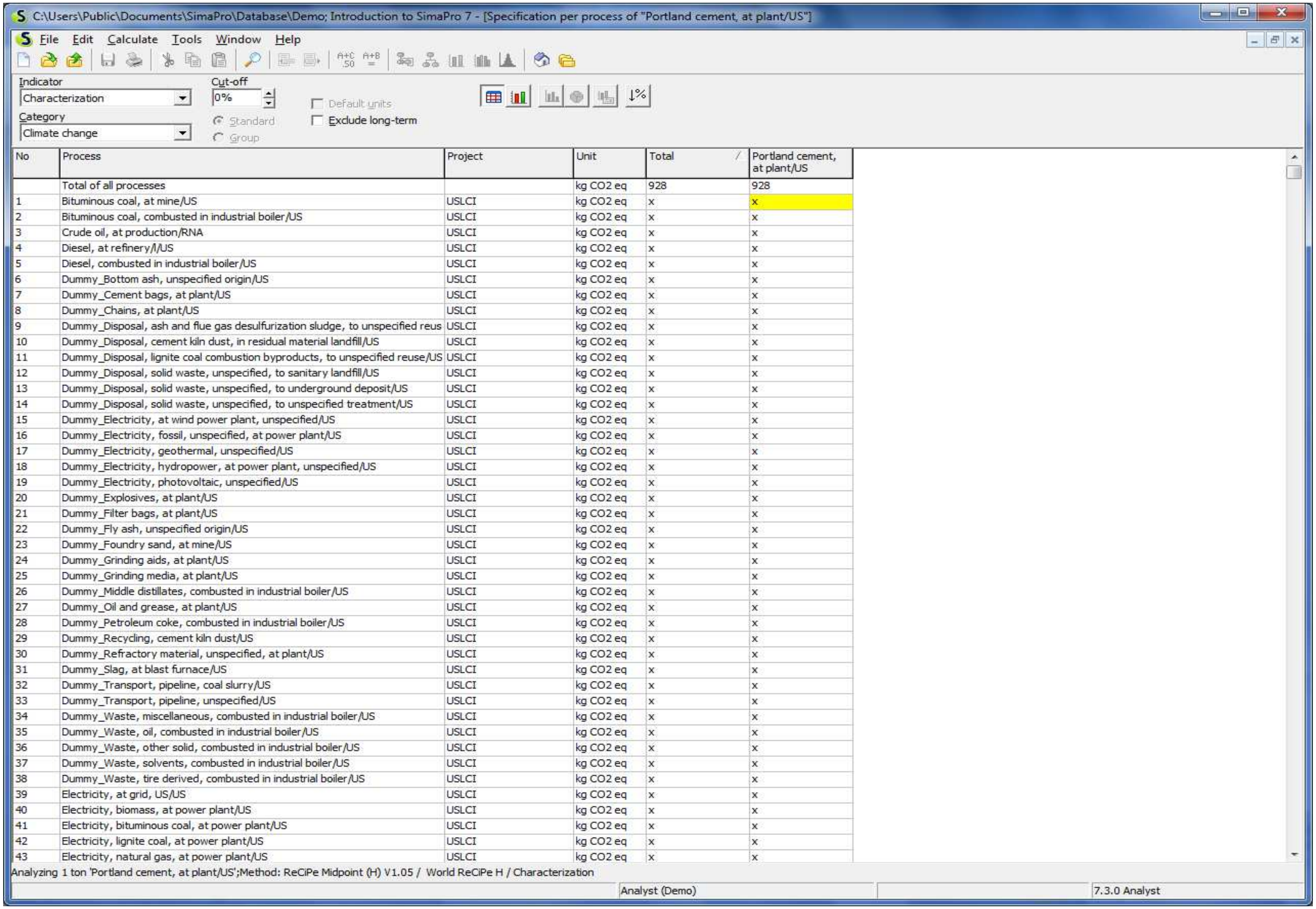


Figure 4.4: Impact Assessment Phase (The text is not meant to be readable, but for visual reference only)



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 4.5: Impact Assessment Phase (The text is not meant to be readable, but for visual reference only)

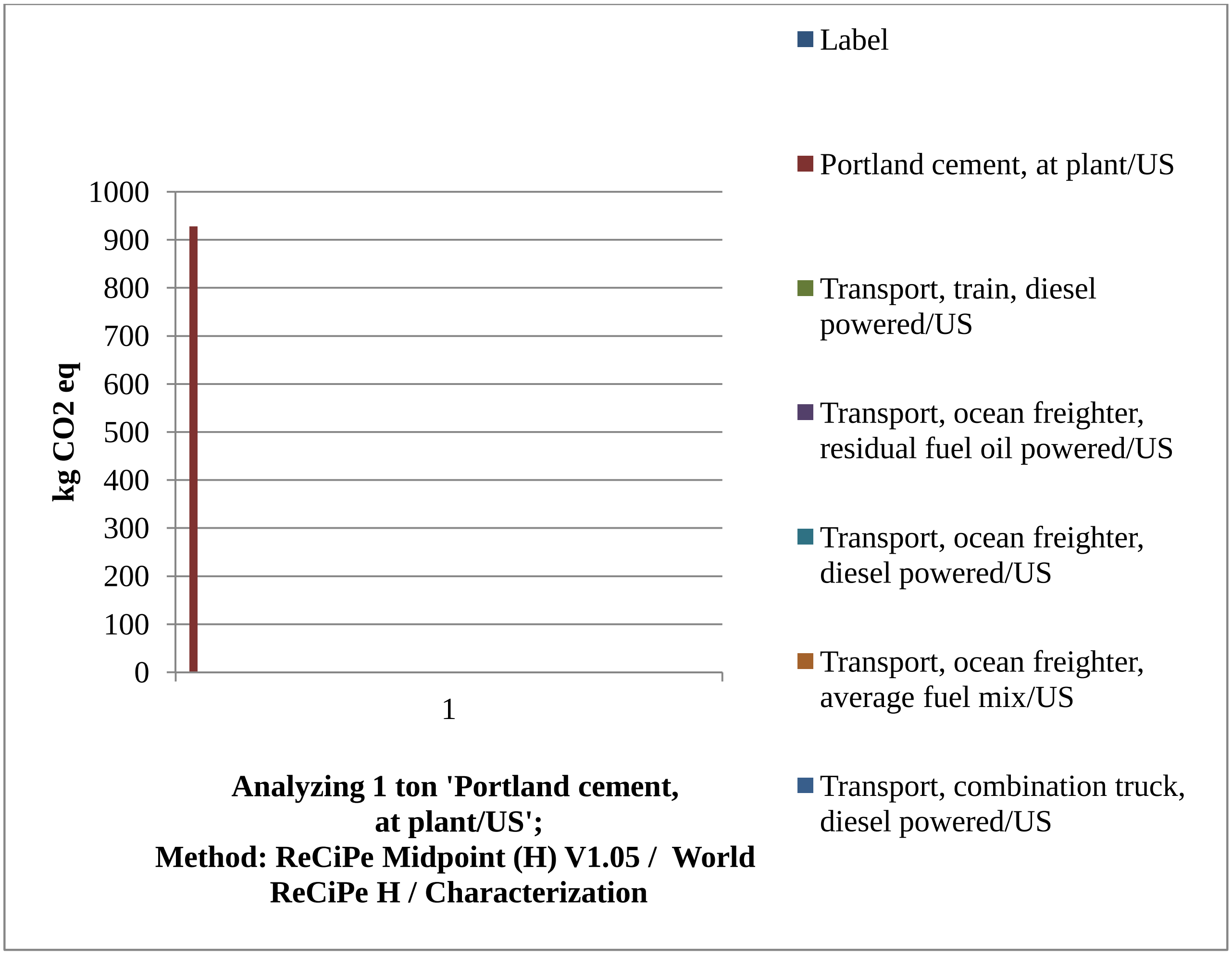


Figure 4.6: Cradle to Gate Analysis of 1-Ton Portland Cement (Pre-Consultants, 2012)

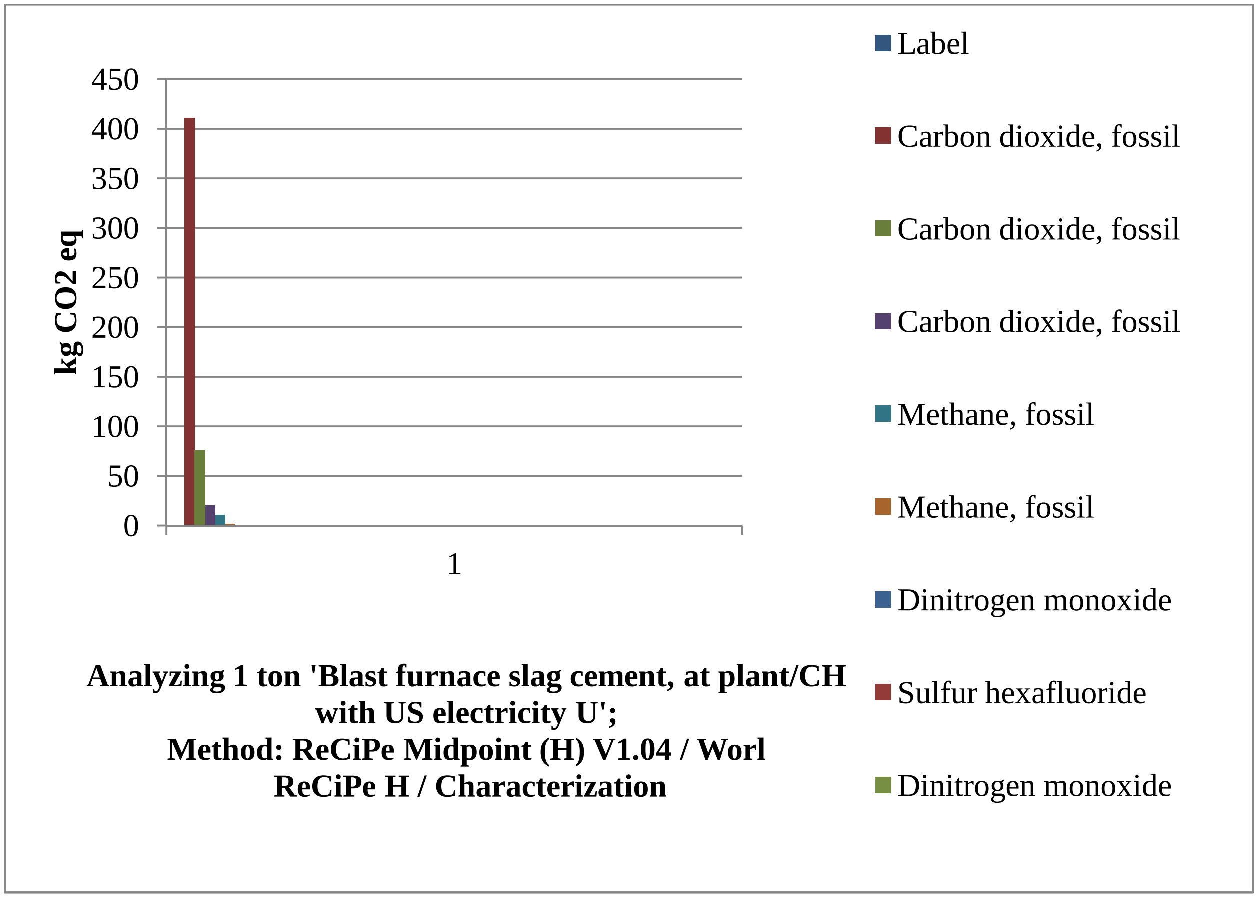


Figure 4.7: Cradle to Gate Analysis of 1-Ton Blast Furnace Slag Cement (Pre-Consultants, 2012)

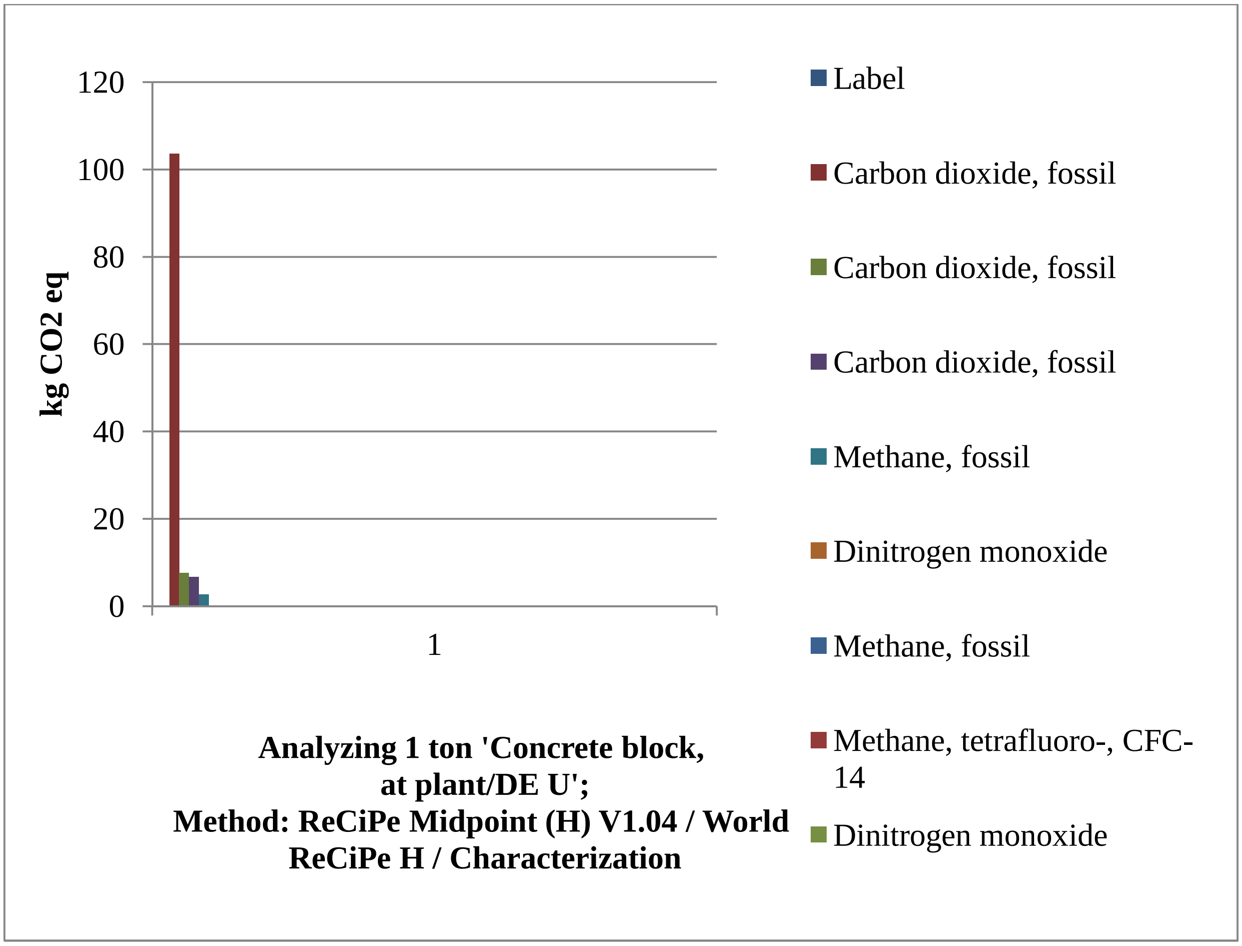


Figure 4.8: Cradle to Gate Analysis of 1-Ton Concrete Block (Pre-Consultants, 2012)

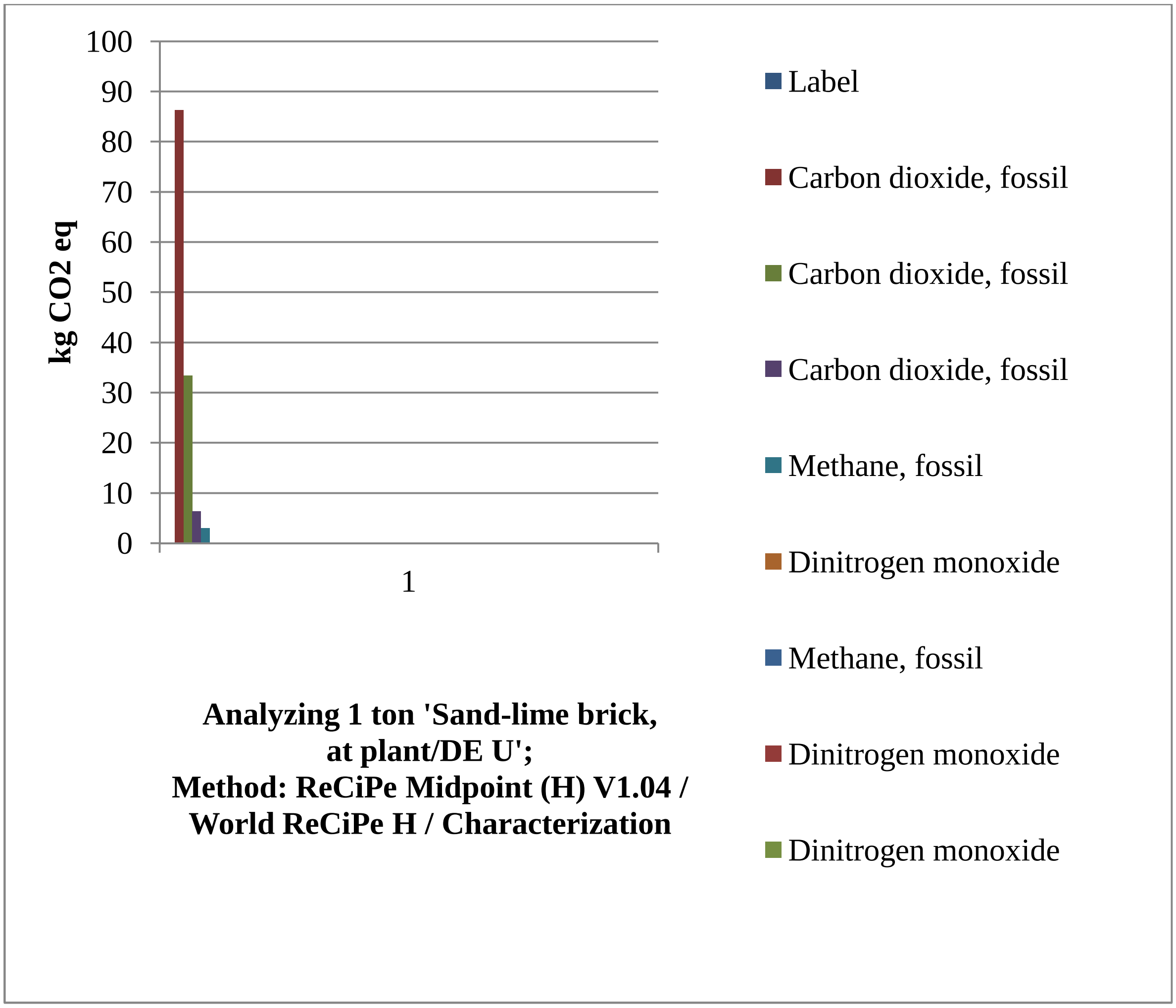


Figure 4.9: Cradle to Gate Analysis of 1-Ton Sand-Lime Brick (Pre-Consultants, 2012)

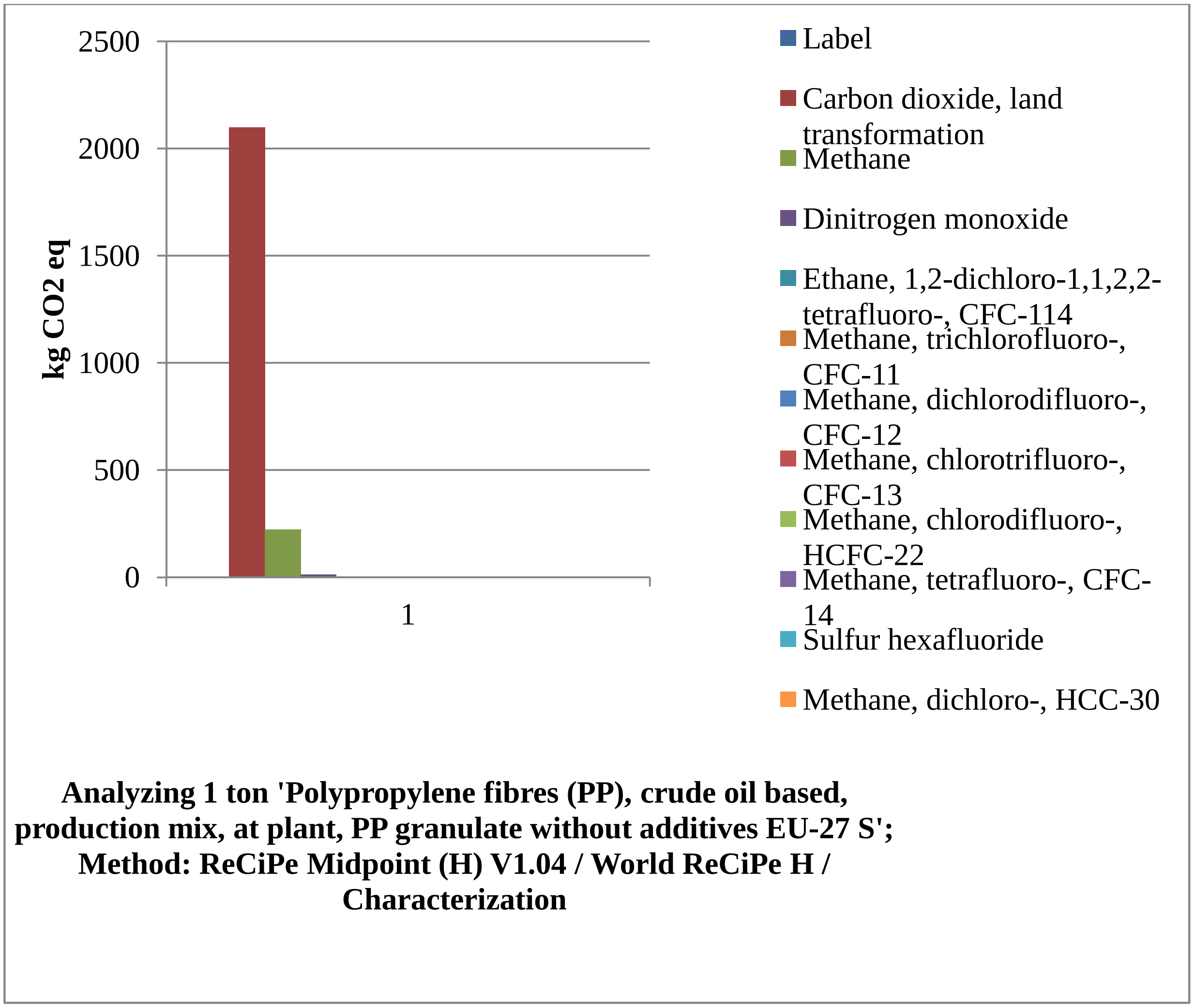


Figure 4.10: Cradle to Gate Analysis of 1–Ton Polypropylene Fibers (Pre-Consultants, 2012)

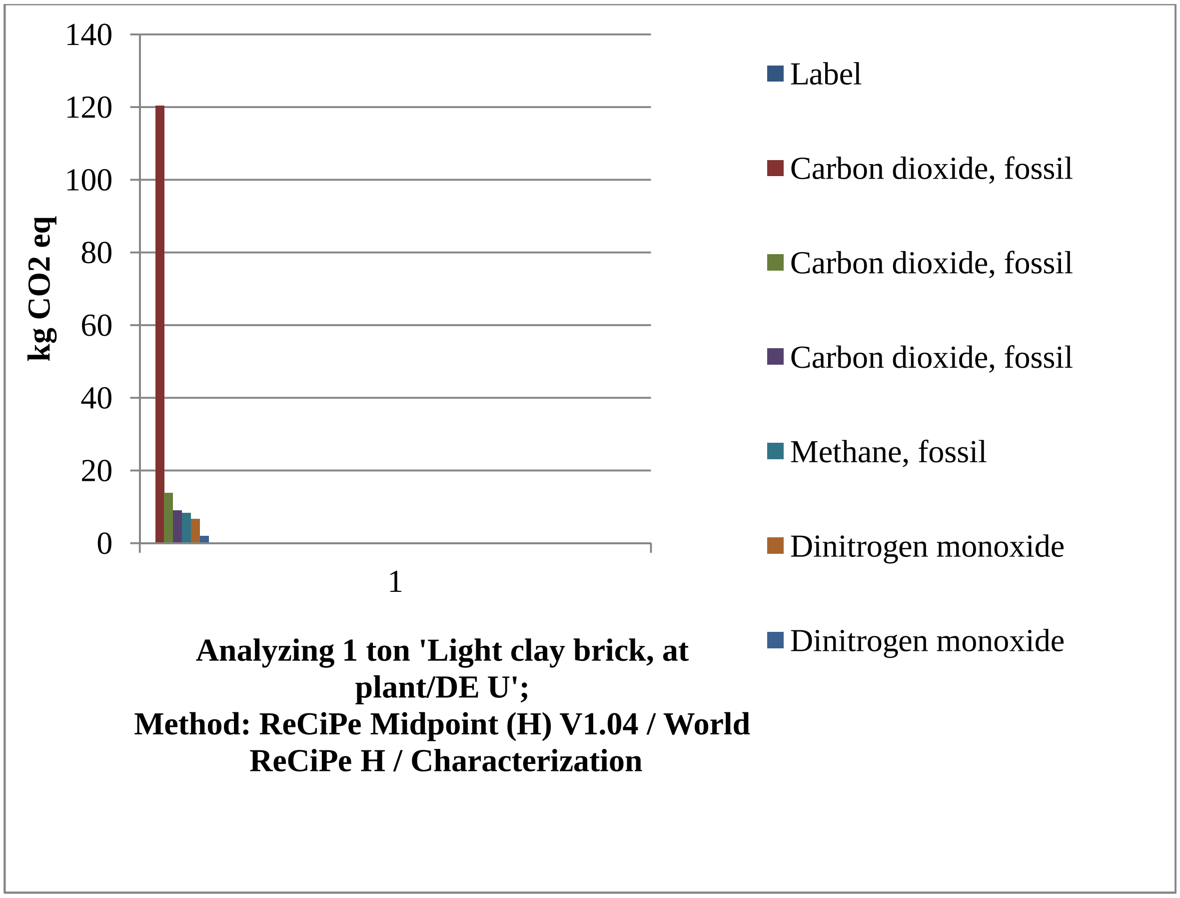


Figure 4.11: Cradle to Gate Analysis of 1-Ton Light Clay Brick (Pre-Consultants, 2012)

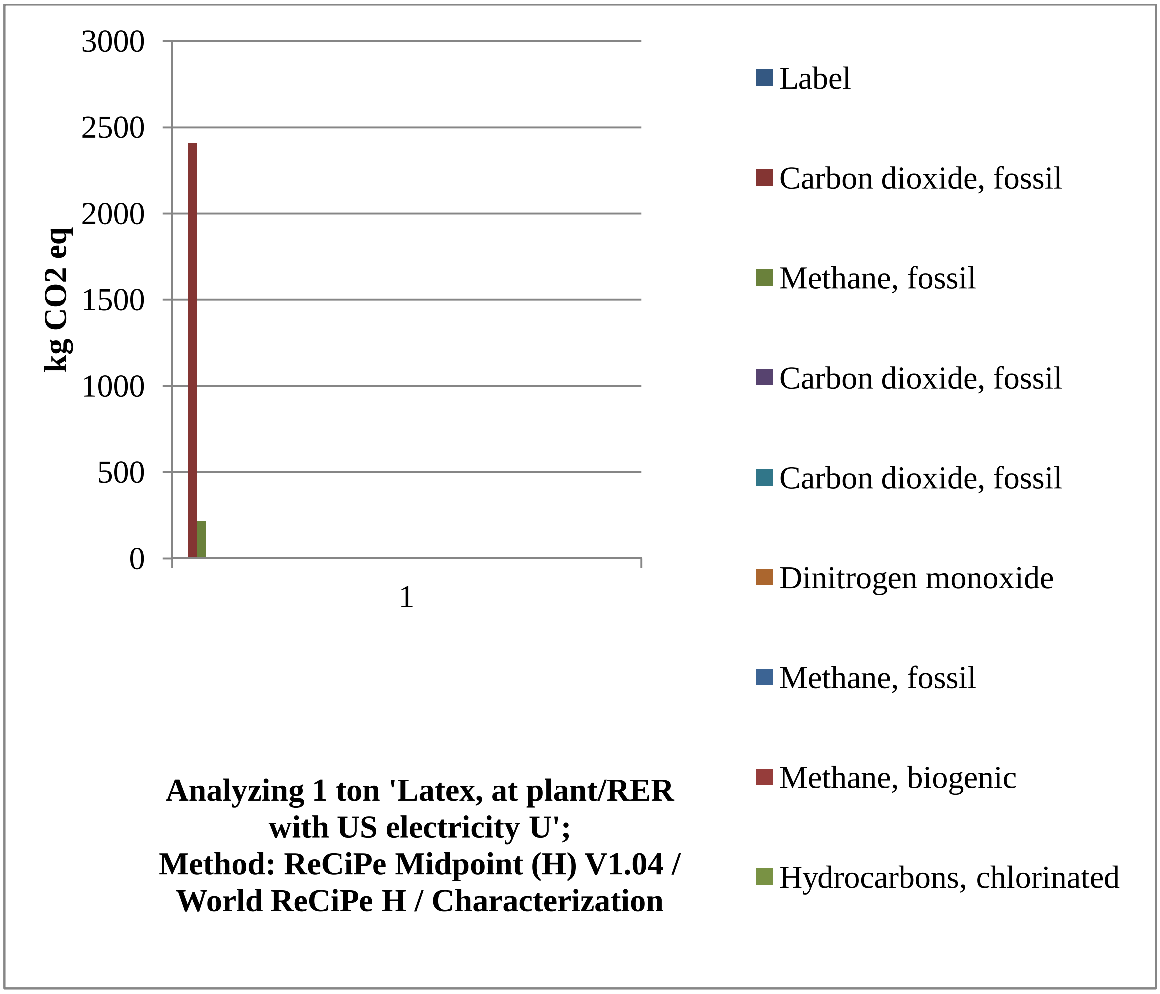


Figure 4.12: Cradle to Gate Analysis of 1-Ton Latex (Pre-Consultants, 2012)

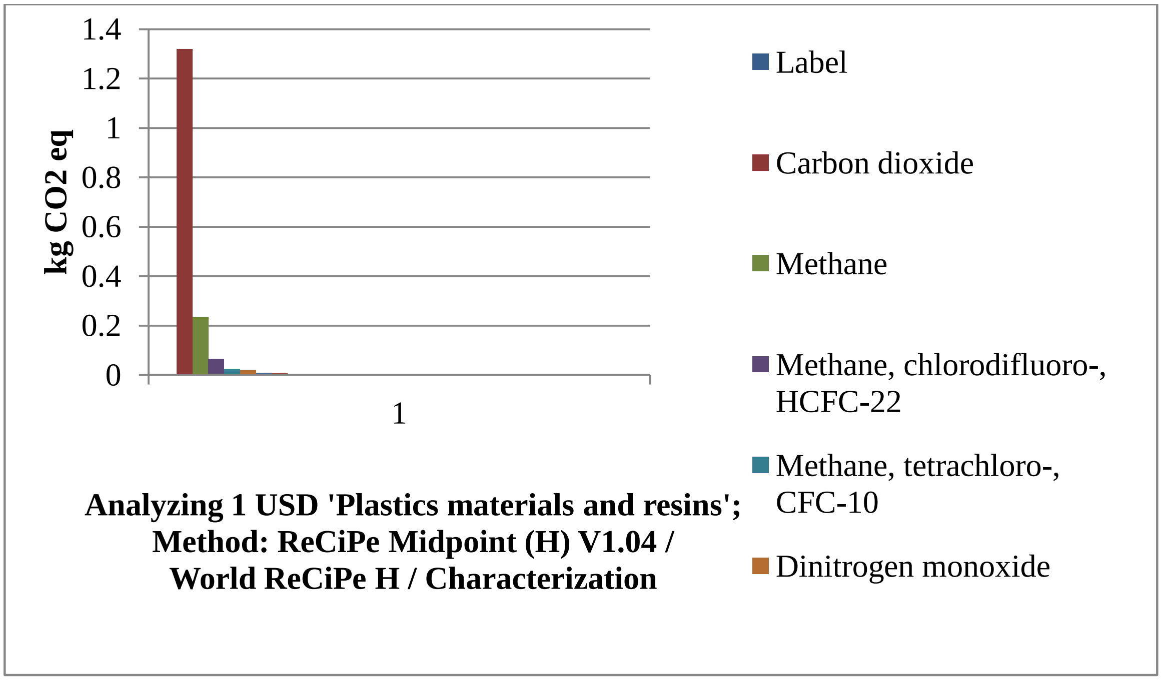


Figure 4.13: Cradle to Gate Analysis of 1-Ton Plastic Materials and Resins (Pre-Consultants, 2012)

Table 4.1: Emission Factors Obtained Using SimaPro (Pre-Consultants, 2012)

Product	Unit	Emission Factor (MT eq. CO_2)
Portland Cement	Ton	.928
Blast Furnace Slag Cement	Ton	.522
Concrete Block	Ton	.121
Sand Lime Brick	Ton	.13
Polypropylene Fibers	Ton	2.33
Light Clay Bricks	Ton	.161
Latex	Ton	2.63
Plastics and Resins	Ton	.00168
Portland Slag Cement	Ton	.776

4.4 GHG Emissions Calculation Guidelines

In order to develop LCA guidelines for the 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 (refer to the format. xlsx) 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 & 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. 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 list the recommended sustainable products from the framework.

Use material estimator show in Table 4.2 for calculating GHG emissions from various materials. Input the quantity of materials corresponding the material selected to determine emissions from that material.

Use equipment estimator from the project estimator tool developed by Mukherjee & Cass (2011) for calculating GHG emissions from various equipment. It is required to enter the number of equipment and the estimated hours of usage of the equipment corresponding to the equipment of selected to calculate GHG emissions from that equipment. All the emissions will sum up which will be the benchmark emissions for the project. At the end of the project, use 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 & Cass, 2012). Investigate strategies to identify alternative products and processes to reduce GHG emissions of products, which 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 4.3 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 4.2: 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 & 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 & Cass, 2011)
Aggregates 21A	Ton	1	0.0061	0.0061	(Mukherjee & Cass, 2011)
Aggregates 21AA	Ton	1	0.0061	0.0061	(Mukherjee & Cass, 2011)
Aggregates 21AA Crushed Concrete	Ton	1	0.0021	0.0021	(Mukherjee & Cass, 2011)
Aggregates 22A	Ton	1	0.0061	0.0061	(Mukherjee & Cass, 2011)
Aggregates 22A Crushed Concrete	Ton	1	0.0021	0.0021	(Mukherjee & Cass, 2011)
Aggregates 22A (For Temp Use Only)	Ton	1	0.0061	0.0061	(Mukherjee & Cass, 2011)

Table 4.2 (cont'd)

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

Table 4.2 (cont'd)

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

Table 4.2 (cont'd)

Section 903 (Admixtures and Curing Materials for Concrete)					
White Membrane Curing Compound for Bridge Decks	Gal	1	0.01255	0.01255	(Mukherjee & Cass, 2011)
Non-Chloride Accelerator	Cft	1	NanoMT	NanoMT	(Mukherjee & 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 & Cass, 2011)
Emulsified Asphalt	Gal	1	0.0071	0.0071	(Mukherjee & Cass, 2011)
Material	**Unit**	**Quantity**	**Emission Factor**	**Emissions (MT CO_2 Eq.)**	**Remarks/Details**
Emulsified Asphalt CSS-1hM	Gal	1	0.0071	0.0071	(Mukherjee & Cass, 2011)
Ashpalt emulsion Chip Seal	Gal	1	0.0071	0.0071	(Mukherjee & Cass, 2011)
Asphalt Emulsion CSS-1hM	Gal	1	0.0071	0.0071	(Mukherjee & Cass, 2011)
Asphalt Emulsion CSS-1mM	Gal	1	0.0071	0.0071	(Mukherjee & Cass, 2011)
Asphalt Emulsion HFRS-2M	Gal	1	0.0071	0.0071	(Mukherjee & Cass, 2011)
Asphalt Emulsion RC-250	Gal	1	0.0071	0.0071	(Mukherjee & Cass, 2011)
Section 905 (Steel Reinforcement)					
Dowel Bar	Ea	1	0.001627	0.001627	(Mukherjee & Cass, 2011)

Table 4.2 (cont’d)

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

Table 4.2 (cont'd)

Structural Steel Pin and Hangers	Cft	1	0	0	(Mukherjee & Cass, 2011)
Section 907 (Fencing Materials)					
Barbed Wire	Cft	1	NanoMT	NanoMT	(Mukherjee & Cass, 2011)
Fence Chain Link (ft)	Ft	1	0.0092	0.0092	(Mukherjee & Cass, 2011)
Fence Gate Chain Link	Cft	1	NanoMT	NanoMT	(Mukherjee & Cass, 2011)
Fence Post Chain Link Corner	Ea	1	0.0722	0.0722	(Mukherjee & Cass, 2011)
Fence Post Chain Link Line	Ea	1	0.0722	0.0722	(Mukherjee & Cass, 2011)
Fence Post Steel	Ea	1	0.0722	0.0722	(Mukherjee & Cass, 2011)
Fence Post Steel Woven Wire	Ea	1	0.0722	0.0722	(Mukherjee & Cass, 2011)
Fence Post Wood	Ea	1	0.0066	0.0066	(Mukherjee & Cass, 2011)
Protective Fence	Ft	1	0	0	(Mukherjee & Cass, 2011)
Fence Woven Wire	Ft	1	0.0092	0.0092	(Mukherjee & Cass, 2011)

Table 4.2 (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 & Cass, 2011)
Bushings	Ea	1	0	0	(Mukherjee & Cass, 2011)
Steel Beam Guardrail	Ft	1	0.0656	0.0656	(Mukherjee & Cass, 2011)
Gaurdrail Approach Terminal 1 B	Cft	1	NanoMT	NanoMT	(Mukherjee & Cass, 2011)
Gaurdrail Approach Terminal 1 T	Ea	1	0	0	(Mukherjee & Cass, 2011)
Gaurdrail Approach Terminal 2 B	Cft	1	NanoMT	NanoMT	(Mukherjee & Cass, 2011)
Gaurdrail Approach Terminal 2 T	Cft	1	NanoMT	NanoMT	(Mukherjee & Cass, 2011)
Gaurdrail Reflectorized Washers	Ea	1	0	0	(Mukherjee & Cass, 2011)
Sleeve Steel	Ea	1	0	0	(Mukherjee & Cass, 2011)
Section 909 (Drainage Products)					
End Section Concrete	Ea	1	0.802	0.802	(Mukherjee & Cass, 2011)
End Section Metal	Ea	1	1.1995	1.1995	(Mukherjee & Cass, 2011)
End Section Grate	Lbs	1	0.0003	0.0003	(Mukherjee & Cass, 2011)
Pipe Cl A	Ft	1	0.1464	0.1464	(Mukherjee & Cass, 2011)

Table 4.2 (cont'd)

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

Table 4.2 (cont'd)

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

Table 4.2 (cont'd)

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

Table 4.2 (cont'd)

Conduit	Cft	1	NanoMT	NanoMT	(Mukherjee & Cass, 2011)
High Intensity Light	Ea	1	0	0	(Mukherjee & Cass, 2011)
Section 919 (Permanent Traffic Sign and Support Materials)					
Reflective Sheeting Material	Cft	1	NanoMT	NanoMT	(Mukherjee & Cass, 2011)
Dileneator Reflector	Cft	1	NanoMT	NanoMT	(Mukherjee & Cass, 2011)
Temporary sign	Sft	1	0	0	(Mukherjee & Cass, 2011)
Sign Cover	Ea	1	0	0	(Mukherjee & Cass, 2011)
Section 920 (Permanent Pavement Marking Materials)					
Pavement Marking Glass Beads	Lbs	1	0.0004	0.0004	(Mukherjee & Cass, 2011)
Pavement Marking Poly Blend-Glass Beads	Lbs	1	0.0004	0.0004	(Mukherjee & Cass, 2011)
Pavement Marking Polyurea	Gal	1	0.059	0.059	(Mukherjee & Cass, 2011)
Pavement Marking Polyurea White	Lbs	1	0.0071	0.0071	(Mukherjee & Cass, 2011)
Pavement Marking Polyurea Yellow	Lbs	1	0.0071	0.0071	(Mukherjee & Cass, 2011)
Reflective Marker	Cft	1	NanoMT	NanoMT	(Mukherjee & Cass, 2011)
Thermoplastic	Lbs	1	0.0071	0.0071	(Mukherjee & Cass, 2011)

Table 4.2 (cont'd)

Concrete Barrier Temporary	Ea	1	0	0	(Mukherjee & Cass, 2011)
Drum Plastic	Ea	1	0	0	(Mukherjee & 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					

4.5 Case Study

4.5.1 Overview

GHG emission tool developed in the study can be used to compare different alternatives and choose the best one which has the lower 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 superstructure. This case study compares two bridge decks one using conventional concrete bridge deck and the other using Fiber Reinforced Polymer (FRP) bridge deck.

4.5.2 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 4.3 using National Bridge Inventory (NBI) website (NBI, 2012).

Table 4.3: 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 %

4.5.3 Design Alternatives

This case study considered two alternatives: Table 4.4 below shows a comparison between conventional concrete mix and alternative blast furnace slag cement concrete mix.

Table 4.4: 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

4.5.4 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

4.5.5 GHG Emission Calculation

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

Table 4.5: 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 Steel	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 4.6: Case Study: GHG Emissions from Transportation

Material	Unit	Type of Transport	Transportation Distance	Emissions

b) Emissions due to transportation of products to site

Table 4.7: 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 4.8: 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	

4.5.6 Results

The emissions due to material are calculated based on emission factor method as shown in Table 4.7. 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 of landfill from the site, type of transport and the total distance travelled. It is required to determine the emissions due to vehicle travelling unit distance. The emission due to transportation can then calculated by multiplying the total distance travelled 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.

4.6 LCA Matrix for the Framework

The LCA matrix shown Figure 4.14 to 4.18 shows that 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 LCA matrix to determine the impact of each criteria. The factor that each value represent is shown in Table 4.11

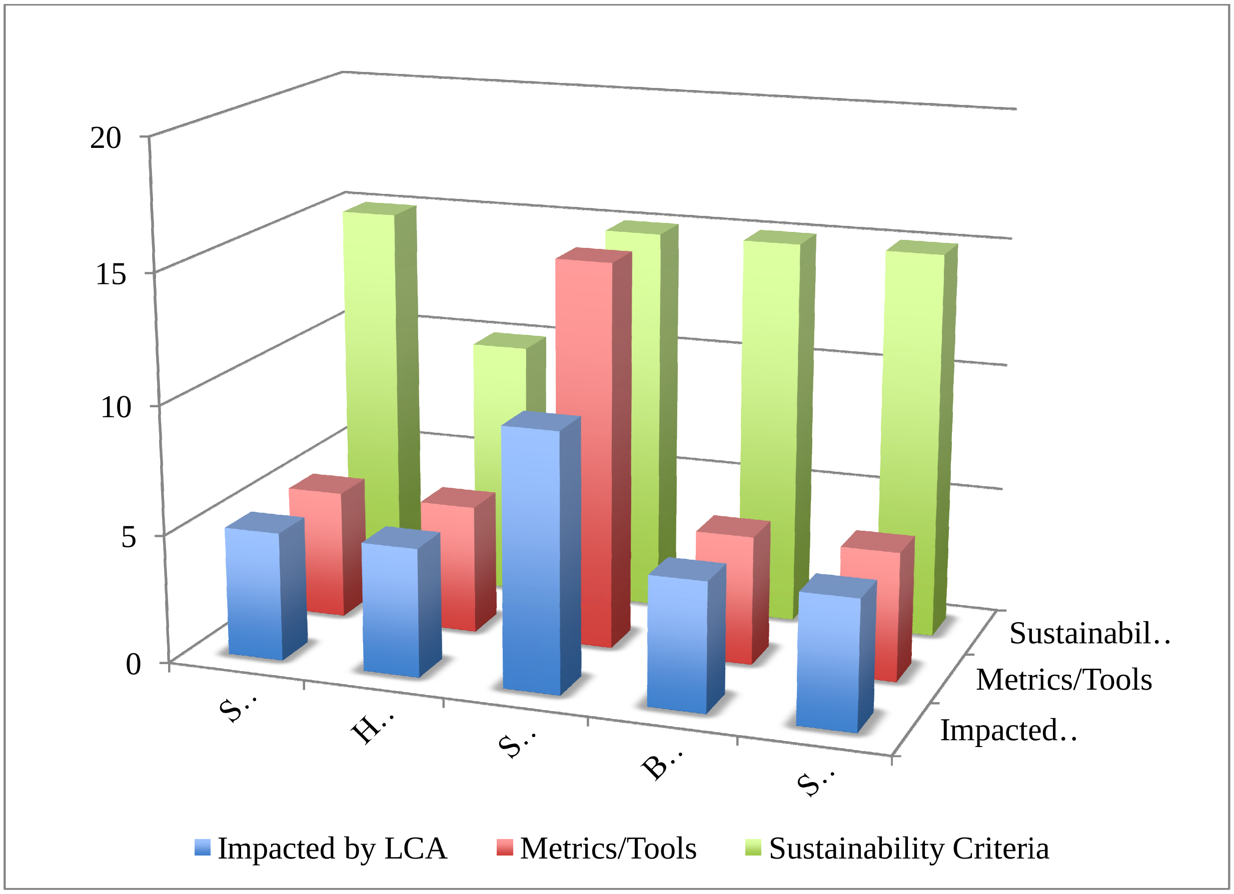


Figure 4.14: Design-Sites Category LCA Matrix

Table 4.9: 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

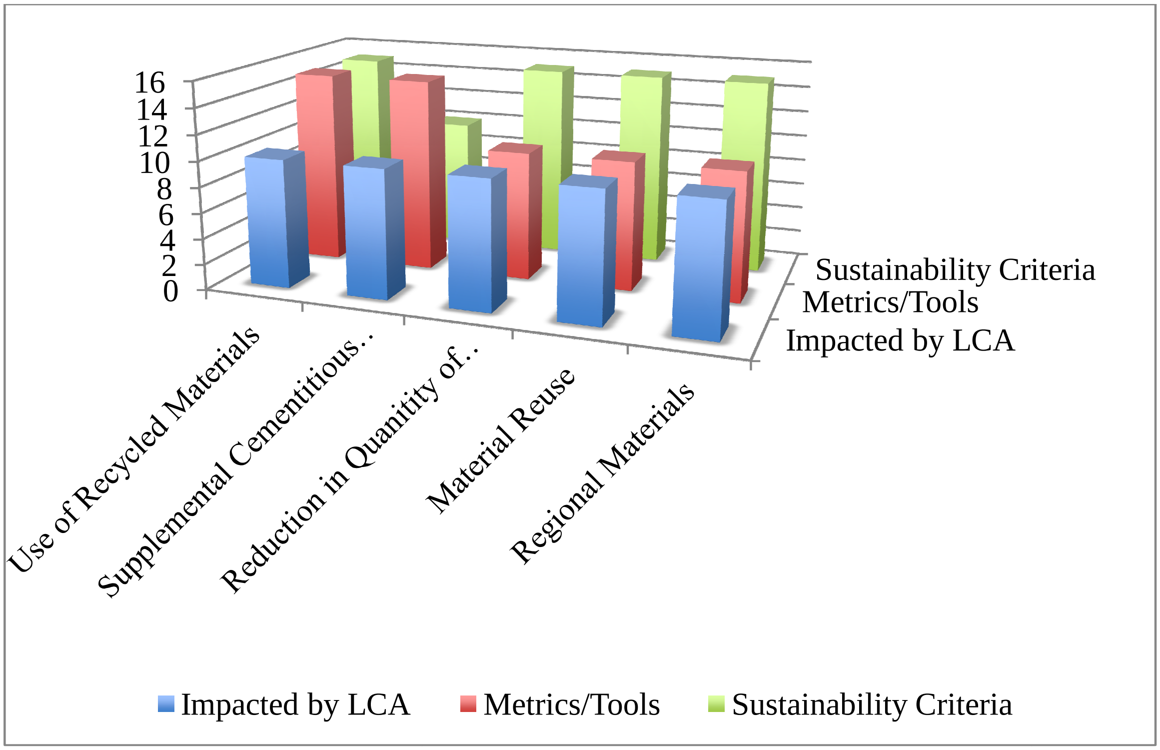


Figure 4.15: Design-Materials Category LCA Matrix

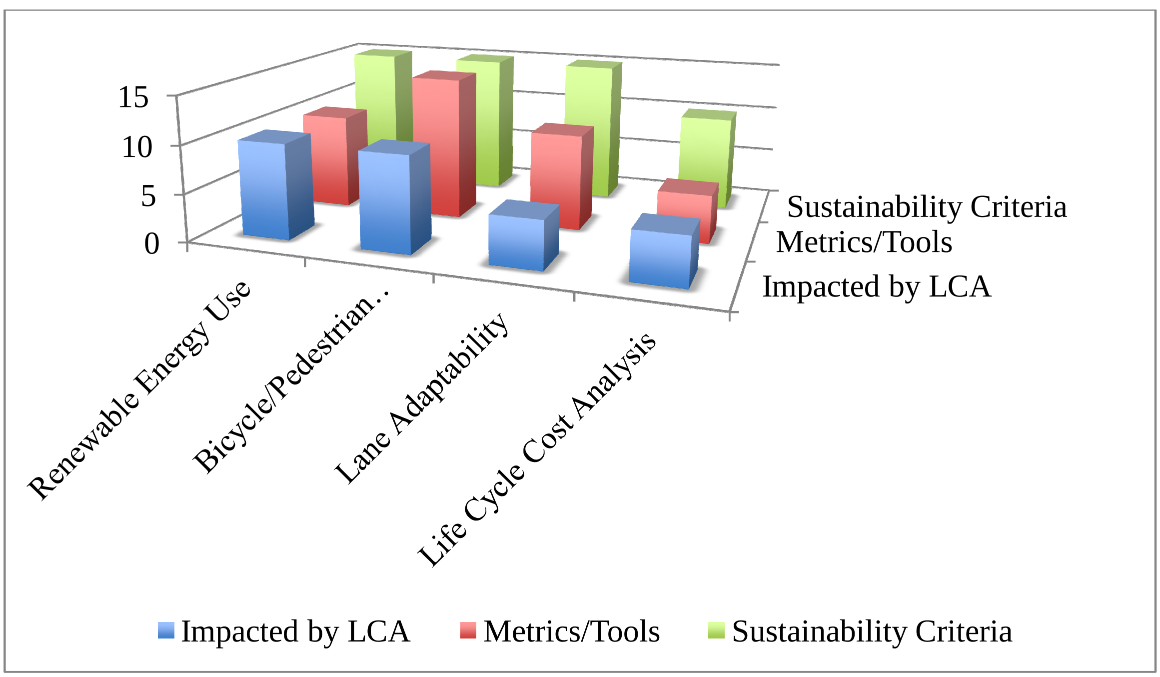


Figure 4.16: Design-Other Category LCA Matrix

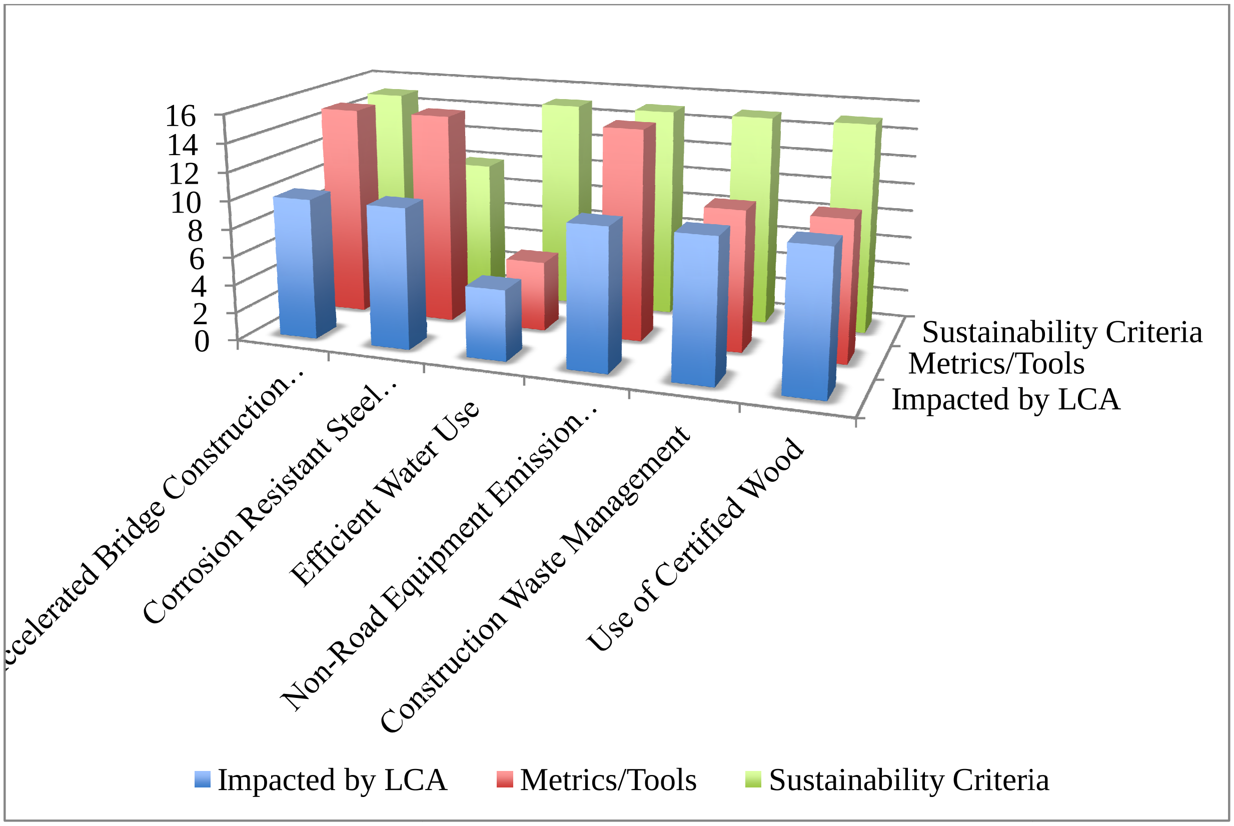


Figure 4.17: Construction Category LCA Matrix

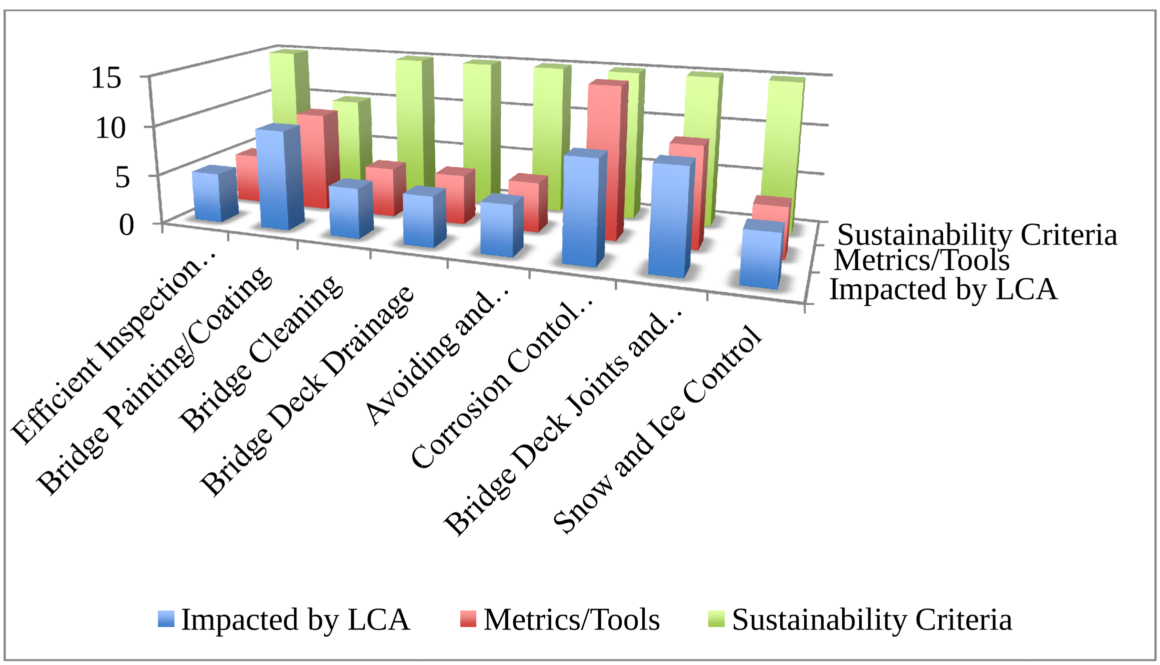


Figure 4.18: Maintenance Category LCA Matrix

CHAPTER 5

RESULTS/CONCLUSIONS/LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Results and Conclusions

The focus of this report was to develop a framework that will assist 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 this study, following results were obtained:

a) Sustainable practices were synthesized which can be used in bridge construction projects.

b) A framework is 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. The details of the design category can be found in MS thesis completed by Awan (2012), which is based on the research work for MDOT titled as "Implementation of Sustainability in Bridge Design, Construction and Maintenance (MDOT, 2012). The 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 conducted by Awan (2012) at MDOT divisions. It is found that Design category carries 47% weightage, construction category carries 31% weightage and maintenance category carries 22% weightage.

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) Excel based tool is developed which consist of material estimator to compute GHG emissions from materials and equipment estimator to compute GHG emissions from equipment.

5.2 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) Life cycle Assessment methodology is focused to assess global warming impact potential and ignores other impact categories.

e) Survey results are used to quantify the rating system and do not use scientific LCA approach.

f) Estimated emission factors may have been taken using old databases and records.

5.3 Recommendations for the 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 like snow and ice control may not be required for other DOT, 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 DOT to meet their own conditions and needs.

2. Quantify the rating system using 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 large collection of data. This is very time consuming process and also due to data availability constraints complete LCA was not performed to quantify the rating system. It is recommended to use 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 on the environment**.** This will help in assessing the overall impact of each criterion across all the 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, rating system was not applied on 20-30 different bridge case studies as due lack of time and data availability constraints. Methodology for determining certification levels used in 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 for attainment to each successive level (NYSDOT, 2008).

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