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A Decision Making Tool for Incorporating Sustainability Measures in Rigid Pavement Design

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A DECISION MAKING TOOL FOR INCORPORATING SUSTAINABILITY
MEASURES
IN RIGID PAVEMENT DESIGN

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
In partial fulfillment of the requirements of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Construction Management

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TABLE OF CONTENTS

ACKNOWLEDGMENTS.....	ii
DEFINITIONS.....	v
ABBREVIATIONS AND ACRONYMS.....	vii
ABSTRACT.....	x
 CHAPTER 1. INTRODUCTION.....	 1
1.1 PROBLEM STATEMENT AND RESEARCH QUESTIONS	5
1.2 GOAL AND OBJECTIVES	6
1.3 RESEARCH APPROACH AND IMPLEMENTATION	7
1.4 CONTRIBUTION TO THE BODY OF KNOWLEDGE.....	11
1.5 REFERENCES.....	11
 CHAPTER 2. LITERATURE REVIEW.....	 13
2.1 INTRODUCTION.....	13
2.2 LIFECYCLE ASSESSMENT (LCA)	14
2.3 PAVEMENT LIFECYCLE PHASES.....	25
2.4 SUSTAINABILITY RATING TOOLS	69
2.5 ENVIRONMENTAL ASSESSMENT.....	73
2.6 SOCIAL LIFECYCLE ASSESSMENT (SLCA)	75
2.7 PERFORMANCE ASSESSMENT MEASURES	76
2.8 LIFECYCLE COST ANALYSIS (LCCA).....	77
2.9 PAVEMENT DESIGN AND SUSTAINABILITY	90
2.10 SUMMARY	96
2.11 REFERENCES.....	97
 CHAPTER 3. NEW FRAMEWORK AND ASSOCIATED DATA COLLECTION PROCESS.....	 114
3.1 INTRODUCTION.....	114
3.2 EXISTING VS. PROPOSED PAVEMENT DESIGN FRAMEWORK	114
3.3 MODULE 1: ENVIRONMENTAL DATA COLLECTION PROCESS	119
3.4 MODULE 2: ECONOMIC IMPACT	134
3.5 DISCOUNT RATE FOR LIFECYCLYE COST ANALYSIS	142
3.6 DATA OUTPUT FROM CHAPTER 3	144
3.7 SUMMARY	144
3.8 REFERENCES.....	147
 CHAPTER 4. IMPLEMENTATION.....	 150
4.1 INTRODUCTION.....	150
4.2 ALTERNATIVE DESIGN COMPARISON MODULE	150
4.3 SOFTWARE DEMONSTRATION	173
4.4 STUDY SIGNIFICANCE: THE BIGGER PICTURE. HOW CAN THIS FRAMEWORK BE USED IN THE REAL WORLD?	181
4.5 SUMMARY	184

4.6	REFERENCES.....	184
CHAPTER 5. DEMONSTRATION OF THE DEVELOPED FRAMEWORK IN CASE STUDIES.....186		
5.1	INTRODUCTION.....	186
5.2	CASE STUDIES IN TEXAS	186
5.3	CASE STUDIES IN LOUISIANA	207
5.4	SUMMARY	287
5.5	REFERENCES.....	288
CHAPTER 6. FINDINGS, CONCLUSION, DISCUSSION, AND FUTURE WORK.....290		
6.1	DISCUSSION	294
6.2	STUDY LIMITATIONS.....	296
6.3	FUTURE WORK	297
APPENDIX A. INDIVIDUAL EPD COMPILATION.....300		
APPENDIX B. INDUSTRY WIDE AVERAGE EPD COMPILATION.....310		
APPENDIX C. SURVEY PERFORMED IN LOUISIANA AND ASSOCIATED RESULTS.....315		
APPENDIX D. RESULTS OF LOUISIANA SURVEY AND DEVELOPED EPD FOR LOUISIANA.....327		
APPENDIX E. INVENTORY VALUES FOR TRUCKS USED IN THE TRANSPORTATION MODULE.....342		
APPENDIX F. LCCA FOR TEXAS.....344		
VITA.....346		

DEFINITIONS

Average data	These are average data points across a number of products, material or process, in case the data comes from more than one supplier.
Characterization factor	A factor extracted from a characterization model and used to convert a lifecycle inventory into a category indicator
Characterization	The process where the lifecycle inventory data are transformed into indicators of impact to human and ecological health. The characterization step allows a comparison of the lifecycle inventory inside each impact category;
Cradle to gate	A part of the lifecycle of a product from the extraction process (cradle) to the gate (the point where the material leaves the factory before inputs as another material into the manufacturing process.
Declared unit	A unit used when the function and the reference unit in the whole lifecycle of the product cannot be determined (ISO 21930)
Eco-label	An Environmental Declaration or label providing information about a product or a service in terms of its environmental performance or specific environmental traits. Eco-labels have various forms, such as statement, symbol, or graphic forms.
Environmental Product Declaration	A claim made to represent the environmental traits of a product or service. It should be noted that an environmental label can take various forms, such as a statement, a symbol, or a graphic (ISO 10420) form.
Equivalent unit	Numerous emissions get in the characterization for the same unit. For example, 1 g N ₂ O contributes as much to the global warming as 310 g CO ₂ . Therefore the 1 g N ₂ O is equal to 310g CO ₂ -equivalents.
Functional unit	The process that defines the service that needs to be delivered by a product.
Impact category	A category representing environmental issues of a concern. The lifecycle inventory results can therefore be assigned to these

Lifecycle assessment (LCA)	environmental categories. The process of evaluating the potential environmental impact of a product through its entire lifecycle (ISO 14040).
Lifecycle inventory	A part of the lifecycle assessment where the quantification and compilation of inputs and outputs for a product throughout the entire lifecycle occur.
Normalization	Expressing the environmental impacts in a manner which can be compared.
Product category	A set of products that can satisfy the same function (ISO 14025).
Product category rule	Specific rules and guidelines to develop Environmental Declaration Type III for a product category (ISO 14025).
System boundary	Principles specifying the unit processes that should be included in a product system.
Third party	A person, body, or entity that is independent of the parties involved. In most of the cases, the parties involved are the supplier and the purchaser.
Type III Environmental Declaration	This is quantified environmental data using a pre-defined set of categories. Also, there is additional environmental information that can be included. The additional set of information is based on ISO 14040 and ISO 14044.
Upstream process	The process of concrete material production which is outside the concrete facility.

ABBREVIATIONS AND ACRONYMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ACEC	American Council of Engineering Companies
ADOT	Arizona Department of Transportation
AP	Acidification Potential
APWA	American Public Works Association
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
BCA	Benefit Cost Analysis
Caltrans	California Department of Transportation
CBW	Concrete Batching Water
CDOT	Colorado Department of Transportation
CEQ	Council on environmental Quality
CE _x C	Net Exergy Consumption
CFC-11	Trichlorofluoromethane
CH ₄	Methane
Cl	Chloride
CO	Carbon Monoxide
CO ₂	Carbon dioxide
CO ₃	Construction Congestion Cost
CO ₄	Carbon tetroxide
CRCP	Continuously Reinforced Concrete Pavement
CWW	Concrete Washing Water
DelDOT	Delaware Department of Transportation
DOT	Department of Transportation
EC	Total Primary Energy Consumption
EconW	Economic Weight
EIS	Environmental Impact Statements
EnvW	Environmental Weight
EOL	End Of Life
EP	Eutrophication Potential
EPA	Environmental Protection agency
EUAC	Equivalent Uniform Annual Cost
FHWA	Federal Highway Administration
GHG	Green House Gases
GWP	Global Warming Potential
H ₂ SO ₄	Sulfuric Acid
HMA	Hot Mix Asphalt
HW	Hazardous Waste
ICC	Internally Cured Concrete
IO-LCA	Input Output LCA

IRI	International Roughness Index
ISO	International Standards Organization
JPCP	Jointed Plain Concrete Pavement
LaDOTD	Louisiana Department of Transportation and Development
lb	Pounds
LCA	Lifecycle Assessment
LEED	Leadership in Energy and Environmental Design
L _L	Layer length
L _T	Layer thickness
L _w	Layer width
LWC	Lightweight Aggregate Concrete
m	Meter
MDOT	Minnesota Department of Transportation
MEPDG	Mechanistic Empirical Pavement Design Guide
MJ	Mega joules
MOR	Modulus of Rupture
N	Nitrogen
N ₂ O	Nitrous Oxide
NEPA	National Environmental Policy Act
NHW	Non Hazardous Waste
NIST	National Institute of Standards and Technology
NO _x	Nitrogen Oxide
NPV	Net Present Value
NRE	Non Renewable Energy
NRMCA	The National Ready Mix Concrete Association
NRMR	Depletion of Non Renewable Material Resources
NYSDOT	New York State Department of Transportation
O ₃	Ozone
ODOT	The Ohio Department of Transportation
ODP	Ozone Depletion Potential
Oz	Ounces
Pb	Lead
PCC	Portland Cement Concrete
PCR	Product Category Rule
PM ₁₀	Particulate Matter (10 micrometers or less in diameter)
PM _{2.5}	Particulate Matter (2.5 micrometers or less in diameter)
POCP	Photochemical Ozone Creation Potential
Psi	Pound per square inch
RE	Renewable Energy
RMR	Use of Renewable Material Resources
RPE	Use of Renewable Primary Energy
RPLCCA	Rigid Pavement Lifecycle Cost Analysis
SAB	Science Advisory Board
SCM	Supplementary Cementitious Material

SETAC	Society of Environmental Toxicology and Chemistry
SLCA	Social Lifecycle Assessment
SMA	Stone Mastic Asphalt
SO ₂	Sulfur Dioxide
STARS	Sustainability Tracking, Assessment & Rating System
TxDOT	The Texas Department of Transportation
U.S	United States
VOC	Volatile Organic Compounds
WFL	Western Federal Lands
WSDOT	Washington Department of Transportation
yd	Yard

ABSTRACT

One of the most important tools in assessing rigid pavement design sustainability (or environmental impact) is a lifecycle assessment (LCA), which may be applied in any stage of a product's lifecycle from cradle to grave, such as pavements. Although LCA was the focus of much research and codification by organizations such as the International Organization for Standards and the Society of Environmental Toxicology and Chemistry, limitations exist, such as a) LCA is time consuming; and b) the used data may become outdated, inaccurate, biased, incomplete, and/or expensive to use. These limitations are not a deficiency in LCA as a tool, but in the manner in which various researchers apply the limitations differently.

The objective of this study is to develop a methodology to assess rigid pavement sustainability using Environmental Product Declarations (EPDs) as a quantification tool. EPDs are defined as quantified environmental data for a product, based on a pre-set category of parameters, defined in the ISO 14040 series of standards (ISO 14025). EPDs were established to homogenize assumptions while performing an LCA. In fact, EPDs follow the same LCA procedure for quantifying the environmental impact. However, the method used to issue an EPD importantly guarantees consistency in the data collection process, thus enabling a comparison between products by fulfilling the same function as well as limiting the discrepancies that could exist when different researchers perform an LCA.

To achieve this objective, a new pavement design framework was developed to incorporate this sustainability evaluation criterion. After the design passes the technical evaluation, the framework will assess pavement sustainability outside the scope.

The framework will enable alternative design comparison between various products, as well as product benchmarking that uses EPD as a data source. The scope includes a cradle to gate analysis (using EPD), as well as the transportation stage from the manufacturer's location to project location. The transportation stage from the manufacturer's location to

project location was assessed using LCA. Various case studies will be provided to validate the new framework. The framework was used to assess the total sustainability score of various alternatives in terms of which one has a higher/ lower score. However, these differences were insignificant. Results also proved that the transportation stage represents an important criteria, and the total environmental impact was sensitive to a change in this factor.

CHAPTER 1. INTRODUCTION

The United Nations defined sustainability in 1987 as “meeting the needs of the present without compromising the future generations to meet their own needs.” This definition gained wide acceptance and was known as the Brundtland Commissions. Moreover, the sustainability definition was defined as having three pillars: environmental, economic, and social aspect.

Later, other sustainability definitions emerged; however, most of them included the three pillars of sustainability, previously defined by Brundtland: the economy, the environment, and social aspect (Georgia Institute of Technology 2011). The three sustainability pillars are illustrated in Figure 1.

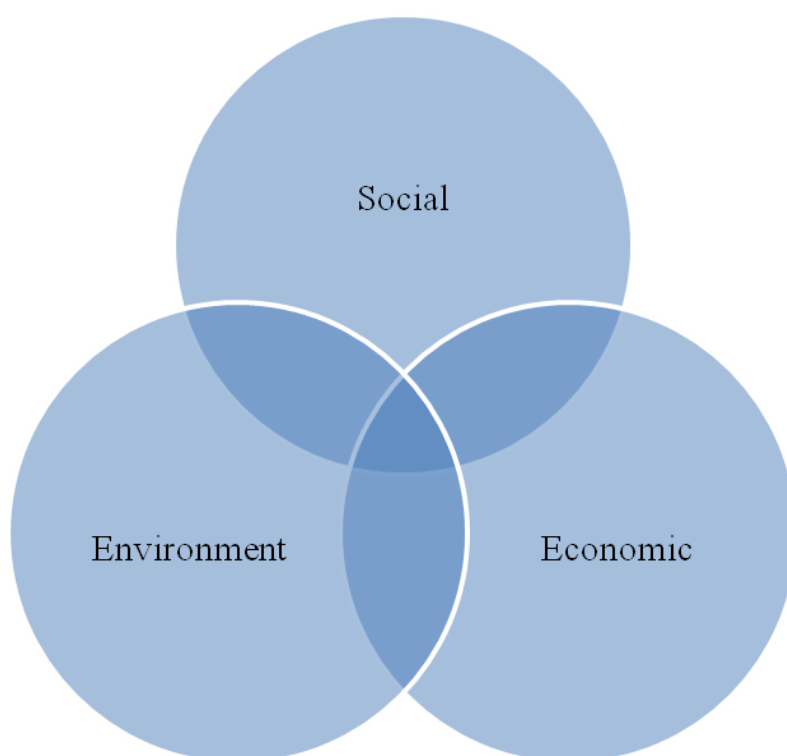


Figure 1. The three sustainability pillars (Green Art Lab Alliance)

Currently, the United States has no national policy on sustainability (Highfield, 2011). The U.S. Department of Transportation has not yet fully incorporated environmental impacts into decision making in applications such as pavement design; more specifically, the

Mechanistic Empirical Pavement Design Guide (MEPDG). The MEPDG is considered a major change for pavement design, and provides a comprehensive method for analyzing new and rehabilitated pavements. The word “mechanistic” denotes the use of engineering mechanics, leading to a design that has the following components (Huang et al., 2015):

- The theory to predict pavement critical responses, such as stresses and strains and their relation to traffic and climatic conditions.
- The relationship between critical pavement response and observed distresses, which is known as the empirical part.

Moreover, the MEPDG includes calibration procedures for local conditions and measures for design reliability. The MEPDG may be used to analyze causes for pavement distresses, such as cracking and faulting in rigid pavement design (FHWA, 2015).

However, despite all these advantages, the MEPDG does not incorporate sustainability into its design framework. In other words, environmental impacts such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Ozone Depletion Potential (ODP) are not evaluated for the designs performed; designs are solely analyzed for technical performance aspects.

One of the tools to assess the first pillar of sustainability (environmental aspect) is lifecycle assessment (LCA). Lifecycle assessment is a method to evaluate the environmental impact of a product or a service. LCA may be applied at any stage of the product’s lifecycle from cradle to grave, such as pavements (Reap et al., 2008). Lifecycle assessment has been the focus of much research. However, despite its popularity and codification by organizations such as the International Organization for Standards, together with the Society of Environmental Toxicology and Chemistry, life assessment still has various drawbacks: Not only does lifecycle assessment remain time consuming, but the accompanying data also may

be outdated and/or inaccurate (University of Michigan, 1995), depending on the data collection method and year.

Moreover, other problems related to the use of LCA include: comparability issues when performing similar studies, using either different data sources or different temporal representations. Such variations may lead to discrepant results. These problems are summarized in Table 1 (Williams, 2009). It should be clearly stated that these discrepancies are caused by researchers who apply LCA differently, and not a drawback in LCA as a tool or method.

Table 1. Problems associated with the use of LCA (Williams 2009)

Category	Data source
Data source	Some sources may be using literature, while others may be using measurements
Technological representation	Laboratory vs. plant data
Temporal representation	Old vs. new data
Geographical representation	One source may be using U.S. data, while the other may be using European data

Other tools to evaluate the environmental impact of a product are Environmental Product Declarations (EPDs). EPDs are defined as quantified environmental data for a product, based on a pre-set category of parameters, defined in the ISO 14040 series of standards (ISO 14025). EPDs were established to homogenize assumptions while performing an LCA (Mukherjee & Dylla, 2017). In fact, EPDs follow the same LCA procedure for quantifying the environmental impact. However, the method used to issue an EPD guarantees consistency in the data collection process (Mukherjee & Dylla, 2017), thus enabling the comparison between products fulfilling the same function (Fet & Skaar, 2006; Fet et al., 2009) and decreasing any discrepancy that could happen, when different researchers perform the same LCA study.

EPDs are based on a document called Product Category Rule (PCR). In this study, the PCR used are concrete PCR. PCR provides reporting criteria for EPD content in order to guarantee its consistency. In other words, PCR were issued to guarantee that EPDs for similar products are based on the same data (Shepherd, 2015). Specifically, PCR outlines the rules for setting up an EPD, such as mandatory and optional impact categories that may be included in EPDs (Carbon Leadership Forum, 2013).

Moreover, the PCR document defines the following criteria to guarantee consistency in the EPDs produced: a) goal, b) PCR validity, c) declared unit, d) use and comparability, (k) system boundaries, (l) impact categories, (m) criteria for the exclusion of inputs and outputs, (n) data selection, (o) data quality and validity, (p) allocation assumptions, and (q) how to report the content of EPD. Also, the PCR document outlines the system boundary, as well as the various processes that should be included, such as:

- Raw Materials Supply: This process includes extraction, handling, and processing of the materials, including fuels used in the production of concrete.
- Transportation: This process includes the transportation of materials from the supplier to the gate of the concrete producer.
- Manufacturing (core process): This process includes the energy used to store, move, batch, and mix the concrete, as well as operate the facility.
- Construction Transportation: This process is optional, and includes transportation of concrete from the producer's gate to the construction site.

The development process of a PCR can be made by various entities such as industry, third party, or a manufacturer (Shepherd, 2015). In case of similar products across the industry, such as concrete, the PCR is developed under the supervision of a technical association or a trade. To guarantee credibility, various stakeholders input the rules for consistency in setting up the PCR (Shepherd, 2015). Afterward, independent experts then

revise the PCR draft for ISO 14044 compliance, in order to guarantee that the LCA data used offers characterization for the environmental impacts of the products used (Shepherd, 2015).

The process of issuing an EPD requires verification to guarantee its accuracy and to ascertain that the EPD is unbiased. This verification process is performed by various stakeholders, as well as a third party verifier (Mukherjee & Dylla, 2017). The third party verifier validates the EPD and makes certain as well that the EPD adheres to the PCR (Mukherjee & Dylla, 2017). After the verification process and after addressing all the comments of stakeholders, the EPD is finally published (Shepherd, 2015).

To assess the second pillar of sustainability (the economic aspect), a lifecycle cost analysis (LCCA) is performed. Pavement LCCA was first discussed in the Red Book in 1960 by the American Association of State Highway and Transportation officials (AASHTO) (Wilde et al., 2001). In early 1990, pavement LCCA was included in the federal literature by using several vehicle-operating cost models (Zaniewski et al., 1982; Watanatada et al., 1987; Paterson & Attah-Okine, 1992; Uddin, 1993). In 1995, FHWA made LCCA a requirement for National Highway System projects costing more than \$25 million. However, this policy was annulled in 1998, by the Transportation Equity Act. Nevertheless, FHWA and AASTHO are still providing guidance for states for developing an LCCA procedure for each state.

1.1 PROBLEM STATEMENT AND RESEARCH QUESTIONS

Based on the previous research for assessing the environmental impact of pavements, a new tool is highly needed to evaluate the sustainability of rigid pavement design. This tool should overcome the current shortcomings of sustainability, mostly related to comparability. The developed tool will be used to answer the following questions:

- What is the impact of the transportation stage on the overall environmental impact per alternative? (based on the scope of this study)
- What is the impact of (raw material extraction and manufacturing) on the overall

environmental impact per alternative? (based on the scope of this study)

1.2 GOAL AND OBJECTIVES

In response to these questions, the goal of this study is to improve the design sustainability of rigid pavements. The objective of this study is to develop a decision making tool to evaluate rigid pavement design sustainability (focusing on environmental and economic aspects, as the social aspect models are still undeveloped), using Environmental Product Declarations previously described, as well as cost data for the State of Louisiana. The use of EPD should therefore resolve existing problems associated with comparability issues.

Moreover, the use of EPD should add more credibility and consistency to the data used, since these data were previously verified. Therefore, the objectives of this study are 1) to alter the existing pavement design framework to include the new sustainability criteria; 2) to design an Environmental Product Declaration database (an EPD scope, covering a cradle to gate analysis); and 3) to design a cost analysis database. Moreover, it should be noted that the scope of the study will include the transportation impact from manufacturing to project location, as illustrated in Figure 2.

Therefore, to cover this stage, the objectives would continue as: 4) a transportation impact analysis to be performed for various truck types and fuel types; 5) a software to be developed to include the databases (the software was fully developed by Qiandong Nie, a programmer, and based on the framework developed in this study), as well as facilitate data incorporation into the new framework; and 6) case studies to be performed to test and validate the new framework.

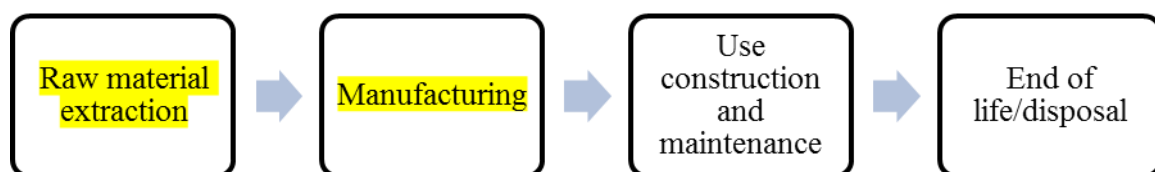


Figure 2. The scope of the study
The scope of the study is highlighted; the arrows represent product transportation.

1.3 RESEARCH APPROACH AND IMPLEMENTATION

To accomplish the aforementioned objectives, this study will perform the following tasks:

1) remodeling the current pavement design framework, 2) designing the EPD database, 3) designing the cost analysis database, 4) performing the transportation impact analysis, 5) modifying and incorporating the data into the framework, and 6) assessing the new framework.

The first task is to remodel the existing pavement design framework to include the new sustainability criteria. This will be accomplished through evaluating both the environmental and economic impacts of the design. The design will no longer be based solely on the technical performance, but will also evaluate the environmental and economic criteria. This process is documented in Chapter 3.

The second task is to design an EPD database. This will be performed through an extensive EPD collection process on a Louisiana level, as well as on a national level. This database will be available online, free of charge for anyone to use; therefore, EPDs for other states will be provided. The EPD data collection process was performed through extensive communication with the industry, an internet web search, and by requesting product data sheets, including mix design breakdowns. This is documented in Chapter 3.

The third task is to design a cost analysis database to perform lifecycle cost analysis for the State of Louisiana. This was performed through an extensive data collection process from the Louisiana Department of Transportation and Development database. The database was divided into two sections: initial cost items (costs occurring at the present) and future cost items (cost for the maintenance and rehabilitation items). The first section contains an initial material cost for the mix design collected from the manufacturer. The second section contains material prices, labor, equipment, and overheads collected from the Louisiana

Department of Transportation and Development database. The future cost includes maintenance and rehabilitation activities that may occur to concrete pavement during its lifecycle. These initial and maintenance and rehabilitation costs are used to perform a lifecycle cost analysis. This process is documented in Chapter 3. Tasks 1, 2, and 3, previously discussed, are summarized in Figure 3.

Moreover, to account for the environmental impact of transportation from the manufacturer to the project location, lifecycle assessment will be performed for various types of trucks and fuels. Trucks were divided by weight into three categories: light duty truck, medium duty truck, and heavy duty truck. Two types of fuels were evaluated: diesel and gasoline. This process is documented in Chapter 3.

Task 1: Changing the current pavement design framework	Task 2: Design EPD database	Task 3: Design cost analysis database
<ul style="list-style-type: none"> • The new framework incorporates the new sustainability factor • EPD database • Cost analysis database • Transportation impact 	<ul style="list-style-type: none"> • Started by EPD collection process: internet search/communication with companies/products data sheets • Individual EPD for companies • Design EPD for the State of Louisiana • Perform a survey 	<ul style="list-style-type: none"> • Initial cost items • Material cost • Initial cost items • Future cost items for the maintenance and rehabilitation activities • Perform a life cycle cost analysis

Figure 3. Work tasks and expected outcomes (Tasks 1, 2 and 3)

To illustrate the process of incorporating the new sustainability criteria into the new pavement design framework, various data modifications were performed to make certain these remain consistent. For example, while the environmental data drew inventory data from the transportation module, the environmental impacts data drew data coming from the EPDs. These data consisted of different units. Moreover, the cost analysis data displayed initial cost

data occurring at the present, while maintenance and rehabilitation costs showed data to occur in the future. Some modifications were performed to assure that the data were evaluated at the same point in time. This procedure is described in the implementation chapter in Chapter 4. As a result, the output of this Chapter should be a complete framework, ready and in place to implement and apply in case studies.

To facilitate the manipulation of the data and their integration into the new rigid pavement design framework, software was developed to store and query data from EPD, cost analysis, and transportation impact. Full design credit for software development goes to the programmer Qiandong Nie, who developed the software based on the framework presented in this study. The software has a simple user interface, requires no programming background, and remains expandable to enable future data expansion. This process is described in Chapter 4. Tasks 4, 5, and 6, previously described, are illustrated in Figure 4.

Finally, case studies will be performed to assess the new framework. Case studies will include various states, such as Texas and Louisiana. These case studies are performed in Chapter 5. Chapter 6 will present the conclusion, recommendations, and future work to be performed later. To facilitate the navigation process, the tasks are also illustrated per chapter number in Figure 5. It should be noted that the literature review was not thoroughly described as a task, since this is a part performed in any study.

Task 4: Performing transportation impact analysis	Task 5: Modifying the data and incorporating into the framework	Task 6: Assessing the new framework
<ul style="list-style-type: none"> • Categorize vehicles based on weights: • Light duty truck • Medium duty truck • Heavy duty truck • Types of fuels used: <ul style="list-style-type: none"> • Gasoline • Diesel • Environmental impact is performed using lifecycle assessment 	<ul style="list-style-type: none"> • Modify the data to make sure it is consistent • Incorporate the modified data into framework • Develop a simple program/user interface 	<ul style="list-style-type: none"> • Perform various case studies to validate the new framework

Figure 4. Work tasks and expected outcomes (Tasks 4, 5, and 6)

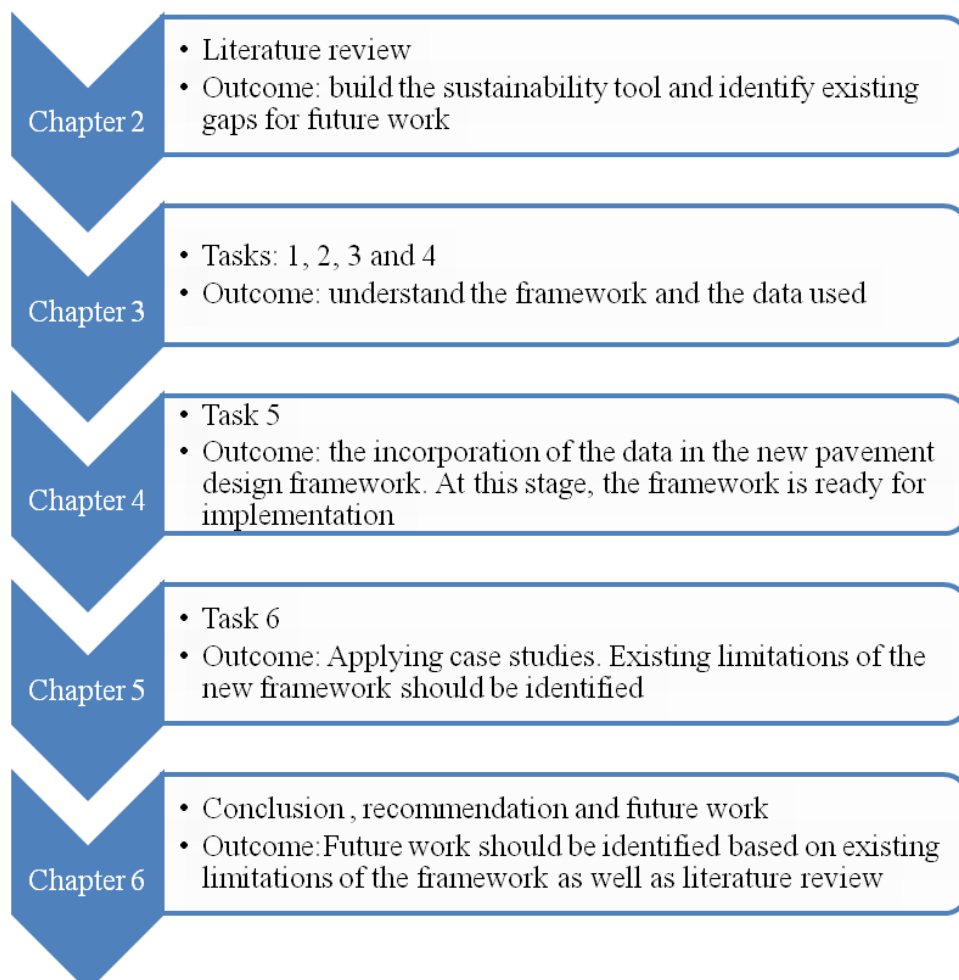


Figure 5. Various chapters and tasks

1.4 CONTRIBUTION TO THE BODY OF KNOWLEDGE

This study develops an innovative methodology for rigid pavement design by introducing a new framework and a ready for implementation tool to quantify the sustainability of rigid pavement design from cradle to gate, using data from EPD. The data are based on a pre-defined set of categories and based on the same system boundary which, in turn, should solve the comparability issue associated with other sustainability tools, such as lifecycle assessment. Moreover, the use of EPD should add more credibility to the results, since EPD are verified data. The new framework assesses designs based on economic and environmental criteria. The new framework should enable the comparison of various alternatives as well.

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CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

This chapter will present existing tools for assessing pavement sustainability. The environmental, social, and economic impacts will be presented as the three pillars of sustainability.

The chapter will explain the tools necessary to assess the environmental impact, such as lifecycle assessment and its various stages, followed by an explanation of problems associated with lifecycle assessment or more specifically, problems associated with pavement lifecycle assessment. This presentation will be accomplished through studying various pavement lifecycle assessment case studies from cradle to grave, in order to highlight all possible issues that may arise while performing a lifecycle assessment, thereby identifying current gaps for future work. Then the chapter will present other tools to assess the environmental impact, such as rating tools, environmental assessment, and environmental impact statements.

Afterward, the chapter will assess another sustainability pillar, the social impact, which will be followed by the economic impact. The economic impact will present concepts such as initial cost vs. maintenance and rehabilitation cost, as well as time value of money and associated equations.

Finally, the current pavement design framework is illustrated and explained at the end of the chapter. The framework does not incorporate any of the sustainability criteria previously illustrated. This framework will be modified in later chapters to incorporate sustainability criteria.

2.2 LIFECYCLE ASSESSMENT (LCA)

Lifecycle assessment dates to the 1960s. The reason for performing LCA emanates from a concern about limitations in raw materials and energy resources, as well as the need to predict future supplies. One of the first studies performed was by Harold Smith, who calculated a cumulative energy requirement to produce chemical intermediates at the World Energy Conference in 1963 (Curran, 2006).

In 1969, researchers performed an internal LCA for the Coca Cola Company. This study opened the door for current methods of lifecycle inventory analysis in the United States. The objective of this study was to compare different beverage containers to evaluate which container not only had the lowest environmental impact, but also consumed less material. The scope of this study included the quantification of those raw materials and fuels which were used. In the 1970's, other companies in the United States, as well as Europe, used LCA for various purposes (Curran, 2006).

From 1975 to the early 1980s, the environmental concerns shifted to hazardous waste. However, at this point in time, inventory analyses were used, and the studies performed focused on energy issues. In 1998, solid waste became a worldwide issue, leading LCA users to expand LCA to include the assessment of solid waste (SETAC 1991; SETAC 1993; SETAC 1997).

Lifecycle assessment evaluates the environmental impact of a product, together with its complex systems of products and processes. LCA examines all inputs and outputs over the lifecycle of a product, starting from the production of raw materials to the lifecycle end. In addition, LCA considers the transportation between the various stages. Lifecycle assessment analysis originally analyzed emissions to air, land, and water. Later, LCA expanded to include energy, resource use, and chemical emissions.

Initially, the focus was on products and packaging, and then the focus moved to infrastructure (Hunt & Franklin, 1996). In the years 1990 to 2000, this LCA method was standardized by the International Organization for Standardization (ISO) (SAIC, 2006). As illustrated in Figure 6, the lifecycle assessment consists of four phases: a) goal and scope definition; b) lifecycle inventory assessment; c) impact assessment, and d) lifecycle interpretation. These phases are explained in the coming section.

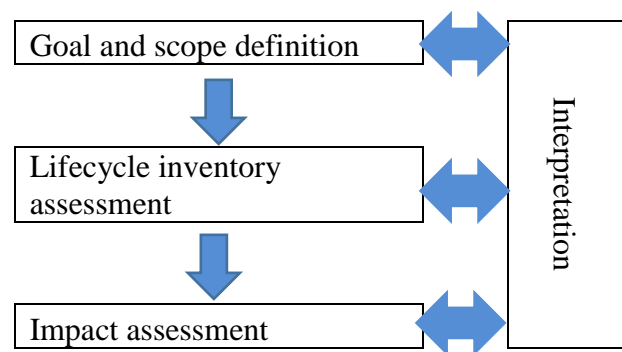


Figure 6. Lifecycle assessment framework (Kendall 2012)

2.2.1 GOAL AND SCOPE DEFINITION PHASE

The goal and scope phase defines the goal and the purpose for conducting a lifecycle assessment for a certain product (EPA, 2006). Definition of the goal, coupled with the scope of the study is the step that will define the amount of time and resources needed in the study from beginning to end. The following points should be considered before setting a goal for the study: 1) determining the goal of the project, 2) determining the level of specificity, and 3) determining what type of information is needed for decision makers (EPA, 2006).

2.2.2 LIFECYCLE INVENTORY PHASE

The lifecycle inventory is the LCA phase where the data collection occurs. The process details a tracking of the flows coming in and out of the system, inclusive of raw material, resources, energy, and water by a specific substance. Figure 7 illustrates the lifecycle inventory phase (Athena, 2017). As illustrated, the system is indicated at the middle of the picture with inputs as well as outputs coming in and out of the system (Athena, 2017).

In this figure, or in this study, the resulting output includes emissions and waste. The output varies, depending on the study.

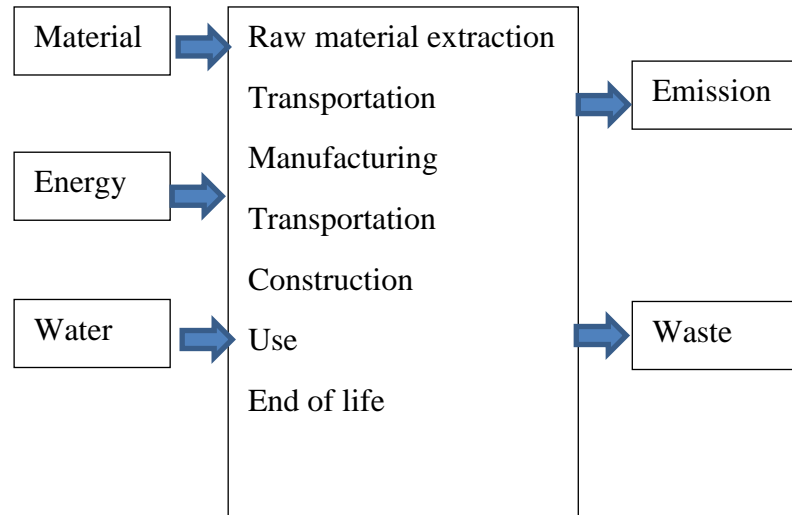


Figure 7. Lifecycle Inventory stage (Athena 2017)

2.2.3 LIFECYCLE IMPACT ASSESSMENT PHASE

Lifecycle impact assessment is a process whereby the magnitude and significance of potential environmental impacts, as well as human health impacts, are identified. The identification involves a product or a service used during the lifecycle inventory stage. Figure 8 illustrates the relationships between a lifecycle inventory midpoint and relevant endpoint impacts that require protection. For example, there are elementary flows causing Global Warming Potential (GWP), which impact human health and the natural environment. Other elementary flows might only impact resource depletion at the midpoint, and/or natural resources at the end.

Moreover, the lifecycle impact assessment phase is composed of many sub-phases such as: a) selection and definition of impact categories, b) classification, c) characterization, d) normalization, e) weighting, f) evaluating and reporting LCIA results, and g) interpretation (EPA, 2006). As defined by ISO 14042, the following steps are mandatory in performing a

lifecycle assessment: definition of impact category, classification, and categorization; the other steps are optional. These sub-phases will be explained in detail below.

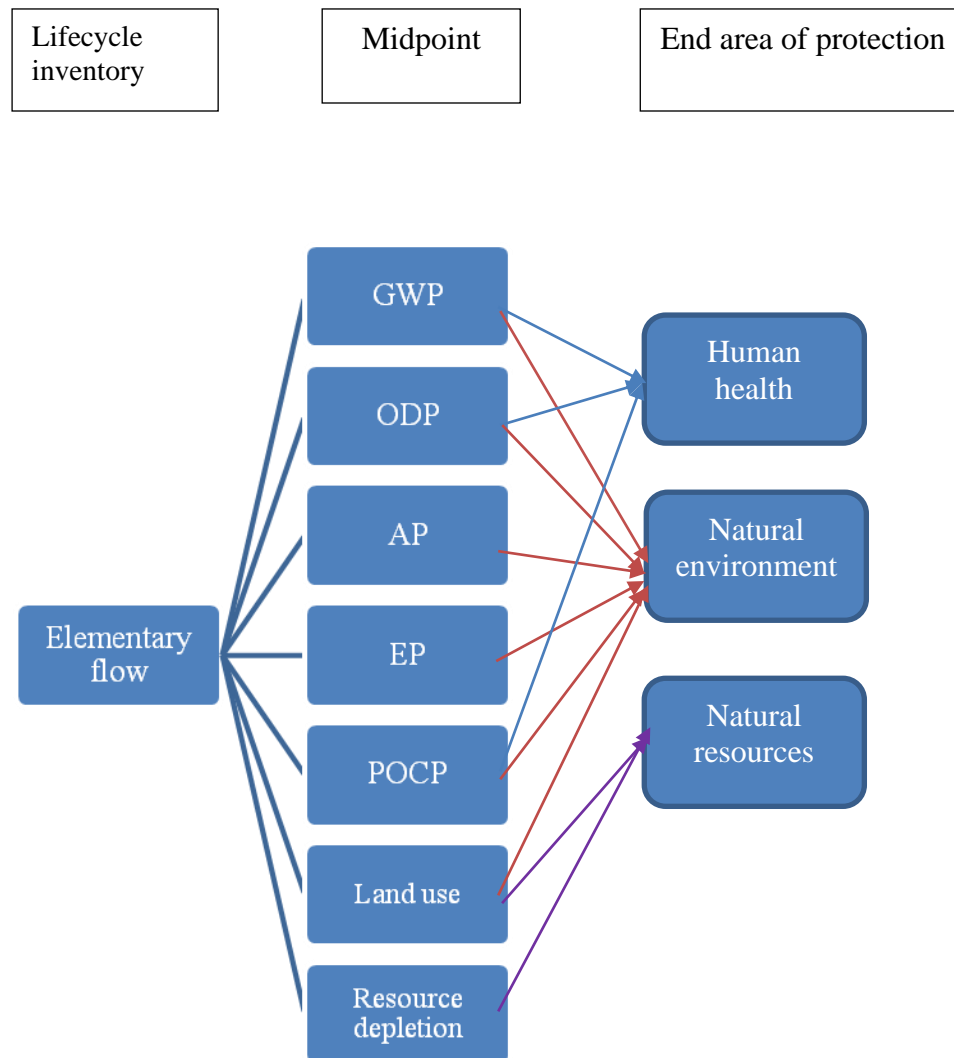


Figure 8. Lifecycle inventory, midpoint and end of area protection (European platform for lifecycle assessment 2017)

2.2.4 SELECTION AND DEFINITION OF IMPACT CATEGORIES

The first step in performing a lifecycle impact assessment is the selection of those impact categories which will be included in both the goal and scope definition. This process should guide the data collection process of the lifecycle inventory. The items included in the lifecycle inventory have both an environmental impact, as well as a health impact. As an

example, an environmental release in the lifecycle inventory phase may have an impact on human health, such as causing cancer, as well as an impact on the environment, such as causing acid rain (EPA, 2006).

2.2.4.1 Classification

The objective of the classification step is to consolidate lifecycle inventory into impact categories (example, GWP, etc...). The process becomes easy for the lifecycle inventory contributing to only one impact category. As an example, Carbon Dioxide only contributes to the Global Warming Potential (EPA, 2006). However, for a lifecycle inventory contributing to more than one impact category, there are various ways to divide this inventory among other impact categories, such as (ISO, 1998),

- Distributing a portion of the lifecycle inventory to the other impact categories these cause. This occurs when results are dependent.
- Conveying all lifecycle inventory to the various impact categories involved. This occurs when results are independent.

2.2.4.2 Characterization

The impact characterization stage is the process where the lifecycle inventory data are transformed into indicators of impact to human and ecological health (EPA, 2006). The characterization step allows a comparison of the lifecycle inventory inside each impact category; as a result, characterization transforms different inventories to impact indicators that may be compared in a more direct fashion. The equation for characterization is illustrated in Equation 1.

$$\text{Impact indicators} = \text{Inventory data} \times \text{characterization factor} \quad (1)$$

As an example, both Chloroform and Methane contribute to GWP. The characterization factor for Chloroform is 9 and for Methane, the characterization factor is 21. Therefore, a quantity of 20 lb Chloroform contributes to a total of: $20 \text{ lb} \times 9 = 180$ towards Global

Warming Potential, while a quantity of 10 lb Methane contributes to $10 \text{ lb} \times 21 = 210$ towards Global Warming Potential.

Importantly, the process of selecting a characterization value is controversial and varies from one impact to the other. There is some consensus on characterization values, such as the value of GWP (EPA, 2006). However, for impacts such as resource depletion, there is no consensus as yet on the characterization value (EPA, 2006). Therefore, any assumptions for the characterization value should be well documented.

As a convention used in this study, Table 2 illustrates the final units that will be used for each environmental impact. For example, there are various lifecycle inventories leading to Global Warming Potential, such as Carbon Dioxide, Nitrogen Dioxide, Methane, etc. Therefore, all these inventories will be converted into units of Carbon Dioxide equivalent. The same concept applies to other environmental impacts

Table 2. Convention used in this study

Name	End point impact	Examples of LCI data	Description of characterization factor
Global Warming Potential (GWP)	Soil moisture loss, forest loss, longer seasons.	Carbon Dioxide (CO ₂), Nitrogen Dioxide (NO ₂), Methane (CH ₄)	Converts LCI data to (CO ₂) equivalents
Ozone Depletion Potential (ODP)	Greater ultraviolet radiation	Chlorofluorocarbons (CFCs), Halons	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Eutrophication Potential (EP)	Phosphorus and Nitrogen enter water bodies causing excessive plants growth	Phosphate (PO ₄), Nitrogen Oxide (NO)	Converts LCI data to Nitrogen equivalent
Acidification Potential (AP)	Water body acidification, corrosion for buildings	Sulfur Oxides (SO _x), Nitrogen Oxides (NO _x), Hydrochloric Acid (HCL)	Converts LCI data to Sulfur Dioxide SO ₂ equivalent
Photochemical Ozone Creation Potential (POCP)	Decreased visibility, eye & lung irritation	Non-methane hydrocarbon (NMHC), Ozone	Converts LCI data to Ozone O ₃ equivalent

2.2.4.3 Normalization

Normalization is used to express the impact indicators in a manner that can be compared among impact categories (EPA, 2006). This process occurs by dividing the indicators by a selected reference value. The equation used for normalization is illustrated in Equation 2.

$$\text{Normalized value} = \text{ImpactA} / \text{Normalization value for impactA} \quad (2)$$

For example, by analyzing values in EPD for a random mix design (1yd³), the GWP = 346 kg CO₂ eq and the Ozone Depletion Potential (ODP) = 3.99E-06 kg CFC-11 eq, which means these values are not on the same scale or units. However, by normalizing these values, the new values then become (Stranddorf et al., 2005) the following:

Normalized value for GWP = (346 kg CO₂ eq) / (24000 kg CO₂ eq) = 0.0144

Normalized value for ODP = (3.99E-06 kg CFC-11 eq) / (0.16 kg CFC-11 eq) = 2.49 × 10⁻⁵

According to EPA (2006), there are various reference values that may be used, such as

- The total emissions or resource use for a given area. These emissions can be either global, regional, or local.
- The total emissions or resource use given for a certain area per capita
- The ratio from one alternative to the other
- The highest value amongst all alternatives

The reference value that will be selected in this study is the total emissions given per capita.

2.2.4.4 Grouping

Grouping is the process of classifying impact categories into sets to ease the interpretation of the results. Normally, the grouping process tends to sort or rank indicators.

Grouping is performed in one of the following ways:

- Indicators are sorted by characteristics, such as emissions (to water, air) or location (regional, global, etc.)

- Indicators are sorted by classifying these into categories of low, medium, high, etc.

2.2.4.5 Weighting

The weighting process for LCA is the process of assigning weights to various impact categories, based on the importance (EPA, 2006). This weighting procedure importantly reflects a stakeholder preference. The weighting procedure could differ, depending on stakeholders' opinions; therefore, the reason for assigning any weight should be documented (EPA, 2006). For example, harmful air emissions are of higher concern in areas with an air attainment zone than in areas with improved air quality; therefore, impacts related to air should be assigned higher weights in air attainment zones (EPA, 2006). According to EPA (2006), the weighting procedure should follow the following rules:

- Identifying the importance of the various impacts to stakeholder;
- Determining the weights to be used for the impacts;
- Applying the weights to the impacts.

The equation used for the weighting step is illustrated in Equation 3:

$$\text{Weighted impact} = \text{assigned weights} \times \text{normalized value} \quad (3)$$

Where:

- The assigned weights are selected by the stakeholder.
- The calculation procedure for the normalization was previously illustrated in Equation 2.

There are various scenarios that occur when assigning weighting. The first is subjectivity: The weighting values will change either from one place to another, or by time. For example, someone located in California may place a higher weight for photochemical smog than someone in Wyoming (EPA, 2006). Therefore, the selection process of the weighting criteria should be well documented and explained.

Another example illustrating the process of assigning weights is the weights assigned by the EPA's Science Advisory Board (SAB) and the Building for Environmental and Economic Sustainability (BEES) models:

In 1990 and again in 2000, the EPA's Science Advisory Board (SAB) developed a list of various important environmental impacts in order to help the EPA allocate its resources. The EPA used the following criteria to develop the lists: (Lippiatt, 2007). At the end, the EPA came up with the weights illustrated in Table 3 for various impacts.

- The spatial scale of the impact
- The severity of the hazard
- The degree of exposure
- The penalty of being wrong

Table 3. EPA's Science Advisory Board weighting criteria (EPA 2000)

Impact category	Relative importance (weight) in %
Global Warming	16
Acidification	5
Eutrophication	5
Fossil Fuel Depletion	5
Indoor Air Quality	11
Habitat Alteration	16
Water Intake	3
Criteria Air Pollutants	6
Smog	6
Ecological Toxicity	11
Ozone Depletion	5
Human Health	11

Later, the BEES performed many calculations and modifications to translate these SAB results into weights for interpreting LCA. For developing these weights, the National Institute of Standards and Technology (NIST) gathered volunteering stakeholders in Maryland on May 2006. Voting interests were grouped into three categories: The first category was inclusive of the producers (building product manufactures), users (green

building designers), and LCA experts. Nineteen different people participated in the panel: seven producers, seven users, and five LCA experts. Gathered from ASTM International, these voting interests developed voluntary standards for balancing final results (Lippiatt, 2007). These final results are illustrated in Table 4.

Table 4. BEES stakeholder panel judgement (Lippiatt 2007)

Impact category	Relative importance (weight) in %
Global Warming	29
Acidification	3
Eutrophication	6
Fossil Fuel Depletion	10
Indoor Air Quality	3
Habitat Alteration	6
Water Intake	8
Criteria Air Pollutants	9
Smog	4
Ecological Toxicity	7
Ozone Depletion	2
Human health (Cancerous Effects)	8
Human health (Noncancerous Effects)	5

2.2.4.6 Evaluating and reporting Lifecycle Impact Assessment (LCIA) results

After performing all the previous calculations, the results accuracy must be explained. The accuracy should be well presented by using the goal and scope definition assigned for the LCA study. When the LCA study is documented, all the assumptions and methodology used should be clearly stated. When performing LCIA (EPA, 2006), there are various drawbacks/limitations associated with the use of LCIA, such as:

- The use of LCA does not provide a temporal scale; for example, a five ton discharge of particulate matter is more dangerous than the same amount released over the entire year.
- Broad inventory: Vague terms are used, such as metals, “VOC” etc...; these words do not provide accurate information toward assessing the environmental impact.

- For example, a ten ton release of a contamination does not mean it is ten times worse than one ton of contamination (EPA, 2006).

2.2.5 INTERPRETATION PHASE

A lifecycle interpretation phase presents a process whereby the results of the lifecycle inventory or lifecycle impact assessment are evaluated. After data evaluation, the impacts are then communicated to decision makers (EPA, 2006). The ISO defined the following two objectives for the lifecycle interpretation phase: 1) to analyze results, by explaining limitations and future recommendations; and 2) to present the final LCA result in a manner that does not contradict the goal of the study (EPA, 2006).

2.2.6 TYPES OF LCA

There are various types of LCA, depending on the goal and scope definition of a pavement LCA study. These types will be explained as follows:

- **Input-Output LCA:** The IO-LCA is a top-down method that embraces the full supply chain of a product in various environmental sectors. The IO-LCA examines all sectors of the economy by analyzing the flow of goods and services among different sectors responsible for producing a unit of output from a specified sector (Carnegie Mellon University).
- **Process-Based LCA:** Process-based LCA is an environmental analysis method that computes the inputs and outputs of every process identified within the system boundary for a given product or service. Each environmental emission related to an individual process is evaluated. Therefore, the process of LCA necessitates that the system boundary is well defined. Process LCA is the most detailed and time consuming analysis that can be performed for a product (Inyim et al., 2016).

- Hybrid LCA: Hybrid LCA is a mix of input-output and process methods. This involves using both economic and environmental data related to a specific process (Inyim et al., 2016).
- Attributional LCA: The attributional LCA is performed to describe the environmental physical flows both to and from the lifecycle system; additionally, attributional LCA uses average environmental data (Attributional and Consequential LCA, 2016).
- Dynamic LCA: Dynamic LCA is defined as an “... approach to LCA, which explicitly incorporates dynamic process modeling in the context of temporal and spatial variations in the surrounding industrial and environmental systems.” (Dynamic LCA, Framework and Application, 2013).
- Consequential LCA: In this type of LCA, the system boundary is performed to guarantee that the activities included in the analysis reflect the change occurring as a consequence of a change in decision making (Attributional and Consequential LCA, 2016).

2.3 PAVEMENT LIFECYCLE PHASES

As previously discussed, LCA can be performed to evaluate the environmental impact of a product or a service during any stage of the product lifecycle, such as pavement. Pavement lifecycle stages are: materials production, design phase, construction phase, use phase, maintenance and rehabilitation phase, and end-of-life phase. These phases are illustrated in Figure 9.

This section is going to thoroughly explain current problems associated with LCA. Literature reviews pertaining to pavement LCA from cradle to grave were thoroughly read to identify current gaps for future work.

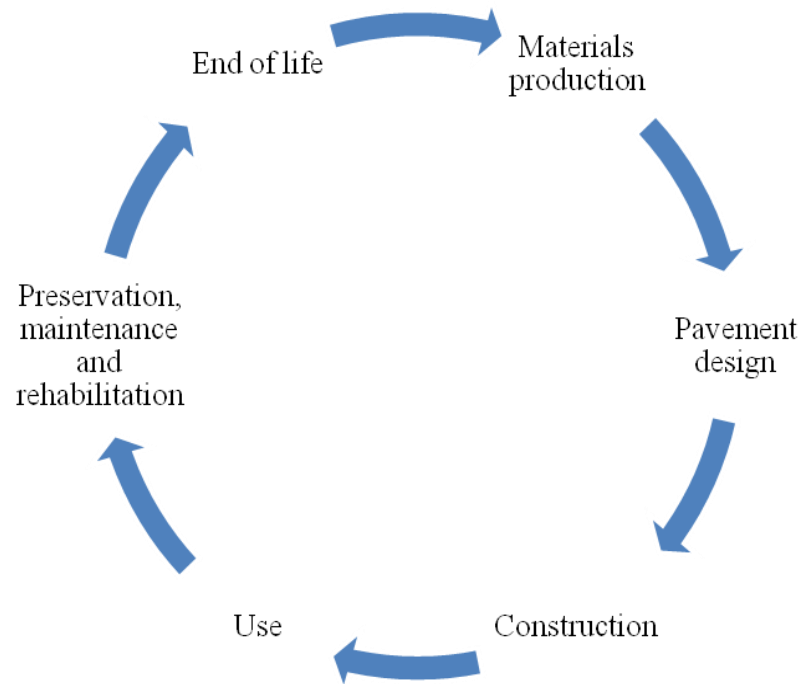


Figure 9. Pavement lifecycle phases (cradle to grave) (Pavement Sustainability 2014)

2.3.1 MATERIALS PRODUCTION

The material production phase includes all activities involved in pavement material acquisitions, such as mining, crude oil extraction, and processing (refining, mixing, and manufacturing) as used (Pavement Sustainability, 2014). In addition, plant processes required to produce concrete, asphalt, mixed aggregates, cement, and additives are included. The material production phase affects air, water, non-renewable resources, human health, the ecosystem, and the lifecycle cost (Pavement Sustainability, 2014).

Various studies were performed to compare the material extraction phases for asphalt and concrete pavement. For example, Horvath and Hendrickson (1998) compared asphalt pavement with steel-reinforced concrete pavements. The study concluded that asphalt pavement consumes 40% more energy than concrete pavement for the material extraction phase. Moreover, the asphalt alternative proved to have lower toxic emissions. The author clearly stated that there is uncertainty in the data, which may be considered one of the limitations of this study.

Other studies discussed the inclusion/exclusion of the feedstock energy of bitumen and its subsequent impact in the material extraction phase (Sanetero et al., 2011). As per the ISO 14044 standards, the feedstock energy in bitumen is defined as “... the heat of combustion of a raw material input that is not used as energy source to a product system, measured in higher heating value or lower heating value” (ISO, 14044). There is an extensive amount of energy stored in bitumen (Sanetero et al., 2011), making a significant issue of the inclusion or exclusion of such energy in LCA.

Feedstock energy was included in various pavement LCAs, such as the work performed by Häkkinen and Mäkelä (1996), Nisbet (2001), Athena (2006), and Chan (2007). The study performed by Häkkinen and Mäkelä (1996) estimated that asphalt pavement consumes a higher, non-renewable energy (almost twice), compared to a concrete pavement alternative, when feedstock energy is included. In cases where the feedstock energy is excluded, the results remained almost similar for both alternatives (Häkkinen & Mäkelä, 1996). This finding confirms the fact that LCA results can be highly affected by the inclusion/exclusion of feedstock energy.

Another study performed by Nisbet (2001) compared air emissions and energy during the material extraction phase for asphalt and concrete pavement used in urban collectors and highway routes. The study was commissioned by the Portland Cement Association (PCA). The concrete pavement is a JPCP design for both urban collectors and highway routes. The study presents the data in a very clear format, including the reference for each source. Results of this study proved that concrete pavement requires less material for both cases, urban collectors as well as highway routes. In addition, the concrete pavement alternative proved to have lower air emissions and lower energy, compared to asphalt. The study also performed a sensitivity analysis on feedstock energy for the asphalt alternative. Results proved that the feedstock energy in bitumen was significant (Nisbet, 2001).

In addition, in 2006 the Athena Institute performed a lifecycle assessment to compare concrete vs. asphalt pavement. The objective of this study was to compare energy and Global Warming Potential for concrete vs. asphalt for the materials production phase. The concrete pavement includes JPCP design. The pavement design was performed using the Mechanistic Empirical Pavement Design Guide (MEPDG). The feedstock energy of bitumen is included in the analysis and accounted for with a significant amount of energy per unit of asphalt. Results of the analysis proved that in the event the feedstock energy is included, asphalt proves to have a higher energy consumption (from 2 to 5 times) than concrete pavement. When the feedstock energy is excluded, asphalt still consumes more energy (0.3 to 0.7 times) than concrete. From all the previous case studies, the inclusion/exclusion of feedstock energy is a significant matter that should be considered in the analysis, as the final results are highly altered.

2.3.2 USE PHASE

The use phase includes all activities occurring while the pavement is in operation, such as rolling resistance, tire pavement noise, lighting, and leaching.

The use phase also includes the interaction that happens between vehicle operation and the environment. Research proves a relationship between pavement type (pavement structure, surface roughness) and condition and fuel consumption. One of the factors affecting fuel consumption is rolling resistance, defined as the process in which pavements affect fuel consumption (Taylor Consulting, 2002). The following factors affect rolling resistance (Taylor Consulting, 2002): pavement structure, vehicle mass, pavement temperature, road roughness, road grade, and vehicle speed. This section will thoroughly present each factor.

2.3.2.1 Pavement structure

The impact of pavement structure may be seen in vehicle fuel consumed while vehicles travel on pavement. The principle that relates pavement structure to fuel

consumption is viscoelasticity, in regard to asphalt pavement (Beuving et al., 2004). This theory is based on the assumption that flexible pavement deflects under the effect of passing vehicles. This deflection absorbs the energy that would have been otherwise used to accelerate the vehicle (Zaniewski, 1989).

Based on this concept, other literature review proves that concrete rigidity prevents this deflection from happening, and therefore vehicles rolling on concrete pavement consume less fuel (Sanetero et al., 2011). Various studies were performed to evaluate the impact of pavement structure/surface on fuel consumption, and specifically, to compare concrete to asphalt pavement. Some of these studies include the work performed by Zaniewski (1989), Taylor and Patten (2006), and Taylor and Patten (2002).

Zaniewski (1989) performed a study to assess the impact of pavement surface type on fuel consumption. The author tried various vehicle types on pavements such as Asphalt Concrete, Portland Cement Concrete, and Asphalt Concrete surface treatments. The minimum speed used in the study was 10 miles per hour and the maximum speed was 70 miles per hour. However, few details were provided about the overall pavement design; also, the study did not consider all pavement conditions, only evaluating pavements in good condition, which could be considered a limitation of the study. The author concluded that concrete pavement provided better fuel consumption for trucks than asphalt, by 1% (Zaniewski, 1989).

Taylor et al. (2006) performed a study to evaluate the impact of pavement structure on fuel consumption. This study was performed in Ontario, Quebec. The report was initially prepared for the Center for Surface Transportation Technology. The pavement types included in the analysis were concrete, asphalt, and composite pavements. The speeds included in the analysis were 60 km/hour and 100 km/hour. The study was performed in various times of the year, and included the seasons of winter, spring, summer (hot and cool) and fall. This study

included only pavements in good condition (smooth); therefore, rougher pavements were excluded.

The author came up with the conclusion that there is little difference between concrete and asphalt in terms of vehicle fuel consumption. At the end of the report, the author recommends the following points for inclusion in future work: a) focusing more on the International Roughness Index, to better estimate the impact that road surface roughness can have on fuel consumption; b) focusing on analyzing pavement with vehicle speeds of less than 60 km/hour; and c) expanding the work scope to study other differences between concrete and asphalt pavement, such as noise absorption and cost of installation (Taylor et al., 2006)

Further analysis into the studies performed by Zaniewski (1989), Taylor and Patten (2006), and Taylor and Patten (2002) should be considered; these studies were sponsored by either the concrete or asphalt industries, and therefore the results might be biased.

Moreover, these studies used various types of vehicles, ranging from light duty to heavy duty vehicles, in order to test the impact of pavement structure on vehicle fuel consumption. Further, these studies used various speeds to test the impact of fuel consumption, with speeds ranging from 30 km/h to 100 km/h. This inconsistency in performing the experiment could lead to a discrepancy in final results and difficulty in comparison across other studies. The inconsistency in performances suggests further analysis.

Also, these studies considered the fuel economy improvement over diverse pavement surface types, such as concrete over asphalt pavement, as well as concrete over composite pavement; however, the findings did not evaluate all other possible pavement types, which can be considered a limitation of the study.

The tests performed on composite pavement include the works of Taylor and Patten. The author demonstrated that PCC and composite pavement decreases the amount of fuel consumed, compared to other pavement types such as HMA (Taylor & Patten, 2002). The study was originally performed for the National Research Council of Canada's Center for Surface Transportation. The research objective evaluated how pavement characteristics such as pavement structure, pavement roughness, vehicular speed, and configuration, affect vehicle fuel consumption. The author used heavy duty trucks in his experiment; the pavement types included concrete pavements, asphalt pavement, and composite pavements. Although this study included composite pavement, the overall pavement design was not characterized.

2.3.2.2 Pavement roughness

Pavement roughness is a measure for irregularities occurring at road surface (Pavement Interactive, 2012). These irregularities range from aggregate texture to road unevenness. In turn, pavement roughness, affects rolling vehicles, by means of vehicle suspension. Moreover, due to pavement roughness, energy in the form of inertia is lost, due to the mechanical work and heat created in vehicles; as a result, findings show a higher fuel consumption (Loughalam et al., 2014).

Pavement roughness is measured using the International Roughness Index (IRI). The IRI index measures "... the suspension motion relative to distance traveled." (Greene et al., 2013). Various researches were performed in this area, seeking to find the relation between pavement roughness and IRI. These researches include the work performed by Sandberg (1990) and Watanatada et al. (1987).

In 1990, Sandberg studied 20 different road surfaces with various road textures. The tests were performed at various speeds of 50, 60, and 70 km/h. Road types included unpaved roads, asphalt mixtures, and chip seals. The results of this study indicated that the fuel

consumption can vary by 11% from the smoothest to the roughest road. However, this study did not include concrete pavement, which can be one of the limitations of this study.

Watanatada et al. (1987) performed a study known as the World Bank study. This study performed a numerical relationship between pavement roughness and fuel consumption. However, this study had various limitations, which prevented performance of a full mechanistic model. First, the study could not isolate factors other than pavement roughness, which affected fuel consumption. It should be noted that various criteria affect fuel consumption, such as inertial forces, gravitational forces, and air resistance. To fully model the effects of pavement roughness, all other criteria should be isolated; that isolation was not performed in this study.

2.3.2.3 Vehicle speed

Other studies proved that when cars speed, the car temperature increases, which in turn affects fuel consumption. For example, a study performed by Louhghalam et al. (2014) proved that fuel consumption on asphalt pavement can be doubled at a temperature of 30° C, compared to the consumption at 10°C. Moreover, this study also proved that when considering car speed reduction from 80 to 20 km/h, the fuel consumption can increase from 3.5 to 8.1 L/100 km for flexible pavement. However, concrete pavement was not sensitive to this criterion.

Stubstad (2009) performed a study to measure vehicle fuel economy traveling on various pavement types. Results found that vehicles travelling on concrete pavements consumed 2% less fuel. Moreover, other studies showed 1% less fuel consumption between asphalt and concrete pavement (Stubstad, 2009). A summary of the study performed is illustrated in Table 5. However, one of the limitations of this study is that the study did not evaluate pavement texture.

Table 5. Factors affecting fuel consumption (Fernando 2006)

Test conducted		Fuel reduction
Impact of vehicle speed on PCC		6.5% (this percent is for each 5 mile per hour decrease in vehicle speed)
Ac vs. PCC	Fuel efficiency van on I-80	1.9% to 3.2% (for PCC)
PCC pavement with diamond grinding, resulting in improving International Roughness Index (IRI)		1.8% to 2.7% (this percentage is for every decrease of IRI by 50 inch/mile)
Impact of tire pressure on PCC and AC pavement.		1.0% to 1.7% (this percent is for each 4 psi decrease in tire pressure)
AC vs. PCC	Fuel efficiency van on I-5	-0.1% to 0.8% There was no statistical difference found

In 2009, Sumitsawan et al. performed a research to study the effect of pavement type on fuel consumption and emissions. This research focused on urban driving, commonly used in the United States. If there were significant differences in fuel consumption and emissions rates across various pavement surface types, then urban driving might result in variances in the total energy consumption during the design life of roadways.

To accomplish this research, fuel consumption measurements were performed using a vehicle driven over two different types of pavement surfaces: AC and PCC, applying two driving modes: one with constant speed and the other with acceleration. To separate the effect of pavement type on fuel consumption, various trials were made to control all factors that could affect the fuel consumption. These factors include tire pressure, wind speed, temperature, and atmospheric pressure (Sumitsawan et al., 2009). The two types of road surfaces had the same geometric characteristics, and the only difference was the type of pavement. Moreover, both road types had almost the same IRI (174.6 in/mile) for PCC pavement, and (180.6 in/mile) for asphalt pavement. The average fuel consumption rates are illustrated in Table 6.

Table 6. Fuel consumption for PCC vs. AC (Sumitsawan et al. 2009)

Pavement	Fuel consumption (average)	Testing criteria
PCC, fixed speed	40.7	Date: 11/7/2008
		Temp: 69°F
AC, fixed speed	42.7	Wind: 7 mph W(tailwind)
		Engine status: warm
PCC, with acceleration	236.4	Tire pressure: 50 psi
		Tank level: full
AC, with acceleration	236.9	IRI (inch/mile): 174.6 for PCC and 180.6 for AC
		Longitudinal slope: +1.2%

Results of this study proved that concrete was more economic in terms of fuel economy at 30 mph with the level of significance at 10 percent. However, there was no significance in the acceleration mode. This study evaluated only the difference between concrete and asphalt, without considering the total pavement structure, which may be considered a limitation.

2.3.2.4 Noise

The noise found in the pavement use phase was due to noise resulting from the interaction of pavement and tires (AzariJafari et al., 2015). Various researches in this area are assessed the impact of various pavement material types on noise. For example, the research conducted in 2005 by Bennert et al. compared the noise from two types of asphalt: Stone Matrix Asphalt (SMA) and dense graded asphalt. Results of this study proved that the Stone Matrix Asphalt produced less noise, compared to the dense graded asphalt, showing that in use, pavement material affects and promulgates noise.

Other research was performed to study the impact of using various types of materials. In this study, three types of materials were tested for noise annoyance: cobblestone asphalt, dense graded asphalt, and open asphalt rubber pavement. Results proved that the noise annoyance level reaches the highest level with the cobblestone pavement, compared to other materials (Sandberg & Ejsmont, 2002). These studies proved that pavement materials do

impact the resulting noise from the passage of vehicles. However, in attempts to model the noise using LCA software, the study found that data is rarely found, making it difficult to use pavement LCA software for modeling noise (Weidema et al., 2013). For example, LCA software Ecoinvent, does not present information about noise, clearly stating that this information will be included at a later time (Weidema et al., 2013); yet no time frame was mentioned.

2.3.2.5 Lighting

Lighting is one of the criteria assessed during the pavement use phase. The AASHTO, as well as other entities, classified road lighting based on road functional classification and pavement material. Roads were classified into four broad categories from R1 to R4. This classification is illustrated in Table 7. Studies that incorporate lighting in the use phase include a study performed by Hakkin and Makela (1996) and Stripple (2001).

Table 7. Road classification (An Informational Guide for Roadway Lighting and Illuminating Engineering Society of North America 2000)

Class	Description	Arterial	Freeway
R1	Portland cement concrete	12	6
	Asphalt with a minimum pf 15% aggregates composed of brightener aggregates		
R2	Asphalt with a minimum of 60% gravel	17	9
	Asphalt and a minimum of 10%-60% brightener aggregates		
R3	Asphalt surface and dark aggregates	17	9
	Asphalt surface and rough texture		
R4	Asphalt with smooth surface	15	8

Hakkin and Makela (1996) performed a Finnish study that incorporated lighting into the use phase. This study used the same classification described in Table 7 for R1 to R4. However, the study applied some Finnish norms. For example, the study states that R2 pavement for asphalt requires 250 Watts per square meter (Williams, 1981), resulting in a 66% higher lighting for asphalt pavement. In addition, this study proved that during a lifespan

of 50 years, asphalt pavement consumes 720 MWh of electricity more than concrete pavement (Williams, 1981).

Other studies focused on asphalt vs. concrete reflectance. For example, there is a study performed by Turk et al., averring that when aging, asphalt reflection increases while concrete reflection decreases. The finding was that with time, both materials can achieve the same level of reflection (Turk et al., 2014).

This lighting technique should be accounted for in pavement LCA. Moreover, it should be noted that this lighting technique varies over time, depending on technology development (Sanetero et al., 2011); therefore, this technology development also should be accounted for over time. In the future, there might be some technologies achieving the same lighting level, while consuming less energy. Therefore, the incorporation of lighting into pavement LCA should account for technology development over time, as well.

2.3.2.6 Leachate

Pavement mixtures results in various runoffs. Therefore, the use of pavements affect the surrounding environment. Various research studies were performed in this area, in order to study the environmental as well as the health impact of leachate resulting from pavement in the use phase. Yet, there is no clear result as to whether pavement leachate affects either the environment or human health.

Kriech (1990) performed a study to test whether the leachate materials from asphalt mixtures are dangerous. The author prepared an asphalt mix design and then tested it for Toxic Characteristic Leachability Procedure (TCLP) by the EPA SW846- 1311 and SW846-351 method. After that the leachate was tested for metals, volatiles, semi volatiles, organics, and (Polynuclear Aromatic Hydrocarbons) (PAH) (Kriech, 1990). Surprisingly, the study came up with the conclusion that metal concentration can leach from pavements to drinking water. However, the results show to be under the dosage recommended by the EPA (EPA,

2004). The results therefore indicate that the leachate imposes no health or environmental hazards.

Other research performed by Brantley and Townsend (1999) claimed that leachate can be severe when using Recycled Asphalt Pavement (RAP). The study collected RAP from old roadways (prior to the year 1999) and found that the samples contained lead above the drinking water standards required by EPA (Brantley & Townsend, 1999) with metals above acceptable standards, since RAP may have been exposed to hazardous materials during the lifecycle.

2.3.3 DESIGN PHASE

The design phase includes processes such as knowledge of the functional and structural requirements for a pavement design, based on given site conditions (subgrade, climate, etc.). Afterwards, the pavement structural composition, inclusive of the necessary materials, are identified. This phase encompasses the processes involved for the design of new pavement, as well as for maintenance and rehabilitation, incorporating overlays, reconstruction, and rubblization. The structural design affects factors such as performance life, construction, durability, and lifecycle cost (Pavement Sustainability, 2014).

One of the methods to perform pavement design is the Mechanistic Empirical Pavement Design Guide (MEPDG). The MEPDG is a major change for pavement design. The word “mechanistic” denotes the use of engineering mechanics, leading to a design that has three components (Knoel, 2008)

- The theory to predict pavement critical pavement responses, such as stresses and strains and their relation to traffic and climatic conditions.
- Materials description and classifications, which are consistent with the associated theory
- The relationship between critical pavement response and observed distresses, which is known as the empirical part.

The MEPDG follows a set of defined procedures to analyze and design new and rehabilitated pavements. The MEPDG also uses common design parameters for traffic, climate, materials, subgrade, and reliability for all pavements design types. In addition, the MEPDG may be used for the selection of a design and design alternatives. Also, the MEPDG presents recommendations for the structure used, including materials and layer thickness for new and rehabilitated pavements. This recommendation is inclusive of a set of procedures to select various items such as: layer thickness, rehabilitation, foundation improvements, etc. (Knovel, 2008)

The output resulting from the MEPDG presents the projected distress, as well as the International Roughness Index, given at the selected reliability level. Therefore, the output is not a design procedure directly involving the thickness, but an analysis tool that may be used by the designer in an iterative method. More specifically, the MEPDG may be used to evaluate a trial design, including a mixture of layer types and layer thicknesses under specific site conditions, as well as failure criteria, given at a specific level of reliability (Knovel, 2008).

2.3.3.1 MEPDG general design approach

The design mechanism in the MEPDG consists of three steps and many procedures. There are various sets of inputs that should be included in the design, such as materials, traffic, and climate inputs. Materials input are a very pivotal part of the design procedure. The modulus, as a major component of the property, is necessary for all layers included in the design pavement structure. In addition, the elastic modulus is required for all PCC layers. For the traffic characterization, the procedure consists of estimating the axle load distribution applied to pavement structure. The MEPDG requires neither a single axle load (ESAL), nor a load equivalency factor. Also, the MEPDG permits a special axle configuration in addition to the standard, single, tandem, tridem, and quad axles (Knovel, 2008).

One major improvement for the MEPDG is the consideration of climatic impacts on pavement design, including materials, responses, and distresses, to be viewed as an incorporated technique. These impacts are evaluated using the Integrated Climatic Model (ICM). This ICM is considered a strong, climatic tool for modeling temperature and moisture for each pavement layer, as well as the foundation. This ICM considers hourly climatic data in various forms, such as temperature, precipitation, wind, and cloud, as well as humidity from different weather stations across the United States. Pavement layer temperatures, as well as moisture predictions, are gathered from the ICM and calculated hourly, and then are used to estimate material properties for pavement layers, as well as for a foundation over the entire design life (Knovel, 2008).

The second stage of the design consists of a structural analysis and an estimation of performance indicators and smoothness. The analysis process is iterative. First, the analysis starts by selecting an initial design, which could be performed by the designer. The design analysis then analyzes the pavement responses and distress models over time. The output of this stage includes material properties, as well as accumulated damage, distresses, and smoothness. When the design does not meet the criteria at a specified reliability level, modifications are performed until satisfactory results are met (Knovel, 2008). The third step is the evaluation of the design, based on a lifecycle cost analysis. This is to guarantee that the design is economical as well (Knovel, 2008).

2.3.3.2 Shortcoming of the current pavement design method

Yet despite all the previous design inputs used in pavement designs, there is no pavement design method that incorporates materials sustainability in the design framework, such as Global Warming Potential. The current pavement design framework is illustrated in Figure 10. Therefore in case materials, sustainability should be evaluated, and this framework should be altered (as performed in later chapters)

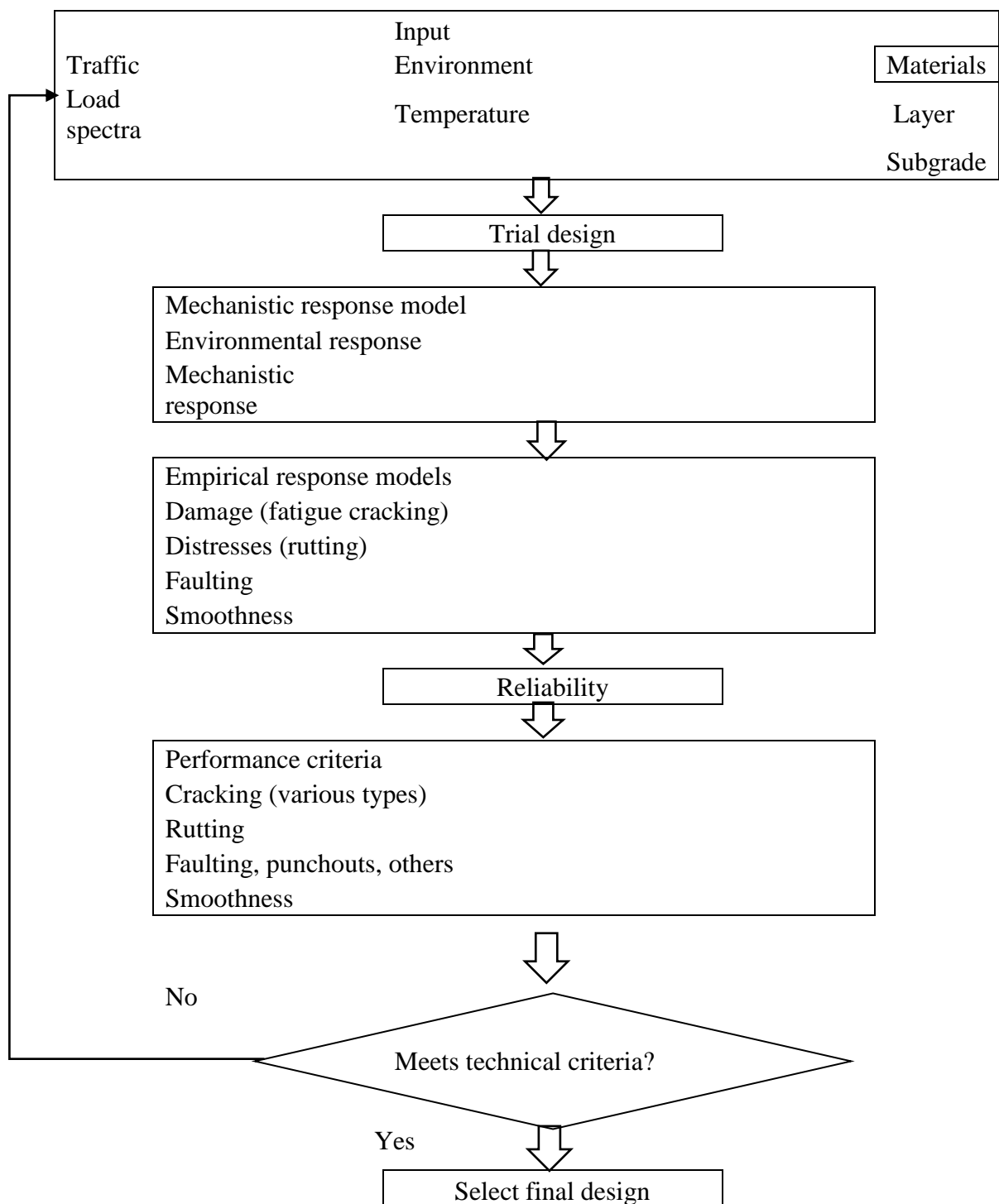


Figure 10. The MEPDG design framework (FWHA 2015)

2.3.4 CONSTRUCTION PHASE

The construction phase includes processes and equipment required for pavement construction (Pavement Sustainability, 2014). The following stages should be considered while evaluating the environmental impact in the construction phase: equipment mobilization and demobilization, equipment use at the site, and transport of materials from the site to final disposal option. The construction phase should also include traffic congestion related to construction activities (Pavement Sustainability, 2014)

Various studies discussed the effect of traffic congestion in the construction phase. Some of the factors affecting traffic congestion in the construction phase include: traffic volume, hourly traffic distribution, project duration, and the like. Studies that reflect the effect of traffic congestion in the construction phase include the works performed by Keoleian et al. (2005) and Chan (2007),

Keoleian et al. (2005) used a tool from the Kentucky Transportation Center to evaluate traffic delay, and afterward used EPA's MOBILE6 tool to convert the delay into various environmental impacts. The study compared two alternatives, concrete and asphalt pavements. The LCA phases included in the study are: material extraction phase, construction phase, use phase, and end of life phase. Results proved that traffic delay in the construction stage can be compared to the materials production phase (which was significant in this study), with respect to CO₂ and energy consumption, in the event of high traffic projects. The study concludes that with respect to CO₂ and energy consumption, the impact of traffic delay in the construction phase is greater than the impact of all the other phases included in the study. In addition, the impact of traffic delay becomes greater when traffic growth rate is included. For example, when the annual traffic growth rate increases from 1% to 2%, traffic impact increases by 13% and 23%, respectively (Keoleian et al., 2005).

In 2007, Chan performed an LCA analysis, incorporating traffic delay. The study compared two alternatives -- asphalt and concrete pavement. However, this study found different results from the one performed by Keoleian et al. (2005). Results of this study found that the material production phase is the most significant phase when compared to other phases, and that the impact of traffic phase is comparable to the material production phase (Chan, 2007); in turn, this finding contradicts the results of Keoleian et al., 2005. In addition, there are various works performed to assess the impact of construction equipment in the construction phase. This includes the work performed by Stipple (2001) and Chan (2007).

Stipple (2001) studied the impact of construction equipment in the construction phase. In this study, Stipple thoroughly presented various types of construction equipment, such as pavers and excavators. However, despite the thorough description for the construction equipment, this study did not include the traffic delay resulting from the construction phase, which could be considered one limitation of this study.

Hovarth and Hendrickson studied the impact of asphalt placement during the construction phase. This installation process results in bitumen fumes (Hovarth & Hendrickson, 1998) from unknown health hazards. These fumes cause eye irritation, as well as carcinogenic health effects. Various studies were performed in several countries to assess health impacts associated with asphalt fumes, such as the Netherlands, Norway, and Sweden (Boffetta et al., 2003). The studies tested the impact of exposing workers to bitumen fumes. Results indicated that workers experienced little lung cancer increase when compared to others who were unexposed to health fumes. However, more research should be conducted in this area.

2.3.5 PRESERVATION, MAINTENANCE, AND REHABILITATION

The maintenance and rehabilitation phase occurs during the lifecycle of a project by applying treatments to an existing pavement to slow the deterioration rate (Pavement Sustainability, 2014). Pavements with an extended lifetime undergo more maintenance and rehabilitation activities than those with shorter lifetimes. Maintenance and rehabilitation may account for a significant fraction of pavement lifecycle impacts. However, the relative importance of the maintenance and rehabilitation activities depends on the pavement design life and the maintenance schedule (Pavement Sustainability, 2014).

Various studies were performed to evaluate the environmental impact of the maintenance and rehabilitation phase. This includes the work performed by Chan (2007), Stripple (2006), and Athena (2006).

Chan (2007) compared two alternatives: asphalt vs. concrete. The study was performed in the United States. The study evaluated the impact of energy consumption, as well as greenhouse gases for both alternatives. The study included the maintenance and rehabilitation phase; however, it did not evaluate/incorporate the schedules of maintenance and rehabilitation activities. The study estimates that the energy consumption for flexible pavements in the maintenance phase reflects 10% of the initial construction (Chan, 2007).

Also, other studies such as Stripple (2006) evaluated the maintenance activities by detailing types of activities such as milling and patching, but the research defined no clear maintenance schedule which might have altered the results. The study evaluated both concrete and asphalt pavements. Results proved that energy consumption for flexible pavements in the maintenance phase accounts for 40% of the initial construction (Stripple, 2006).

Häkkinen and Mäkelä (1996) also analyzed the maintenance and rehabilitation phase. This study was performed according to the Nordic maintenance and rehabilitation schedule, making it very difficult to compare to studies performed in the United States.

Also, there are other studies performed by Berthiaume and Bouchard (1999). The purpose of the study was to compare the performance of concrete vs. asphalt pavement. The study included the maintenance phase of concrete. However, one of the limitations of the study was that it not only oversimplified the maintenance activities, but also provided a minimum of detail. For example, regarding the maintenance activities of concrete, the study only stated that half of the concrete top layer was changed for maintenance activities, and provided specific details for the maintenance type.

Moreover, the study of Moureh et al. (2000) included the maintenance phase. The purpose of the study was to analyze various types of pavement structures, mostly asphalt pavement. The study assumed that all the alternatives had the same maintenance and rehabilitation activities and therefore, the phases canceled one another's activities from the overall LCA analysis. The assumption that all the alternatives display the same maintenance and rehabilitation activities was based on the premise that all these alternatives deteriorate at the same rate, which could not be the case (Moureh et al., 2000). Therefore, this assumption may be considered as one of the limitations of this study.

Other studies that included maintenance and rehabilitation activities include the work performed by the Athena Institute in 2006. The study compared concrete vs. AC alternative. Various structures from each type were included in the analysis. This study was performed in Canada; therefore, all the data and assumptions performed pertain to the Canadian region. This study focused on intensive maintenance and rehabilitation activities, such as the use of new materials as well as overlays. Yet, the inclusions of minor maintenance and rehabilitation activities such as crack sealing, etc. were not included in the analysis, under an

assumption that the activities were insignificant. In this study, the concrete alternative had various maintenance and rehabilitation activities, including AC overlays that occurred at the last half of the design life. Moreover, the other concrete alternative went through full maintenance activities, including full reconstruction at the last year of the design period. As for the asphalt, the option went through more intensive maintenance activities, which included asphalt overlays, asphalt milling, and full reconstruction. Results of the maintenance phase indicated that the asphalt alternative consumed more energy, compared to the concrete alternative. The study estimated maintenance to be over 120%, compared to the initial construction (Athena, 2006).

Yet, through analyzing all previous studies, various studies clearly did not include the maintenance and rehabilitation schedule of the activities. Moreover, some of the studies did not include minor maintenance and rehabilitation activities, and accounted for only the major maintenance and rehabilitation activities. These studies occurred in various countries, which resulted in making an overall comparison for the maintenance activities between countries without resolution.

2.3.6 END OF LIFE OPTION

The pavement end of lifecycle is defined as “the final deposition and subsequent reuse, processing or recycling of any portion of a pavement system that has reached the end of its lifecycle.” The end of life option includes reuse, recycled, or landfill options. For asphalt pavement, end of life options includes central plant recycling, as well as full depth reclamation and landfills. The concrete pavement end of life options includes recycling, reuse, and landfills. However, each end of life option is a pathway requiring a unique approach to quantify the environmental impact.

A detailed economic and environmental analysis for recycling and reusing pavement should be performed to quantify various end of life options. For example, pavement recycling

is affected by materials transportation, compared to using virgin materials that are directly transported to the construction site (Horvath, 2003). Important factors to consider are technology, disposal costs, transportation, application, and quality.

- **Technology.** Technology determines whether on site or off site recycling would be better. The on site recycling requires construction equipment. This choice includes both cold and hot in-place recycling, as well as full depth reclamation. The other option consists of recycling pavement in a central plant. This would require environmental costs such as demolition at the job site, as well as crushing, screening, and stockpiling at the plant.
- **Disposal Costs.** When disposing recycled materials in a landfill, the total disposal costs will include demolition, transportation, and landfill tipping fees. These fees range from \$10 to \$70 per ton. The range varies widely, even for small distances. However, it is important to realize that landfill areas are diminishing.
- **Transportation.** For recycled materials, the necessary transportation can carry a high environmental burden, as a result of material transportation from job site to landfill, from job site to a central plant for processing, or from the plant back to the job site.
- **Application.** Reused pavement may be reused in base layers or surface layers. It can also be reused in embankments and fills.
- **Quality.** The original quality of the recycled materials, such as its processing, storage, and local specifications, determines the final applications. Not only does the quality for using recycled pavement differ for concrete and asphalt pavement, but the potential contamination of recycled pavement may limit its use.

One more thing to note about literature review, as related to end of life options: Little literature review exists about the landfilling option, which seems to be less attractive due to the economic value associated with recycling. Moreover, landfill areas are already

decreasing. As a result, the landfill option becomes less attractive (Rajendran & Gambatese, 2007).

When using the recycling option, the welfares and impacts of recycling should be divided amongst the manufacturer and the user; this division will involve allocation and specifically, open loop allocation. Further analysis into literature review, as well as the ISO 14040 Standards for allocation procedure, reveals that allocation does exist in the ISO 14040 Standards; yet the open loop allocation is not defined (ISO, 2006). This resulted in various literature reviews that proposed various allocation methods; however, none of these methods are commonly accepted (Sanetero et al., 2011)

For example, in a study performed by Ekvall and Tillman (1997), the objective of the study was to make the allocation effect oriented, rather than cause-oriented. The study first defined an allocation based on ISO Standards, as well as the current problems associated with allocation methods. The authors then proposed eight allocation methods for end of life (Ekvall & Tillman, 1997). Moreover, the authors concluded that the allocation method is very specific to each study, depending on the goal and scope of the study. As a consequence, the study presented no rigid method or theory for allocation, since the findings would be study specific.

Other studies performed on allocation include the work performed by Nicholson et al. (2009). The study proposed only five different allocation methods. Moreover, the study came up with a different conclusion. The study stated that the selection of an end of life option can impact material selection (Nicholson et al., 2009).

The work performed was related to landfilling and recycling options. As a result, various work was performed to evaluate the environmental impact of landfill (EPA, 2006), under the premise that this option was easier to predict, compared to the recycling option.

Studies that included the end of life option include the work of Huang et al. (2007), and Horvath and Hendrickson (1998).

Huang et al. (2007) performed a study on the impact of using recycled materials for asphalt pavement (Huang et al., 2007). The paper discussed the impacts of using recycled materials such as glass, tires, etc. as an alternative for virgin materials. The study concluded that the benefits of landfill option and the use of virgin materials is counteracted by the negative impacts of leaching that can occur in a landfill (Huang et al., 2007). The study concluded that the use of recycled materials can be an added advantage, provided that such use would be used appropriately.

Horvath and Hendrickson (1998) also studied the end of life option. The author first started by giving statistics for the amount of recycled asphalt vs. concrete materials. He based his statistics on a survey performed by the Federal Highway Administration: The survey was performed in 29 highway agencies; the statistics indicated that 80% of removed asphalt was recycled into highway application , resulting in more than 70 million metric tons of asphalt not going to landfill per year (U.S. Department of Transportation, 1993). The author then gave some examples of the applications of recycled asphalt in various Departments of Transportation.

Results indicated that each Department of Transportation had a different issue with using the recycled asphalt. For example, the Arizona Department of Transportation had problems with the uniformity of the recycled asphalt (Horvath & Hendrickson, 1998). The author concluded that the performance of recycled materials/asphalt for the long term is not documented, which in itself constitutes a problem. The study then recommends that future work be required for predicting the long term performance of recycled materials.

2.3.7 PAVEMENT LCA CRITICAL REVIEW AND CURRENT GAPS

After presenting a detailed analysis of the existing problems in each phase of pavement LCA, this section will critically review the previous studies per phase. However, before a critical review, it should be noted that there are common problems between all studies that pertain to the performance of LCA.

Each of these studies presents a different system boundary, uses a different functional unit, and was performed in a different country. Consequently, the use of data pertaining to each country makes the comparability issue almost impossible across all studies. The multiple variations make a consistency in comparison unattainable. Moreover, depending on the goal and scope definition of each study, each author used a different LCA, ranging from attributional to dynamic to hybrid LCA.

For example, the study performed by Häkkinen and Mäkelä (1996) was performed in Finland. The author used a process LCA that covered LCA phases included materials, construction, use, maintenance, and rehabilitation items, and the functional unit used was 1 km.

The study was performed by Park et al. (2003) in Korea. The author used a hybrid LCA, while the included phases constituted materials, construction, maintenance, rehabilitation, and an end of life option. The functional unit used was energy consumption. These differences already rendered a comparison across all studies virtually impossible. However, the current gaps per phase will be presented in this section.

2.3.7.1 Material extraction phase.

The material extraction is the phase that was mostly included in LCA. In addition, this is the phase that contributed to the most environmental impact compared to other phases. Issues related to the material extraction phase mostly revolve around the inclusion/exclusion

of the feedstock energy. The inclusion of the feedstock energy, highly alter results, compared to an earlier lack of inclusion in the analysis. More research is required in this area.

2.3.7.2 Design phase

The major shortcoming in the design phase, when evaluating the MEPDG, is that there is no evaluation/incorporation of the environmental impact of those materials used in its framework. More research should be performed to characterize and evaluate the environmental impact, especially towards helping decision makers in the decision making process. Pavement design should not be evaluated based on technical performance only, but should also include the environmental impact.

2.3.7.3 Construction phase

Although the construction phase includes the following criteria: equipment mobilization and demobilization, equipment usage at the site, and transport of materials from the site to the final disposal option, the construction phase should also include traffic congestion, related to construction activities. None of the presented research included all the criteria. For example, some research focused on equipment use alone, while others focused on traffic congestion.

Future work should then focus on integrating all the criteria affecting the construction phase together. Moreover, more work should focus on studying/modeling the impact of traffic congestion, as traffic congestion is very specific to each project and should not be generalized to all projects. Also, the construction phase can be ameliorated by using sustainable construction practices. There are various approaches for a sustainable construction, such as reducing fuel consumption in construction equipment and operations. This reduction will have environmental and economic impacts. The environmental impact may be seen in lower environmental emissions, while the economic impact may be seen in lower fuel consumption, and therefore lower fuel cost. Also, by reducing construction time,

this reduction will lead to less lane closure, and as a favorable consequence, lower vehicle emissions (FHWA, 2015).

2.3.7.4 The maintenance and rehabilitation phase

Most of the studies did not define the maintenance and rehabilitation activities occurring in this phase. Moreover, some studies assumed that the performance of all alternatives remains the same, and therefore the environmental impact of the maintenance and rehabilitation activities would cancel out one another's impacts, which is incorrect. It should be noted that detailed maintenance and rehabilitation activities should be performed for each design, and the environmental impact should be modeled accordingly.

2.3.7.5 The use phase

Various issues are associated with the use phase. As previously illustrated, factors affecting the use phase include: pavement structure, pavement roughness, vehicle speed, noise, lighting and leachate. Each one of these factors needs future research consideration as follows:

- Pavement structure and pavement roughness: Studies rarely characterized the overall pavement design used in each study. Moreover, not all pavement roughness was taken into consideration. Future characterization should be performed to model all pavement types and designs.
- Noise: More research should be performed in this area, as noise was not much included in the literature review. Also, more information should be put into LCA software in order for stakeholders to use this information in performing LCA.
- Lighting: More research should be performed in lighting technology. The more the technology advances in the lighting area, the less energy will be consumed, and therefore huge energy savings may be achieved while performing an LCA.
- Leachate: More research should be performed to assess the impact of leachate on the environmental as well as the health system.

Moreover, each of the previous factors was modeled separately in the literature review. For example, some literature reviews studied the impact of noise, while others studied the impact of lighting, and still others studied the impact of leachate. However, no study integrated all factors together in a single model. Therefore, the interaction between all these models does not exist in a combined model.

2.3.7.6 End of life option

Gaps associated with the end of life option include predicting the long term performance of recycled materials. Moreover, in case of using the recycling option, there should be proper allocation methods. As illustrated in the past literature reviews, there is no fixed rule for allocation and to date, this is project specific, depending on the study. More research should be performed in this area to determine proper allocation methods.

2.3.8 ANALYSIS OF CONCRETE VERSUS PORTLAND CEMENT PRODUCTION

After examining pavement LCA phases in detail for both concrete and asphalt pavement, more detailed analysis should be performed for concrete. To be more specific, a comparison will be performed between LCA literature review for concrete and cement, a component contributing to significant environmental impact during concrete production (8). The analysis will be performed from cradle to gate and will be focusing on two of the four LCA stages: scope and goal definition and lifecycle inventory analysis. The objective is to determine existing limitations and areas requiring future work.

2.3.8.1 Portland cement

Portland cement production is composed of the following stages: extraction of raw materials, and preparation of raw materials as well as blending, bioprocessing, grinding with gypsum, packaging, and finally shipping the final product (Innovations in Portland Cement Manufacturing, 2011). The inclusion of the transportation stage is very important in Portland cement production, as it occurs over most of cement lifecycle.

Literature review reported that the processing part of the Portland cement is the most energy-intensive part, contributing to 90% of the total energy used in cement production (Medgar et al., 2007). As for the raw material extraction, this stage is not considered significant in the whole lifecycle. Despite the fact that this stage does not consume much energy, the stage nevertheless contributes to high emissions of particulate matter. One more thing to note here is that the inventory values for raw material preparation, grinding, milling, and transportation stages are not much provided in literature review, since these stages are considered negligible (Gorse, 2014). Also, although the impact of each of these stages might be negligible, the combined group effect might be significant.

Few literature reviews focused on studying different types of cement, such as blended cement in the United States. In fact, this finding is due to regulations in the United States that restrict the use of blended cement (Boesch et al., 2010). Therefore, when studying blended cement in the United States, external data sources should be reviewed.

During the cement production stage, energy is consumed in various forms such as fuels and electricity. The fuel used depend on the manufacturer and the technology used, therefore imposing another source of variability from one manufacturer to the other (Oss, 2005). As for electricity, it is used for crushing, grinding, and rotating the kiln. As for the energy consumption data used during production, these are mostly national averages. Detailed information about variations in these energy data are not evaluated, which causes problems for researchers requiring detailed information about energy consumption. As, for the inventory/data from upstream, in case the clinker is imported, the data from the country of origin is not taken into consideration. Instead, both domestic and imported clinker are assumed to be produced using similar technologies (Medgar et al., 2006).

Also, clinker production requires a huge amount of heat requirement. Waste fuel are used as a provider of heat requirement. These are first prepared before combustion in the

cement kiln. The common waste fuel used is tires. These tires require shredding, which is also a heat intensive process, 45 Kilowatts hour/ton (Boesch et. al., 2010).

The amount of clinker required for cement production can be decreased by the use of supplementary cementitious materials (SCM) such as fly ash and natural Pozzolans (Cyr, 2013). The use of (SCM) has various advantages such as: reducing the amount of material going to landfill and reducing the amount of clinker required for the production of cement. Therefore, these SCM can contribute to lowering the environmental impact as well as the total cost. The use of natural Pozzolans can reduce up to 25% of cost per cement bag for contractors. This reduction might also be an incentive to build new infrastructure (Mihelcic et. al., 2007). In countries such as Philippines, a developing country, the use of pozzolans was linked to socioeconomic indicators (Harris et al., 2008), therefore contributing to sustainable development. Also, when studying the strength of blended cements including Pozzolans, results proved that it is comparable to the use of pure cement until a substitution level of 25% to 60% (Cyr, 2013).

One more thing to note, Portland cement might be blended with other materials such as Ground Granulated Blast Furnace Slag (GGBFS). Depending on the type of blended material, the required heat/ energy will vary. For example, the GGBFS is related to higher environmental impact because it has lower particles and sometimes requires extra drying requirements. For example, GGBFS requires 95 Kilowatts hour/ton to prepare slag, before mixing it with GGBFS (Skokie, 2003) and 7 Kilowatts hour/ton for fly ash preparation.

2.3.8.2 Portland cement concrete

At the present, concrete production contributes to more than five percent of Carbon Dioxide produced annually, due to the production of cement clinker. In 2011, an amount of 3 billion metric tons were produced worldwide (Geological Survey, 2011), contributing to 2.6 billion metric tons Carbon Dioxide (Mehta, 2008). Around half of these emissions result from

fossil fuel combustion, because cement Portland cement requires extensive energy at 4 to 5 billion metric tons/ton (Mehta, 2001). The other half goes to the calcination process for limestone. It should be stated that in general, for 1 million tons of Portland cement clinker, 0.85 ton is emitted to the atmosphere (Cement Industry Energy and CO₂ Performance, 2009). It should be noted that this amount varies by different factors such as technology, location, and production efficiency (Gursel, 2014). Also, it should be stated that Carbon Dioxide is not the only emission resulting during concrete production, and that there are other emissions.

It should be noted that concrete is a mixture of various products. Therefore, to study concrete, concepts such as allocation should be understood (Gorse, 2014). The allocation procedure should facilitate how the inputs and outputs should be divided among different products, based on the relationship between these products. However, existing literature reviews do not employ allocation. The allocation process is either done arbitrarily, or on a 100% basis (Gursel, 2014), leading to biased results. In regard to admixture inclusion, little literature review focused on admixtures, under the assumption that these are included in concrete with little percentage (1%), and therefore, their impacts are negligible and not worth studying (Gorse, 2014).

Also, not all the environmental impacts/emissions were equally examined in literature review. For example, various literature reviews focused on greenhouse gas emissions, and did not much focus on other criteria such as Volatile Organic Compounds (VOCs). VOCs are particulate emitted after the concrete manufacturing process (Gorse, 2014). Therefore, more research is required in accessing criteria such as VOC's, especially for concrete containing chemical admixtures (Environmental comparability of cement and concrete, 2005). Also, emissions of heavy metals were not much studied in concrete LCA studies (Gorse, 2014), which requires future research. As for the waste resulting from the manufacturing process, not all waste types were included in the analysis. Solid and liquid waste from concrete

batching and water production were not thoroughly studied and need future research (Gorse, 2014).

To conclude, concrete and cement materials are vital construction materials used worldwide. Cement from among other concrete constituents, as one of the major contributors to greenhouse gas emissions, was mostly studied. However, other constituents must be further studied; this procedure will require proper knowledge of criteria such as allocation.

In addition to these specific drawbacks that occur while performing LCA to evaluate Portland cement concrete and Portland cement, there are further drawbacks associated with the use of LCA itself, that are reported in literature review. For example, there is a lack of application regarding regional and technological variations (Gursel, 2014). This criteria is really important, since criteria such as footprint, should be evaluated based on local data. However, what currently exists is that only industry wide average data are provided. This makes it difficult for a certain company to use, since the factors used pertain to a specific region, such as the electricity grid (Gursel, 2014).

Other drawbacks related to the application of LCA by various researchers is the use of different functional units. Although not currently performed, it is highly recommended to use a functional unit that includes all concrete aspects and properties, for strength and durability.

2.3.8.3 THE DEVELOPMENT OF ENVIRONMENTAL PRODUCT DECLARATIONS

Based on a previous analysis of LCA and its limitations, there should be another method in place for assessing the environmental impact of a product, as an emerging method for quantifying the environmental impacts of a product which employs Environmental Product Declarations (EPDs), or a Type III Environmental Declaration. The overall objective of EPD is: “the communication of verifiable and accurate information that is not misleading on the environmental aspect of products and services, to encourage the demand for and supply of those products and services that cause less stress on the environment, thereby

simulating the potential for market driven continuous environmental improvement” (ISO, 14020).

2.3.9 ENVIRONMENTAL PRODUCT DECLARATION METHODOLOGY

Environmental information in EPDs shall be based on procedures and results from a lifecycle study based on an ISO 14040 series of standards. To date, EPDs have been based on a lifecycle approach using LCA. This section will explain methodological options for issuing EPDs. There are various ways for issuing an EPD. The common element between all options is that these are based on a lifecycle interpretation based on ISO 14040, ISO 14041, and ISO 14043. Yet the routes to a final declaration can vary, depending on the inclusion of items such as data analysis as well as the inclusion of additional information (ISO 14025:2006). These routes are illustrated in Figure 11. Existing routes are as follows, according to (ISO 14025:2006):

- Route A: based on lifecycle inventory analysis (based on ISO 14040, ISO 14041, and ISO 14043)
- Route B: based on lifecycle inventory and lifecycle impact assessment (ISO 14040, ISO 14041, ISO 14042, and ISO 14043)
- Route C: based on lifecycle inventory and lifecycle impact assessment (ISO 14040, ISO 14041, ISO 14042, and ISO 14043), plus any additional analysis of the data. However, this additional analysis does not follow the ISO 14042.

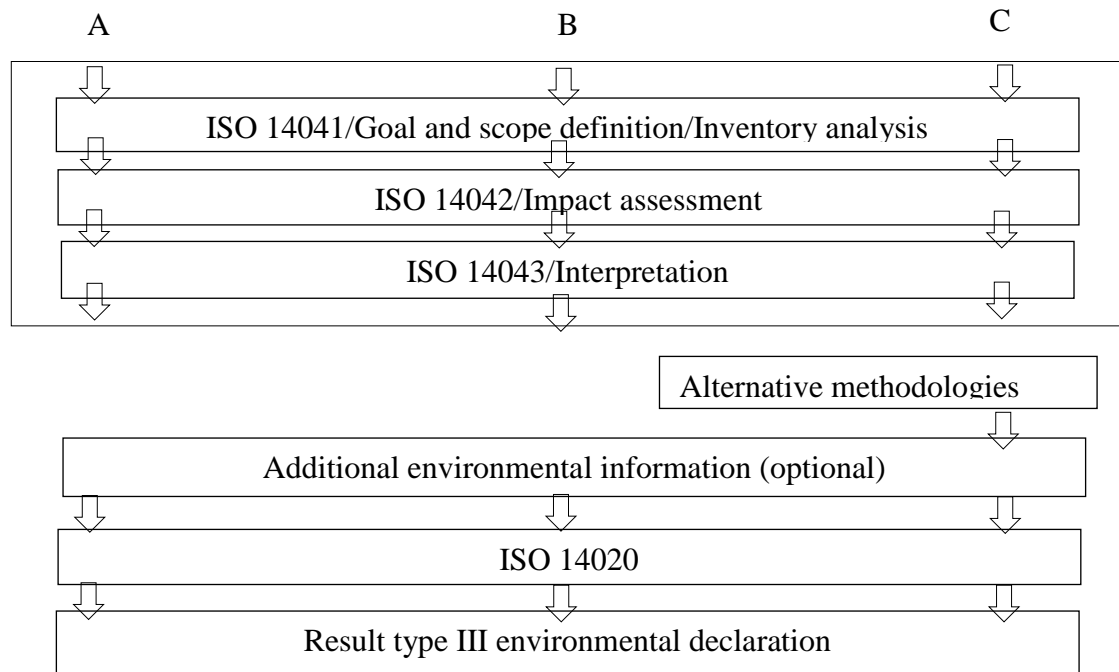


Figure 11. Various routes for issuing an EPD (ISO 14025)

It should be noted that the main purpose of EPDs is to offer measurable environmental data, which are verifiable and not misleading. Although EPDs do not include comparative claims, the information may be used to make a comparison between products (ISO 14025:2006).

A relationship exists between LCA and EPD, as shown in Figure 12; EPDs are the summary of the data collected in LCA. These are verified by a third party to guarantee transparency, based on ISO 14025.



Figure 12. LCA and EPD relationship

2.3.10 CONTENT OF ENVIRONMENTAL PRODUCT DECLARATION BASED ON PCR

It also should be noted that a critical review is used to attest whether the LCA study performed follows international standards, such as ISO 14040, ISO 14041, ISO 14042, and ISO 14043. The evaluation process should follow the critical review method of 7.3.3 in ISO

140:1997. The critical review should validate the scientific and technical soundness of the LCA performance, i.e., whether the data used is valid and in accordance with the goal and the scope of the overall study and finally, ensure that the final report produced is transparent. Moreover, the critical review should also contain information on the content and format of the external verification (ISO 14025:2006). Table 8 illustrates which items should be included/excluded in the EPD (North American Product Category Rules 2012).

The full system boundary is illustrated in Figure 13. This should limit any inconsistencies in performing an LCA, when performed by various researchers.

Table 8. Information in/out of PCR (North American Product Category Rules 2012)

Information included in PCR	Information excluded from PCR
The name and address of the manufacturer.	Production, manufacture, and construction of buildings and capital goods
The construction product use and the declared unit related to the data described	Production and manufacture of concrete production equipment and concrete delivery
An identification of the construction product by name.	Personal related activity, such as travel and furniture
A list including the product components and the associated ASTM standards.	Energy and water use related to company management.
The name of the EPD program used and associated program operators, including names, addresses, websites, and logo.	
The date the declaration was issued and the period of validity (5 years)	
Raw material supply, inclusive of the following: extraction, handling and processing of raw materials used for concrete production, cement, additional cementitious materials, aggregate (including coarse and fine), water, admixtures, and any additional materials or chemicals used.	
Transportation: The transportation process includes the transportation of the materials from suppliers to the gate of the concrete producer.	
Core processes/manufacturing: This process includes the energy used for storing, batching, mixing, and	

Table 8 (cont.)

Information included in PCR	Information excluded from PCR
distributing concrete and identifies the operating facility/ concrete plant.	
Water used in the mixing and distribution process of concrete.	

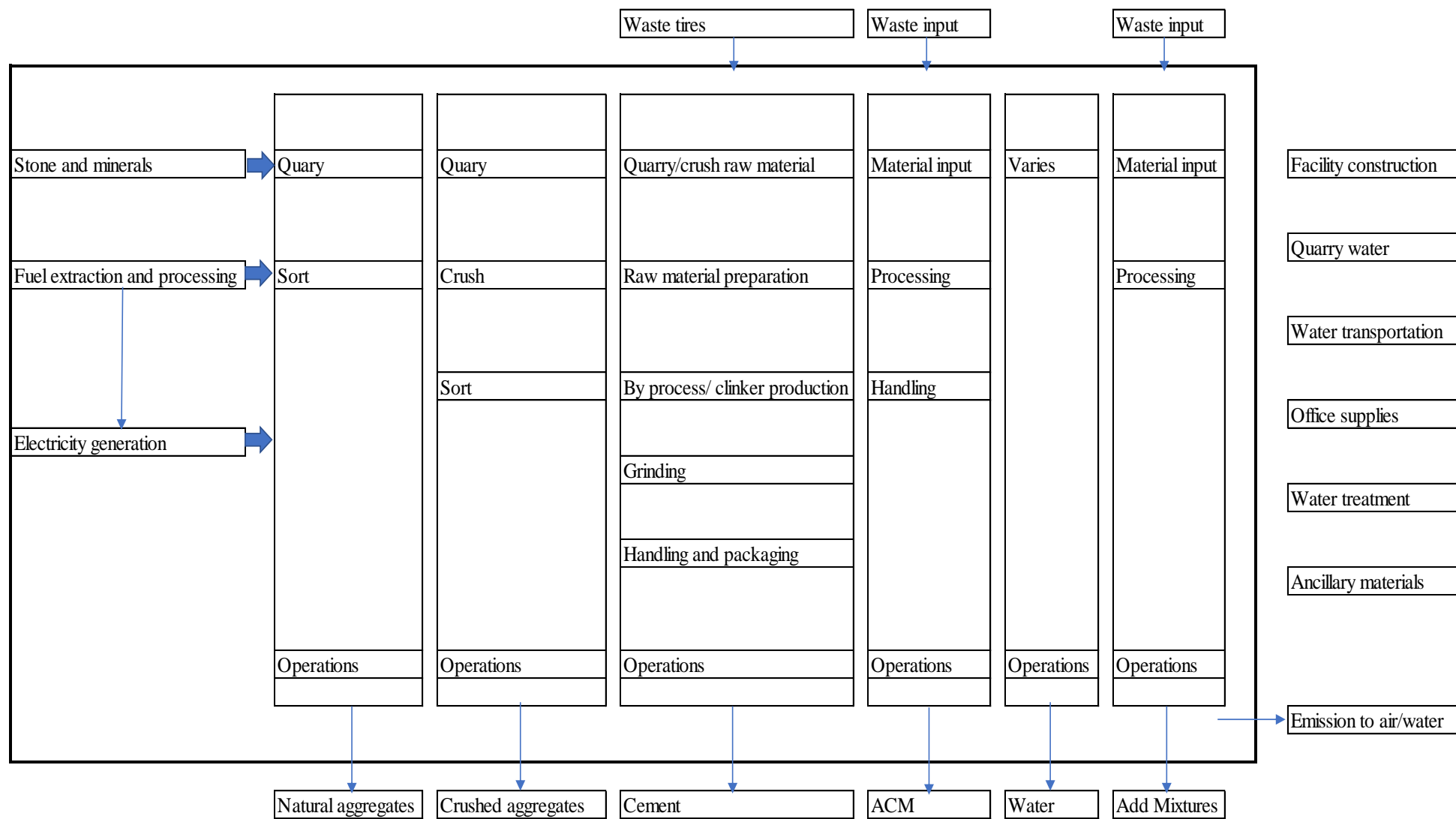


Figure 13. System boundary based on PCR (North American Product Category Rules 2012)

2.3.11 CRITICAL REVIEW OF PRODUCT CATEGORY RULE (PCR)

Although many modifications exist in PCR, improvements are still necessary. For example, there is a section in PCR called: additional environmental information. This section presents an opportunity to discuss and align conventional LCA indicators and other indicators that were seldom treated by LCA methods in the past, such as: biodiversity, land use, impact on threatened species, toxicity from direct exposure, and working conditions, etc. (Ingwersen & Stevenson, 2016).

Moreover, PCR does not yet include a consideration for benchmarking (Fores et al., 2015). PCRs provide no section for data interpretation. Consequently, the resulting EPDs only provide and report environmental information, with no provision for benchmarking or interpretation criteria (Fores et al., 2015). Also, PCRs do not provide information on how to assess site-specific environmental impacts, nor do they assess human health toxicity (Fores et al., 2015). Another dimension that should be added to PCR is material content, through a listing of chemicals, or what is termed health product declarations. As a result, this PCR solely provides guidance on environmental information, and reports no information on either social or economic aspects (Fores et al., 2015).

Another point to highlight is the scope of the PCR, which only covers a cradle to gate analysis, rather than the entire lifecycle of the product (from cradle to grave). Given this scope, it should be noted that the PCR takes only a snapshot of the product lifecycle in order to analyze it, and therefore durability consideration is not considered. As an example, if a product offers twice the service life of another alternative, is it a good alternative if it has 75% more initial impacts? This is not currently discussed in the current PCR (Shepherd, 2016).

2.3.12 THE USE OF ENVIRONMENTAL PRODUCT DECLARATIONS (EPDs)

Manufacturers and practitioners use EPD for different purposes. Table 9 illustrates these different purposes (Understanding Environmental Product Declarations). Both manufacturers and practitioners use EPDs for assessing product transparency. Manufacturers use EPDs to a) identify product improvement opportunities, b) to help in understanding LCA, c) to verify product information, and d) to show Carbon footprint reduction. However, practitioners use EPDs for different purposes, such as in LEED credits, Green Globes credits, in a comparison of similar products, and to aid in understanding LCA.

Table 9. Use of EPD by manufacturers and architects (Understanding Environmental Product Declarations)

	Manufacturers	Practitioners
Product transparency	√	√
LEED® credit		√
Green Globes credit		√
To compare similar products		√
To identify product improvement opportunities	√	
To aid in understanding LCAs		√
To validate marketing claims	√	
To verify product information	√	
To show Carbon footprint reduction	√	

2.3.13 USING EPD FOR ACCREDITATION

The green building industry continues to grow at an increasing rate. According to McGraw-Hill, the construction industry is estimated to make 48-55% of the non-residential building market, following 29-38% of the residential building market in 2016. The industry published the EPDs for products such as wood, and the steel and asphalt industries are engaged in presenting EPDs as well. Therefore, a similar study/EPD is required for the concrete industry (NRMCA, 2016).

The LEED vs. 4, Architecture 2030 Challenge for products and the International Green Construction Code entails that building manufacturers must submit Environmental Product Declarations (EPDs) to prove the environmental performance of their products

(NRMCA 2016). LEED vs. 4 gives two points for projects that can document that 1) The projects have 20 products/materials with EPDs; and 2) The projects have 50% in cost of their products, demonstrating lower impacts than the industry baselines through EPDs.

The LEED vs. 4 points are given as follows (NRMCA, 2016):

- Self-declared EPDs are worth $\frac{1}{4}$ value (not verified by a third party).
- Industry wide EPDs are worth $\frac{1}{2}$ value (verified by a third party). These industry wide EPDs and industry baselines will allow producers to compare their products against a baseline.
- Plant-specific verified EPDs are worth full value (verified by a third party).

The scope of the study included 72 ready mix concrete products produced by various companies. This study was performed in accordance with the requirements of the Carbon Leadership Forum (CLF) Product Category Rules (PCR) for ISO 14025 TYPE III Environmental Product Declarations (EPDs) for Concrete vs. 1.1 December 2013 (Athena, 2016).

This EPD project report evaluates the impacts for a range of ready mixed concrete products. The specifications used are ASTM C94: a) standard specifications for ready-mixed concrete, b) ACI 318, c) building code requirements for structural concrete, d) A23.1-09/A23.2-09 (R2014), using concrete materials, methods of concrete construction/test methods, and standard practices for concrete, e) UNSPSC Code 30111500 ready mix, and f) ACI 211.1: standard practice for selecting proportions for normal, heavyweight, and mass concrete (Athena, 2016).

The intended application of this industry wide EPD is Business to Business communication (B to B). The intended audience is inclusive of architects, engineers, professionals, LCA practitioners and tool developers, academia, governmental organizations, and policy makers (Athena, 2016).

The regions were divided into the following 8 regions, illustrated in Figure 14:

1. Eastern Region
2. Great Lakes Midwest Region
3. North Central Region
4. Pacific Northwest Region
5. Pacific Southwest Region
6. Rocky Mountains Region
7. South Central Region
8. South Eastern Region

In addition to the previous eight regions, a U.S. national average was produced. Values are provided in Appendix B. Table 10 illustrates the production data summary for each region, such as the number of plants, the percentage transit plants, the percentage central mix plants, the average production, the total production, and the maximum and minimum production.

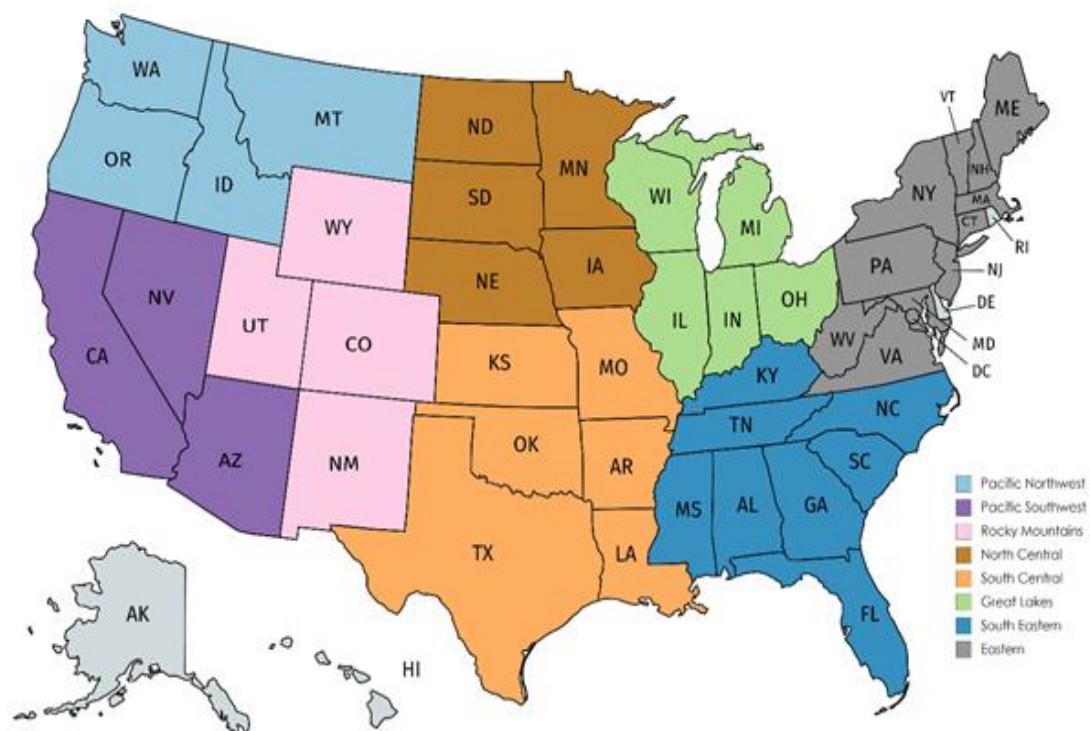


Figure 14. Industry wide average regions (NRMCA 2016)

Table 10. The production data summary for each region (NRMCA 2016)

Region	U.S. national	Eastern region	Great Lakes Midwest region	North Central region	Pacific Northwest region	Pacific Southwest region	Rocky Mountains region
Number of plants	469	59	51	32	19	49	16
% Transit mix plants	83%	68%	66%	69%	58%	68%	59%
% Central mix plants	17%	32%	34%	31%	42%	32%	41%
Average production (yd ³)	47,702	53,984	59,200	30,232	50,654	76,956	48,510
Total production (yd ³)	22,372,23	3,185,06	3,019,20	967,416	962,432	3,770,84	776,157
Minimum production (yd ³)	596	1,734	4,690	2,278	1,652	7,561	6,831
Maximum production (yd ³)	403,143	266,909	267,999	168,000	347,014	403,143	165,575

The compressive strength distribution for each region is illustrated in Table 11. The compressive strength range value was divided into three categories: ≤ 3500 , > 3500 & ≤ 5000 , and > 5000 .

Table 11. Compressive strength distribution per region as well as per national average (NRMCA 2016)

Compressive strength (psi)	U.S. national	Eastern region	Great lakes Midwest region	North central region	Pacific northwest region	Pacific southwest region	Rocky Mountains region
≤ 3500	49%	52%	25%	14%	47%	55%	36%
> 3500 & ≤ 5000	45%	42%	60%	83%	47%	40%	59%
> 5000	6%	6%	15%	3%	6%	5%	5%

2.3.14 BENCHMARKING PROCESS USING EPD

As previously discussed, this industry wide EPD will allow decision makers in the concrete/or pavement industry to compare their products against a baseline. Based on this comparison, the decision maker will then be able to evaluate the accreditation status. The

benchmarking process, illustrated below, is performed by the National Ready Mix Concrete Association. For example, a company in Texas was used to benchmark the environmental impacts of its concrete products with respect to the industry wide average study performed. In fact, this company has issued its own EPD.

Table 12 illustrates the individual EPD produced by the company for a certain product, while Table 13 illustrates the industry-wide average study. Values will be illustrated for GWP, ODP, Acidification Potential (AP), Eutrophication Potential (EP) and Photochemical Ozone Creation Potential (POCP). Since the State of Texas is located in the south central region, previously illustrated in Figure 14, the industry-wide average results for the south central region were selected for comparison. These values are illustrated in Table 11. As may be seen, products produced by this company are higher than the industry-wide average for the GWP, AP, and POCP values, and are lower for the rest (ODP and EP values).

Table 12. Individual EPD for a certain company

Compressive strength value (psi)	GWP	ODP	AP	EP	POCP
3000	340	4.15E-06	1.914	0.059	27.1

Table 13. Industry wide average study for the central region

Compressive strength value (psi)	GWP	ODP	AP	EP	POCP
3000	320.82	8.17E-06	1.10	0.39	22.73

The units are as follows:

- GWP are given in units of kgCO₂ eq
- ODP are given in units of kg CFC-11 eq
- AP are given in units of kg SO₂ eq
- EP are given in units of kg N eq
- POCP are given in units of kg O₃ eq

This was given as an illustration. However when documented, the user can select any other values for benchmarking..

2.3.15 EPD AS A TOOL FOR PAVEMENT SUSTAINABILITY QUANTIFICATION

To date, EPDs are not used as a tool to quantify pavement sustainability, due to reasons discussed above. The most important rationale is that the foundation for building an EPD must be improved. However, whenever the EPDs are available, these may be used to assess pavement sustainability (FHWA technical meeting).

2.3.16 IMPACTS OF USING EPD IN A PROJECT

The use of EPD involves more material research than materials that do not rely on EPDs. The use of EPD forces the designers to look more seriously into LCA information in EPDs. The use of EPD also increases communication between manufacturers, due to documentation requirements for the EPD credit. Designers also noticed that the use of EPDs requires specifications to be written in a different manner than other projects, which do not require EPDs (Gelowitz & McArthur, 2016).

In general, the specifications are written in an open ended manner, whereby contractors can choose any manufacturer, provided that the product meets or exceeds the criteria. Yet when EPDs are used, the specifications must be tighter (Gelowitz & McArthur, 2016).

2.3.17 BENEFITS OF USING AN EPD IN A PROJECT

From a designer's perspective, the following are some of the advantages of using EPD in a project (Gelowitz & McArthur, 2016).

- The fact that EPDs represent verified documents about the environmental impacts of a product
- Using EPDs allows an informed decision about a product
- The use of EPDs provides transparent information about a product

From a contractor's perspective, the following represent some of the advantages of using an EPD in a project (Gelowitz & McArthur, 2016).

- Better transparency in material performance
- Consistency of materials selected through the use of a standard document (ISO 140025:2006).

2.3.18 DRAWBACKS FOR USING AN EPD IN A PROJECT

One drawback for using an EPD in a project includes an upcharge for products with EPDs. In addition, products sent from further distances means more shipping costs. The warranties for certain products depend on the use of adhesives that have no EPDs, which in turn creates a problem for the contractor (Gelowitz & McArthur, 2016).

2.3.19 PROBLEMS FACING EPDs IN THE UNITED STATES

The United States faces many issues for the development and use of Environmental Product Declarations. First, the current infrastructure is inadequate to support the development and use of EPD in the United States. Second, there is almost no legislation requiring the use of EPD in the United States, making the use of EPDs optional. It is highly recommended that the EPA takes the lead in developing a strong lifecycle inventor (Schenck, 2010). Third, there is no support for product category rules. For a proper development of LCA, these product category rules should first be well developed (Schenck, 2010). Currently, EPDs are not used in decision making. There is, however, a tendency to use them in decision making when these are fully developed.

2.4 SUSTAINABILITY RATING TOOLS

A sustainability rating system is a checklist of sustainability best practices related to a common metric. This metric is usually a set of points that quantifies best practices in a common unit. By following this method, all the sustainability best practices (energy saved, ecosystem, water runoff, etc.) can be assessed in common units (points) (FHWA, 2015).

Presently, there are various rating systems used by the Department of Transportation. These rating systems have different scopes and different rating score systems. Rating systems

usually focus on practices that match existing regulations, but remain above the minimum requirement. Rating systems are criticized most of the time, due to the following: 1) These are considered to be simplistic, and therefore miss the required details; 2) The rating systems do not include all the scope for sustainable solutions; 3) There is difficulty in deciding which items to include/exclude in the analysis (FHWA, 2015). This section will present some of the sustainability rating tools used in various states.

2.4.1 ENVISION

Envision was developed by the Institute for Sustainable Infrastructure (ISI), with the cooperation of the Zofnass Program for Sustainable Infrastructure at the Harvard Graduate School of Design. This rating system rates infrastructure such as water storage and treatment, energy generation, landscaping, transportations, and information systems. The system was formed by three organizations: The American Public Works Association (APWA), the American Society of Civil Engineers (ASCE), and the American Council of Engineering Companies (ACEC). Envision has 60 sustainability credits that are arranged into five categories: quality of life (13 credits), leadership (10 credits), resource allocation (14 credits), natural world (15 credits), and climate and risk (8 credits). The program encourages the use of lifecycle analysis in planning, designing, construction, and operation in order to improve project sustainability performance by means of a two-process evaluation system.

2.4.2 GREENROADS

In 2009, GreenRoads was developed by CH2M HILL and the University of Washington. The model simulates sustainability in highway construction by awarding credits to projects that incorporate sustainability in design practices. As a model, the guide evaluates sustainability for new construction, reconstruction, and rehabilitation. It also addresses maintenance and rehabilitation through an operation and maintenance plan.

Evaluation criteria are divided into two categories: required and voluntary. Each project

should meet 11 requirements. These requirements are: Environmental Review Process, Lifecycle Cost Analysis, Lifecycle Inventory, Quality Control Plan, Noise Mitigation Plan, Waste Management Plan, Pollution Prevention Plan, Low Impact Development, Pavement Management System, Site Maintenance Plan, and Educational Outreach (GreenRoads, 2012c).

The voluntary categories include six categories: Environment and Water (8 criteria), Access and Equity (9 criteria), Construction Activities (8 criteria), Materials and Resources (6 criteria), Pavement Technologies (6 criteria), and Custom Credits (2 criteria) (GreenRoads, 2012b)

2.4.3 INVEST

INVEST (Infrastructure Voluntary Evaluation Sustainability Tool) is a web based tool for self evaluation. The analysis covers the full lifecycle of transportation services. INVEST is divided into four modules that cover the full transportation lifecycle: System Planning for States (SPS), System Planning for Regions (SPR), Project Development (PD), and Operations and Maintenance (OM). There are 81 criteria organized by module. The criteria are classified according to sustainability practices as follows:

- System planning for states: This module includes 16 criteria, plus one bonus criteria that agencies can score, based on their first three criteria.
- System planning for regions: This module includes 16 criteria, plus one bonus criteria for which agencies are eligible, based on their first three criteria.
- Project delivery and systems planning and process module: This module includes 17 criteria.

- Project development module awards (33 criteria); these are generally organized from planning to design to construction.
- Operations and maintenance module (14 criteria); four of these are focused towards internal operations and ten are focused towards maintenance and operation of the highway system.

This rating system does not have a third party evaluator, which leads the FHWA to consider the rating unofficial. The credit rating system of INVEST is heavily weighted towards the planning phase of the project, allotting 43% to the system planning, 36% to operations and maintenance, and 22% to project development (Ramani et al., 2011)

2.4.4 GREENLITES

Another method to evaluate sustainability is GreenLITES, developed by the New York DOT and launched in 2008. The objective for this tool development was the incorporation of ethics and sustainability into asset management, a comprehensive program, and capital investment decisions. Furthermore, this tool integrates ecological, structural, safety, and economic needs into a transportation decision making process. The program awards up to 175 credit points under five categories. Rating categories include GreenLITES certified, GreenLITES Silver, GreenLITES Gold, and GreenLITES Evergreen awards (NYDOT, 2012).

At present, GreenLITES is mandatory for all projects in New York City (Krekeler et al., 2010). Projects are accessed during the conceptual and design phase. Project stakeholders and the project team review the score card and determine which items are to be included in the design. Divisions such as Transportation Maintenance, Traffic, Safety, and Mobility, etc., use this rating system as a tool to measure performance (Krekeler et al., 2010). NYDOT is developing a Pilot GreenLITES to rate regional projects using a triple bottom line (NYDOT, 2010). Credit points are assigned as follows: 33% energy and atmosphere, 27% sustainable sites, and 23% materials and resources. Since GreenLITES was originally developed for the

domestic use of NYDOT, this tool is mostly applied in the planning and maintenance phase of the project. This system is not designated for adoption by other DOTs. The system was found to have the highest distribution of points for environmental concerns.

Moreover, the sustainability rating tools categorize sustainability into three pillars of knowledge and assigns weights to these accordingly. However, the weight assignment varies from one rating tool to the other. Figure 15 illustrates the weight assignment per software/rating tool. As illustrated, the points are assigned differently to the environmental, social, and economic impacts.

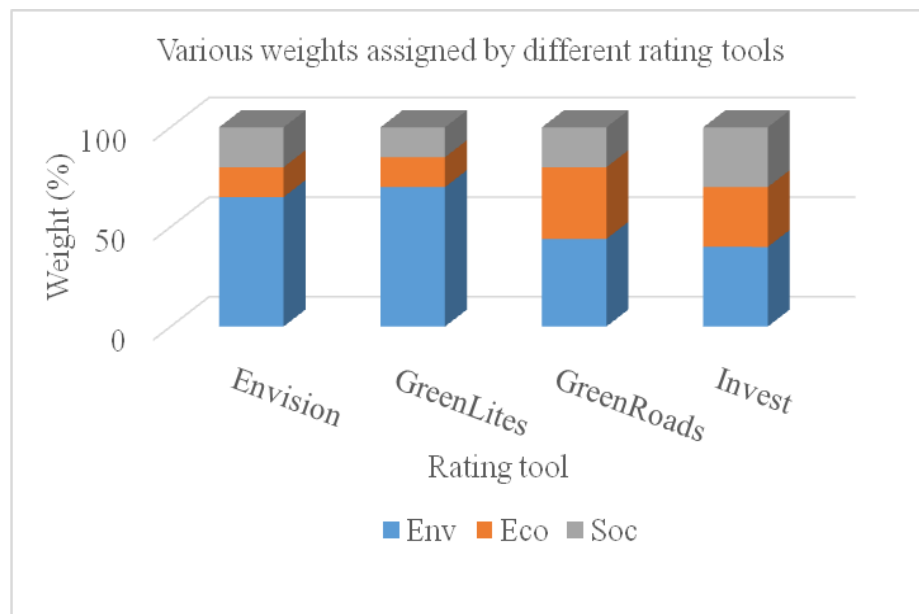


Figure 15. Sustainability rating tool points distribution (Ramani et al., 2011)

2.5 ENVIRONMENTAL ASSESSMENT

In 1969, the United States Congress passed the National Environmental Policy Act (NEPA) to establish a National Policy, "... which will encourage productive and enjoyable harmony between man and his environment; to promote efforts which will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of man; to enrich the understanding of the ecological systems and natural resources important to the Nation;" (Environmental Assessment, 2011).

The National Environmental Policy Act (NEPA) of 1969 urges federal agencies to perform environmental reviews to evaluate the potential impacts of proposed projects. This NEPA process asks for coordination between local, state, and federal agencies during the planning and project development decision making process (FHWA, 2014; LaDOTD, 2014). The project development stage should consider various alternatives that minimize potential impacts to the society and the environment. Stakeholders affected by the project can participate and ask questions about existing alternatives and associated environmental impact (FHWA, 2014; LaDOTD, 2014).

When the environmental impacts about a certain project are unclear, an Environmental Assessment (EA) is prepared. This (EA), as a public document, presents evidence as to whether the current impacts require further analysis (FHWA, 2014; LaDOTD, 2014). The EA should present various alternatives for the existing project. For example, another NEPA requirement is that federal agencies should consider “all reasonable alternatives.” The term “all reasonable alternatives” is undefined and very broad. However, it is well understood that the term “all reasonable” means that all feasible project alternatives that satisfy the economic, as well as the technical aspects of the project (FHWA, 2014; LaDOTD, 2014).

Moreover, the Federal Highway Administration set procedure for implementation of the NEPA process for decision making (FHWA, 2014; LaDOTD, 2014):

- Assessment of the social, economic, and environmental impacts of a product or a service.
- Analysis of a range of alternatives, based on project’s needs.
- Mitigation such as avoidance, minimization, and compensation.

When a project is believed to have a significant impact on the environment, an Environmental Impact Statement (EIS) should be prepared.

2.5.1 ENVIRONMENTAL IMPACT STATEMENTS (EIS)

An environmental impact statement is a procedure that describes and analyzes any suggested action, which would have a significant impact on the environment. EIS should include the following information: a) a description of an action including the pros and cons; b) a description of the area that is going to be affected; c) an analysis of the environmental impacts resulting from the action; and d) an analysis to “reasonable” alternatives to the action, thus providing ways to avoid the environmental impacts (What is an Environmental Impact Statement). Environmental impact statements include the following phases: purpose and need, alternatives, affected environment, environmental consequences, comments, coordination, and a list of preparers.

2.6 SOCIAL LIFECYCLE ASSESSMENT (SLCA)

The United Nations Environmental Program, in tandem with the Society of Environmental Toxicology and Chemistry, defined the term “social lifecycle assessment” as a method to assess the social and socio economic aspects of products and the potential positive and negative impacts along the lifecycle (Dasmohapatra, 2012). SLCA follows the ISO 14040 framework. However, some aspects might differ or be amplified at each phase of the study (Social Lifecycle Assessment).

Multiple methods have been developed to assess social impacts of a project, based on a study performed by Jørgensen et al. (2012). The SLCA is still in development, allowing many improvements to be performed. The Center for European Policy Studies (CEPS), together with the evaluation partnership (TEP), launched a study to explain, compare, and examine different ways to perform a Social Impact Assessment (SIA). Results indicated that this area is less developed than the economic and environmental area, and therefore is not widely used.

2.7 PERFORMANCE ASSESSMENT MEASURES

Performance assessment involves evaluating pavement performance with respect to its intended function and the specified characteristics required to meet this function. Performance assessment metrics vary. However, the metrics include the a) traditional condition and distress rating (e.g., rutting, cracking, and faulting), b) composite condition rating systems, c) pavement structural capacity, d) material design attributes (thickness, asphalt content, compressive strength, and gradation), as well as mechanisms to compare these attributes to expected or design parameters. Most of the time, performance is addressed with respect to current standards and practices. If the current asphalt pavement is expected to last 15 years, the values of an alternative surface are determined, based on how the projected life compares to the standard of 15 years.

Behn identified eight main criteria for good performance measures: to evaluate, to control, to budget, to motivate, to promote, to celebrate, to learn and to improve (Behn, 2003). Researchers identified that measures should be customized to fit culture and constraints of each transportation agency. Although transportation agencies do have similar focus areas, the agencies can use different data collection methods, or different benchmarks. Therefore, adequate evaluation criteria are required to evaluate performance measures. Zietsman found 15 features for a good performance measure, consisting of measurability, relevance, sensitivity to change, and illustrative to trends (Zietsman, 2000). Likewise, Marsden et al. (2010) collected a set of attributes for good performance indicators (Marsden et al., 2010). The performance indicators should be a) relevant to organization, b) clearly defined, c) based on available measurement, d) limited in number, e) timely, f) non-corruptive, g) statistically valid, h) comparable, i) responsive, j) innovative, and k) capable of aggregation. Another study, published in a report on environmental sustainability indicators, provides a comprehensive analysis for selecting performance measures by categorizing the

measures into the following three categories: 1) representation of reality, 2) monitoring and operation, and 3) management and policy (Joumard & Gudmundsson, 2010).

2.8 LIFECYCLE COST ANALYSIS (LCCA)

The concept of lifecycle cost analysis dates to 1960 when the American Association of State Highway Officials (AASHO) introduced the first book on lifecycle cost analysis, entitled the Red Book. At this stage LCCA was introduced for decision makers to evaluate projects in the planning phase. In the same year, two projects used LCCA to evaluate two projects. Later, Winfrey collected data about vehicle operations; to be used during LCCA for pavement (Winfrey, 1969). After that, the LCCA passed through various stages through a number of years. In 1972, the AASHO issued a Pavement Design Guide recommending the use of lifecycle costing in a project. In 1981 the FHWA issued the Pavement Type Selection Policy Statement. This guide stated that a) decisions should be based on performing a lifecycle cost analysis; b) Lifecycle cost estimation would become more accurate when pavement management systems became more advanced, thus enabling an accurate estimate of lifecycle cost analysis.

In 1984, MSDOT/FHWA issued a guide enhancing Pavement Selection based on Life Cycle Cost '84. This guide compared the lifecycle cost analysis of concrete vs. asphalt pavement built since the year 1960. Results from the analysis estimated that the initial cost of asphalt pavement was lower than the concrete alternative, which could save money that could be spent for other purposes. However, this same study estimated that on the long term, the concrete option has the lowest average lifecycle cost per mile, built since the year 1984.

In 1991, LCCA was mandated by legislative acts and was required during the design and construction of tunnels, bridges, and pavements (ISTEA, 1991). The FHWA mandated that the Department of Transportation perform an LCCA for all projects with costs above \$25 Million (FHWA, 2004). In 1995, the National Highway System (NHS) mandated that states

perform a lifecycle cost analysis for projects with a cost of \$25 million or more. This was titled the NHS Designation Act of 1995, Section 303 (Kane, 1996). It is clearly represented in Section 303 that the performed LCCA should include initial cost, future costs such as maintenance and rehabilitation, and resurfacing over the entire pavement life. In 1998, the FHWA Interim Tech Bulletin was published. This interim report established detailed procedures for performing LCCA. Moreover, it introduced the concept of probabilistic LCCA. Also, it introduced the foundation for the RealCost software (Walls, 1998).

According to the Transportation Equity Act for the 21st Century (TEA-21), lifecycle cost analysis is defined as: "... a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment." The basic LCCA requires defining a schedule for initial and future activities, for a specific alternative. After estimating the costs of each of these activities, the same analysis method should be used to evaluate different alternatives (Van Dam et al., 2015). LCCA provides a method to measure the economic impact of design, materials, construction techniques, maintenance stage, and the end of life phase.

2.8.1 NET PRESENT VALUE

The net present value is used to select different design or rehabilitation alternatives that are believed to provide the same performance, over the same analysis period. The equation used to calculate the net present value is illustrated in Equation 4.

$$NPV = \text{initial costs} + \sum \text{Rehab Cost} \left[\frac{1}{(1+i)^n} \right] \quad (4)$$

Where:

- i = discount rate
- n = year of expenditure
- $\left[\frac{1}{(1+i)^n} \right]$ = present value factor

Pavement initial cost is defined as the cost that occurs at the start of the project. These initial costs can be summarized as the cost of the material used in pavement, such as: shoulders, base, sub-base, pavement drainage, joint seal, and traffic control, etc. (Caltrans, 2013).

The maintenance and rehabilitation items are defined as activities that occur throughout the project lifecycle (Caltrans, 2013). For rigid pavement, the maintenance and rehabilitation items include activities such as: cleaning and filling existing longitudinal pavement joints, cleaning and resealing existing longitudinal and transverse pavement joints, cleaning and sealing cracks, full depth corner patching of jointed concrete pavement, and partial depth patching of jointed concrete pavement. These items are discussed in detail as follows:

- Cleaning and filling existing longitudinal pavement joints: This process consists of removing existing sealant in longitudinal joints and refilling them, based on specifications and plans. Existing joints and pavement surfaces should be cleaned of current sealant materials or any debris. Afterward, the joints are cleaned with sand blasting or water to make certain they are free of dust. The joint should then be completely dry before being refilled (LaDOTD Standard Specifications, 2006).
- Cleaning and resealing existing longitudinal and transverse pavement joints: This process consists of removing existing sealant in longitudinal and transverse joints and refilling them, based on specifications and plans. The same procedure applies as well. Existing joints and pavement surfaces should be cleaned of current sealants, materials, or any other debris. Afterward, the joints are cleaned with sand blasting or water to make certain they are free of dust. The joint should then be completely dry before being refilled (LaDOTD Standard Specifications).
- Cleaning and sealing cracks: This process consists of cleaning and sealing longitudinal, transverse, and diagonal cracks in accordance with plan requirements. The minimum

crack width to be sealed should be 10 mm at pavement surface. Before sealing, cracks should first be cleaned by sand blast. Cracks are then sealed with a hot sealing. The specifications of the sealant vary from one project to the other (LaDOTD Standard Specifications, 2006)

- Full depth corner patching of jointed concrete pavement: This process consists of full depth removal and replacement of PCC at corner breaks. Locations of these corner breaks should be indicated in the plans. Deteriorated concrete should be removed with approved tools, without damage to pavement lower layers (LaDOTD Standard Specifications, 2006)
- Partial depth patching of jointed concrete pavement. This process consists of the partial depth patching of jointed concrete pavement, according to specifications and plan (Indiana Department of Transportation, 2011)
- In most of the cases, patches are located in places where concrete shows distresses at the surface. At this point in time, the decision to patch concrete is taken. However, the distress may be larger than the one appearing at the surface. Moreover, the surface distress does not show the depth of the damage at the pavement. Therefore, when the patching process is performed, it is recommended to continuously check for the sound concrete and remove the damaged concrete. The check to distinguish sound from damaged concrete can be performed by dropping a reinforcing bar on the concrete. Sound concrete will respond by producing a solid sound, while damaged concrete will respond with a hollow sound. At the end of this procedure, it is really important that only the sound concrete remains and the damaged concrete would be totally removed. In performing the partial depth patching, the technician should make certain the removed concrete is within the limits. (Indiana Department of Transportation, 2011)

- Full depth patching of jointed concrete pavement. The full depth patching of jointed concrete pavement is the process of full depth removal and replacement of PCC pavement with joints at the locations indicated in the plans. A concrete saw can be used to saw the concrete at the required concrete parameter. Damage resulting from saw cutting should be repaired, including the damage relating to the saw cut area. The full depth patch starts from the patch location until sound concrete is found. The bottom of the full depth should be indicated in the contract (Indiana Department of Transportation, 2011)

2.8.2 EQUIVALENT UNIFORM ANNUAL COST (EUAC)

Should the benefits be the same, even if the analysis period differs, an equivalent uniform annual cost (EUAC) should be used to evaluate different alternatives. The EUAC method assumes that activities/strategies are repeated at the end of the analysis period. Another method recommended by FHWA is to use the same analysis period (generally the shortest of those being considered) for all alternatives, as well as inclusion of the remaining value at the end of the analysis period (salvage value, or value of remaining service life) as a benefit or negative cost at the end of the analysis period.

If benefits should vary among alternatives, such alternatives should not be compared solely based on cost, and the method should be used for evaluation. If all benefits can be expressed monetarily, then the benefits can be expressed in the same method as the cost. This method is called Benefit Cost Analysis (BCA). This method evaluates the ratio of the discounted benefit to discounted cost. However, a simplistic BCA can lead to a false strategy selection. Due to simplicity, NPV is preferred over the BCA method.

There are other factors existing in the selection of alternatives that cannot be evaluated monetarily, such as environmental impacts and safety. Therefore, LCCA is not solely sufficient for decision making between different alternatives.

2.8.3 DISCOUNT RATE

It is widely accepted that all future values should be estimated in current dollars and discounted to present value by using a real discount rate that combines both interest and inflation rates. For pavement LCCA, the discount rate should reflect historical trends over long time periods (Van Dam et al., 2015). The equation used to calculate the discount rate is illustrated in Equation 5.

$$D = [(1 + I_{int}) / (1 + I_{inf})] - 1 \quad (5)$$

Where

- D = Real discount rate
- I_{int} = Real interest rate, %
- I_{inf} = Real inflation rate, %

2.8.4 END OF LIFE ANALYSIS (RESIDUAL VALUE): SALVAGE VALUE VS. REMAINING SERVICE LIFE VALUE

It is necessary to assign a value (either positive or negative) at the end of the LCC period to capture either the value of the remaining service life value, or if there is no remaining service life, the salvage value from pavement structure. This salvage value may be computed as the value of the existing pavement to serve as a support for an overlay at the end of the analysis period (i.e., recycling or repurposing the pavement in place). These two options are mutually exclusive, meaning that no analysis can contain both a salvage value and a remaining service life value. (Van Dam et al., 2015)

2.8.5 USER COST ESTIMATION

User costs originally occur from vehicle operating costs, such as vehicle wear and tear, fuel consumption, delay costs, and crash costs. The value of road users cost is a general debate. Many considerations come into play when calculating user delay costs, such as vehicle class and trip type. While user costs should be considered in decision making, these

costs should not be considered in the same LCCA stream as agency costs, for several reasons. Although various literature reviews exist on this topic, the quantification of user costs is subject to debate and uncertainty. Computing user costs may be so large as either to delay the decision process or to drive that decision process toward an option that the agency cannot afford. Therefore, it is recommended by the FHWA that user costs be weighted differently than agency costs (Van Dam et al., 2015).

2.8.6 DETERMINISTIC LCCA VS. PROBABILISTIC LCCA

The use of fixed values for all LCCA inputs to produce a single output value is referred to as the deterministic approach to LCCA. While this approach is very simple and needs few inputs, it does not account for the variability in actual initial costs and discount rates over time, or for the uncertainty in timing and costs of planned maintenance and rehabilitation. In fact, the output of a single value resulting from the analysis may imply a degree of certainty that may prove to be inappropriate in a conclusion (FHWA, 2010). Therefore, sensitivity analysis can be performed to determine the accuracy of the results.

A probabilistic approach to LCCA is more realistic. Such an approach uses a statistical description of the probability distribution of each input value in order to account for an input associated variability that in turn creates uncertainty in the analysis output. A distribution of output value simulations is produced to provide users with sufficient information for understanding the variability of the results, together with the confidence that can be placed in the analysis. The development of appropriate input value distribution is time consuming, especially if the required data to input the distributions are not available. The collection of good pavement cost data, maintenance, and performance activities remain important for a good LCCA.

2.8.7 THE APPLICATION OF LCCA BY STATE DOTs

LCCA practices were reviewed in the following states: California, Colorado, Florida, Georgia, Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Oregon, Pennsylvania, Texas, Utah, Virginia, Washington, and Wisconsin. Table 14 summarizes the findings in these states as illustrated (Evans, 2011).

- Six states: California, Colorado, Florida, Indiana, Oregon, and Washington from the selected states use FHWA's Real Cost software. The Michigan Department of Transportation (MDOT) uses AASTHO's Darwin program.
- Three states developed a custom, software package for performing LCCA: Georgia, Minnesota, and Pennsylvania DOTs use a custom spreadsheet for performing LCCA (Evans, 2011). The analysis period is estimated to be 40-50 years in most states.
- Almost 50 % of the states investigated use a discount rate of 4 percent. States such as: Colorado, Michigan, Minnesota, and Washington use a rate based on recommendations from the Federal Office of Management and Budget.
- Although FHWA recommends the use of LCCA, the following states do not include user costs for LCCA: Illinois, Minnesota, New York, Ohio, Virginia, and Wisconsin (Evans, 2011).

Table 14. Selected states' LCCA tools and parameters (Evans 2011)

State	LCCA tool	Analysis period (years)	Discount rate (percent)	User costs include
California	Real Cost	20, 35, 55	4	Yes
Colorado	Real Cost	40	Determined annually (OMB)	Yes
Florida	Real Cost	40	3.5	Optional
Georgia	Custom spreadsheet	30, 40	3	Yes (factor in weighted

Table 14 (cont.)

State	LCCA tool	Analysis period (years)	Discount rate (percent)	User costs include
Illinois	Not specified	45	3	No
Indiana	Real Cost	At least 50 (for new)	Generally, 4, though consider a range of 0 to 10	Yes
Michigan	Darwin and custom software	10 to 20	Determined annually (OMB)	Yes
Minnesota	Custom spreadsheet	35 to 50	Determined annually (OMB)	No
New York	Not specified	Range	4	No
Ohio	Not specified	35	Range of 0 to 6	No
Oregon	Real Cost	40 (new) 50 (Interstate)	4	Optional
Pennsylvania	Custom spreadsheet	50	4	Yes
Texas	Custom software	30	Not specified	Yes
Utah	Not specified	25 to 40	4 (recommended)	Yes
Virginia	Not specified	50	4	No
Washington	Real Cost	50	4 (based on OMB)	Yes

As indicated in Table 14, each state has its own practices in regard to performing an LCCA, LCCA tools used, the analysis period, the discount rate, and an inclusion of user costs.

States such as California, Colorado, Florida, Indiana, and Washington use Real Cost software. States such as Georgia, Minnesota and Pennsylvania use a custom spreadsheet. Illinois, New York, Ohio, Utah and Virginia do not specify software. The State of Michigan uses a combination of Darwin and custom software. This custom software is named

Construction Congestion Cost (CO3); the software's purpose is to help traffic engineers evaluate user cost analysis during the pavement selection process. In addition, the State of Michigan uses a project cost software, which includes stored data for all unit prices, to be selected by the user. Texas developed its own customized software (Evans, 2011)

Similarly, the analysis period differs from one state to another; states such as California and Georgia have multiple analyses periods: 20, 35 and 55 years for California, with 30 and 40 years for Georgia. States such as Colorado and Florida have a design period of 40 years. States of Illinois, Ohio, and Texas have a single value of 45, 35, and 30 years, respectively. In Indiana, the minimum analysis period is around 50 years. Other states such as Michigan, Minnesota, New York, and Utah carry ranges of value with 10 to 20 years, 35 to 59 years, a range of values not specified, and 25 to 40 years, respectively. States such as Pennsylvania, Utah, and Washington have an analysis period of 50 years (Evans, 2011).

By analyzing the discount rate, most states, such as California, New York, Oregon, Pennsylvania, Utah, Virginia, and Washington, consider that rate to be 4%. Some states consider the rate to be 3%, such as Georgia and Illinois. Other states determine the discount rate annually, such as Colorado, Michigan, and Minnesota. Some states have a range in the discount rate, such as Indiana and Ohio; states such as Texas have no fixed value (Evans, 2011)

The selection of the discount rate is most critical. A high discount rate will be positively biased towards projects with a low initial construction and a higher maintenance cost. A low discount rate will be positively biased towards projects with a high initial cost and a low maintenance cost (Evans, 2011)

There are states that consider user costs, while other states do not. States such as California, Colorado, Indiana, Michigan, Pennsylvania, Texas, Utah, and Washington consider the user cost in their calculations. However, states such as Illinois, Minnesota, New

York, Ohio, and Virginia do not consider the user costs. States such as Florida and Miami consider the inclusion of user costs as optional, but states such as Georgia consider user cost as a factor in a weighted average (Evans, 2011).

The definition of user costs, as a result, varies from state to state. In California, user costs and agency costs are considered to have the same value. In Florida, the user cost includes: motorist delay time, accident costs, and vehicle operating costs. In Georgia, user costs and agency costs are calculated separately and are assumed to be different; therefore, the costs are never summed together. The user cost value is evaluated separately in a decision making matrix to evaluate the importance (Evans, 2011).

Each state performs its LCCA, based on special conditions. For example, in the State of Colorado, the LCCA is performed to compare concrete to asphalt pavement for new or reconstructed projects with an initial value of \$2 million; a comparison is performed for asphalt and concrete surface treatments with an initial value of more than \$2 million, in the event that both pavement alternatives are considered feasible. The State of Colorado has a leadership role that incorporates statistical research and experience from a current project in order to integrate the data into long term plans (Evans, 2011).

The State of Illinois performs an LCCA for both new and reconstructed pavements with more than 4,750 square yards of pavement and/or pavement, costing more than \$500,000. In the event that the economic analysis for one option shows to be no greater than 10% cheaper, the pavement selection process will be based on alternate bidding (Evans, 2011)

In Indiana, an LCCA is performed when there is more than one alternative. The LCCA is also performed for new and rehabilitated pavement with a mainline pavement more than 10,000 square yards. Should two scenarios be evaluated and the net present value is within 10%, the alternatives are considered the same. In this case, other factors such as: initial

costs, constructability, work zones, and user costs are applied to make the final decision. The user costs considered here are inclusive of user delay costs during construction, vehicle operating and accident expenses, fees, and other spending costs during the lifecycle. Also, Indiana requires a changing pavement design life in order to test LCCA sensitivity based on current pavement conditions. This also applies in New York, where a sensitivity analysis is performed to evaluate the sensitivity of LCCA for a particular variable (Evans, 2011).

In Ohio, an LCCA is performed when more than one feasible alternative exists. When the lifecycle costs of more than one alternative are within 10% of the lowest lifecycle cost alternative, these choices are considered to be equal to the lowest alternative. Any of these equal alternatives may be selected. However, when alternatives are not within 10% of the lowest alternative, the alternatives are eliminated. If no alternatives exist within 10%, the lowest cost is selected automatically. When alternatives are not within 10% of the lifecycle cost of the lowest pavement, the lowest cost alternative is selected (Evans, 2011).

The State of Minnesota considers the remaining life of the pavement. The remaining life is defined as the “prorated” share of the cost of the latest activity, based on the service life extending after the analysis period. The State of Oregon performs LCCA when constructing new pavement with more than one mile, or in the case of major pavement rehabilitation involving total reconstruction or rehabilitation. Also, an LCCA is performed when pavement design strategies are less than the minimum value of 15 years (Evans, 2011).

In regard to the State of Pennsylvania, an LCCA is performed for all structural improvements, with a value exceeding \$3 million for total projects costs on the interstate and \$15 million for all other facilities. When comparing two alternatives, both should have the same analysis period. Also, the LCCA is performed without a separate inflation rate. When there is a difference of 10%, this is sufficient to determine the type of pavement. It should also be noted that Pennsylvania depends on historical data to develop LCCA inputs. A

positive example from Pennsylvania is that the state reached out to the industry, which in turn increased transparency (Evans, 2011).

The State of Texas uses two different software for performing an LCCA: The Rigid pavement lifecycle cost analysis (RPLCCA) and the Texas pavement type selection (TxPTS). The RPLCCA is used to evaluate various pavement designs, together with all the associated costs over pavement life, and then ranks these according to cost. A performance assessment model is included in RPLCCA, which evaluates the distress rate for each pavement type. However, RPLCCA requires many inputs, including factors difficult to determine, such as emissions, accidents, vehicle operating costs, etc. On the other hand, TxPTS as a tool allows for the comparison of several pavement strategies, and then ranks these according to their cost. The TxPTS is similar to RPLCCA, except that the TxPTS needs fewer user inputs and does not calculate distresses, which renders the tool easier to use. However, it should be noted that TxPTS includes flexible pavement, while RPLCCA only considers overlays (Evans, 2011).

Utah uses two manuals for determining LCCA: The Pavement Management and Pavement Design Manual, and the Lifecycle Cost Analysis. The Utah DOT does not consider either salvage value or energy costs when evaluating LCCA. Factors that are included, however, are: funds availability, project specific information such as environmental conditions, and project specific information. The user costs are evaluated by the regional pavement engineer (Evans, 2011).

As a practice, the Virginia DOT uses the present worth method to evaluate an LCCA. However, when design life is not the same, the EUAC method is used. When the performed LCCA results are within 10%, other factors are evaluated. For the State of Washington, the user cost considered is associated with user delay, as linked to traffic volumes, construction periods, etc. However, when one of the alternatives is 15% greater than the other, the least

expensive one is selected. When an alternative is within 15% of the other alternative, the DOT performs an engineering analysis. The State of Wisconsin bases its pavement type selection on the outcome of an LCCA. The lowest cost alternative is selected. Yet when a 5% difference occurs between the desired design and the lowest priced one, then Wisconsin requires more documentation before making a final decision (Evans, 2011).

2.8.8 LCCA IN THE STATE OF LOUISIANA

A Lifecycle cost analysis for the State of Louisiana follows the FHWA's methodology, as specified in the interim technical bulletin report. An analysis period of 40 years is to be used for new pavement construction, with an analysis period of 30 years to be used for overlays (Temple et al., 2004)

The timings of various activities are illustrated in Table 15. The assumptions performed for rigid pavements consist of patching with joint resealing at year 20. In addition, at year 30 there is additional patching with surface retexturing (Temple et al., 2004). Table 15 may be used as guidance while performing maintenance and rehabilitation for the State of Louisiana.

2.9 PAVEMENT DESIGN AND SUSTAINABILITY

Sustainability factors were previously explained, together with the environmental and economic pillars. This section will analyze existing pavement design framework by taking the MEPDG as an example. The Mechanistic Empirical Pavement design guide previously illustrated in the design phase may be simplified in Figure 16. The framework, as illustrated in Figure 16, will be modified later to include the new sustainability criteria.

In regard to the reasons discussed earlier, should the environmental impact of the material used be assessed, the assessment might lead to discrepancy in the final results if LCA were to be used. For example, a user might take the functional unit as 1 mile, and another one might take it as 1 km. Also, the system boundary used may be different from one study to the other, leading to inconsistent results.

Table 15. Maintenance and rehabilitation schedule based on the State of Louisiana (Temple et al., 2004)

Project Type	Alternate	Year 0	Year 15	Year 20	Year 30
Interstate Overlay	Rigid	New bounded PCC Overlay	No action	Clean/seal joints 3 patches per mile	N/A
	Flexible	New AC Overlay	Cold plane and overlay	No action	N/A
Interstate New Construction	Rigid	New JPC Pavement	No Action	Clean/Seal Joints Patch 1% of Joints	Retexture Patch 3% of Joints
	Flexible	New AC Pavement	Cold Plane & Overlay	No Action	Cold Plane & Overlay
Other Arterial Joints New Construction	Rigid	New JPC Pavement	No Action	Clean/Seal Joints Patch 1% of Joints	Retexture Patch 2% of joints
	Flexible	New AC Pavement	Cold Plane & Overlay	No Action	Cold Plane & Overlay

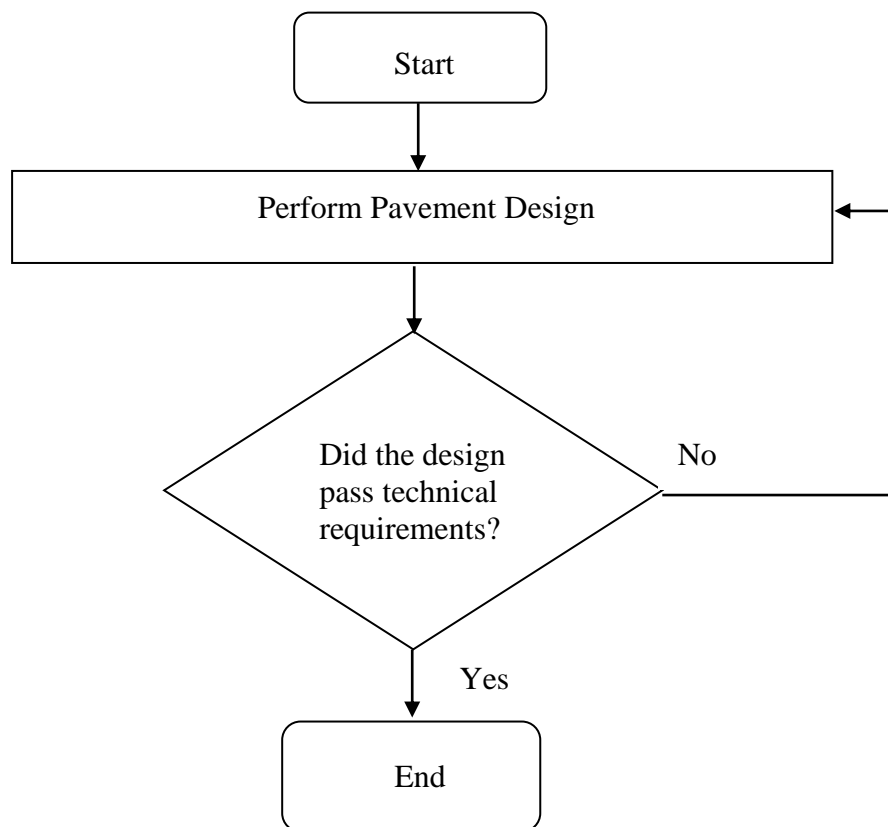


Figure 16. Old pavement design framework (Current pavement design)

Moreover, someone might base the study on data from Europe, while another might apply data from the United States. Therefore, the use of another tool to evaluate pavement sustainability is highly necessary.

Depending on a stakeholder, the sustainability measures previously discussed (performance measure, LCA, LCCA and sustainability rating tools) can be used either apart or together. However, the use of all sustainability measures together will give a more comprehensive idea for sustainability, since each component evaluates a specific sustainability criterion (FHWA, 2015) for pavement.

The use of rating tools can be a good criterion to evaluate sustainability, as the rating systems transform sustainability criteria into a common point system. However, rating systems tend to sacrifice details when evaluating sustainability. Therefore, rating systems should be used with precaution (FHWA, 2015).

The use of LCA and LCCA together is a good choice to evaluate the economic as well as the environmental criteria. However, there remain shortcomings to this assessment, since the social criteria is not included (FHWA, 2015).

2.9.1 FEDERAL HIGHWAY ADMINISTRATION CURRENT TREND- TYING SUSTAINABILITY

PILLARS TOGETHER

Currently, the Federal Highway Administration is working on a program to integrate the sustainability criteria. In 2010, the FHWA launched a sustainability pavements program for advancing knowledge about pavement sustainability practices. This program developed five deliverables to help transportation agencies implement sustainable pavement practices. These deliverables include:

- A comprehensive reference document for sustainable pavement design
- A framework for performing pavement lifecycle assessment
- A series of various sustainability topics to cover sustainability

- A collection of technical resources on sustainability
- Five briefs, entitled 1) Pavement Sustainability, 2) LCA of Pavements, 3) Pavement Climate Change, 4) Strategies to Ameliorate Sustainability of Flexible Pavements, 5) Strategies to Ameliorate Rigid Pavement, as well as various webinars focusing on sustainability for various pavements lifecycle stages. Goal areas were categorized into four phases.

Figure 17 illustrates goals 1 and 2. The first goal is targeted at pavement systems. The first task is to develop a sustainable framework for pavement, as well as to define LCA and LCCA. The framework should help stakeholders during the decision making process. The second goal is to provide relevant information associated with LCCA. This will be accomplished through the provision of relevant LCCA documents for guidance, as well as associated software such as RealCost software (FHWA, 2017).

Goal 1 Pavement systems	Goal 2 Assessing sustainability for pavement
<ul style="list-style-type: none"> • Develop a sustainable framework for pavement • Define performance metrics associated with LCCA and LCA and associated data collection • Develop a framework to help in the decision making process. This framework should check pavement performance, LCCA and LCA 	<ul style="list-style-type: none"> • Provide up to date LCCA document for guidance • Provide up to date RealCost software and integrate updated LCCA recommendation • Provide guidelines on the starting process of LCA

Figure 17. FHWA goal areas (goals 1 and 2) (FHWA 2017)

The third goal is to provide training associated with the use of LCA and LCCA. This is to guarantee that stakeholders are aware of how to use LCA and LCCA, as well as to promulgate an increased awareness of pavement sustainability. This outreach will be

performed through webinars and case studies. The fourth goal is the implementation stage. The objective of this task is to provide an actual tool for stakeholders to benchmark the implementation of sustainable design practices. Goals 3 and 4 are illustrated in Figure 18 (FHWA, 2017).

Goal 3 Outreach and guidance	Goal 4 Implementation
<ul style="list-style-type: none"> • Provide training for LCCA and LCA • Provide online webinars • Perform case studies showing sustainability practices • Increase awareness level about pavement sustainability 	<ul style="list-style-type: none"> • Provide various tools for agencies to help them evaluate individual projects as well as benchmarking • Establish pilot programs to implement sustainable pavement practices • Perform pavement sustainability report cards for benchmarking the implementation of sustainable design practices

Figure 18. FHWA goal areas (goals 3 and 4) (FHWA 2017)

Moreover, this program is summarized in Figure 19, which ties everything together as an LCA with required data and policy. In Figure 19, the triangular shape indicates that the base items are most important, because the upper elements cannot be completed without fulfilling the base items. Moreover, the elements above the LCA framework indicate those elements that need work in the context of North America. The bottom of the triangle is based on a strong framework for LCA, then the figure rises until it reaches the policy level (Dylla, 2016), such as California No. 262. The pyramid illustrates not only the importance of the data, but also that EPD could be a good source of data to fill in the gaps (Dylla, 2016).

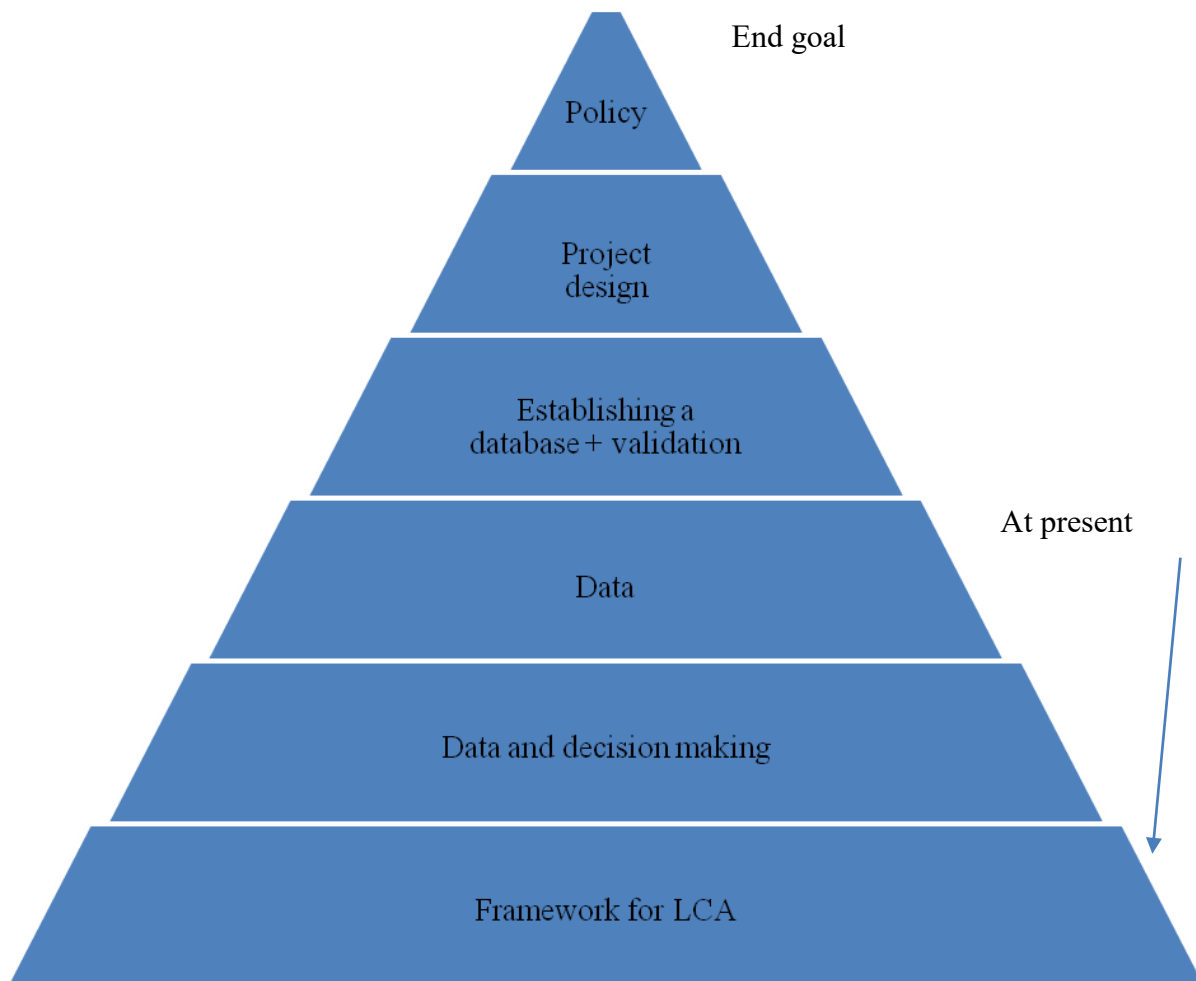


Figure 19. Requirements for a successful implementation of LCA (Dylla, 2016)

2.9.1.1 California Policy No. 262

The State of California declared that the devastating impact of the Global Warming Potential endangers the State of California, and thus there is a need to act to decrease the Global Warming Potential level. The state also stated that there is a huge amount of emissions released during the manufacturing and transportation of materials used for infrastructure projects.

Executive order Number B-30-15 mandates agencies to take into consideration the Global Warming Potential while planning for infrastructure projects. Moreover, a lifecycle cost analysis should also be performed to evaluate a project (California Legislation, 2017).

The California Policy No. 262 imposes specific bidding requirements for a project. The bill is entitled the “Buy California Clean Act.” This act will mandate publishing a

maximum level of Global Warming Potentials for the materials used in a bid. This will be performed by January 1, 2019. To be a successful bidder, the bidder shall submit an Environmental Product Declaration for his/her products. The Global Warming Potential for a specific material should not exceed the limit assigned by the authority at this point in time (California Legislation, 2017). In 2022, these materials will be checked again for the purpose of adjusting the Global Warming Potential for a specific material downward; to reflect improvement in the industry (California Legislation, 2017).

2.10 SUMMARY

This chapter first started by defining LCA as a general concept and then explained its various phases. After that, it moved to pavement LCA and its associated problems. LCA problems were explained through the selection of various pavement LCA studies covering all pavement lifecycle phases.

Results proved that various discrepancies can occur while performing an LCA due to the following reasons: the selection of a system boundary, the selection of a functional unit, the selection of data (someone might be using data from Europe and the other might be using data from the United States, etc.). All these discrepancies lead to incomparable results at the end.

To solve this comparability issue, EPDs were then discussed. As standardized documents, with a pre-defined system boundary, These would evaluate the environmental impact of a product, to solve the problems previously described in LCA.

The chapter then moved to the second sustainability pillar as the social impact, then to the third pillar as the economic impact. The chapter then presented concepts such as initial vs. the maintenance and rehabilitation activities for a rigid pavement. After that, the chapter discussed the time value of money to perform a full lifecycle cost analysis

Finally, the chapter analyzed the current pavement design framework to evaluate how to integrate the previous sustainability factors into the current pavement design framework and how the current pavement design should be changed to integrate these new sustainability pillars.

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CHAPTER 3. NEW FRAMEWORK AND ASSOCIATED DATA COLLECTION PROCESS

3.1 INTRODUCTION

The objective of this chapter is to present the proposed pavement design framework integrating the new sustainability criteria; and then reveal how this framework differs from the old framework previously described in literature review. This chapter will also explain the sustainability data used (composed of two components: an environmental and an economic one), and the process of data collection for replication.

The data is divided into environmental and economic impact sections. The environmental impact section is divided into an Environmental Product Declaration (EPD) which covers the extraction of raw material, as well as transportation of the extracted raw material to manufacturing. Inventory data used to perform LCA is also included in the environmental impact section, in order to oversee the transportation impact module from the manufacturer to the project location. The economic impact is composed of two sections that present an initial cost (cost occurring at the present time), and a maintenance and rehabilitation section (future cost through the whole lifecycle of the project). The initial cost, shown in two sections, displays both the material cost collected from the manufacturer, and the initial cost which includes equipment, profits, and incorporated overheads.

3.2 EXISTING VS. PROPOSED PAVEMENT DESIGN FRAMEWORK

The current pavement design framework is illustrated in Figure 20. As previously described and illustrated in the literature review, the current pavement design framework includes no sustainability criteria; the design is solely evaluated for technical performance. Therefore, to enable the integration of a new sustainability factor, this current framework should be changed. Due to the fact that the technical performance of the material is

important, the sustainability criteria should be evaluated, once the design passes the technical performance and is safe to use.

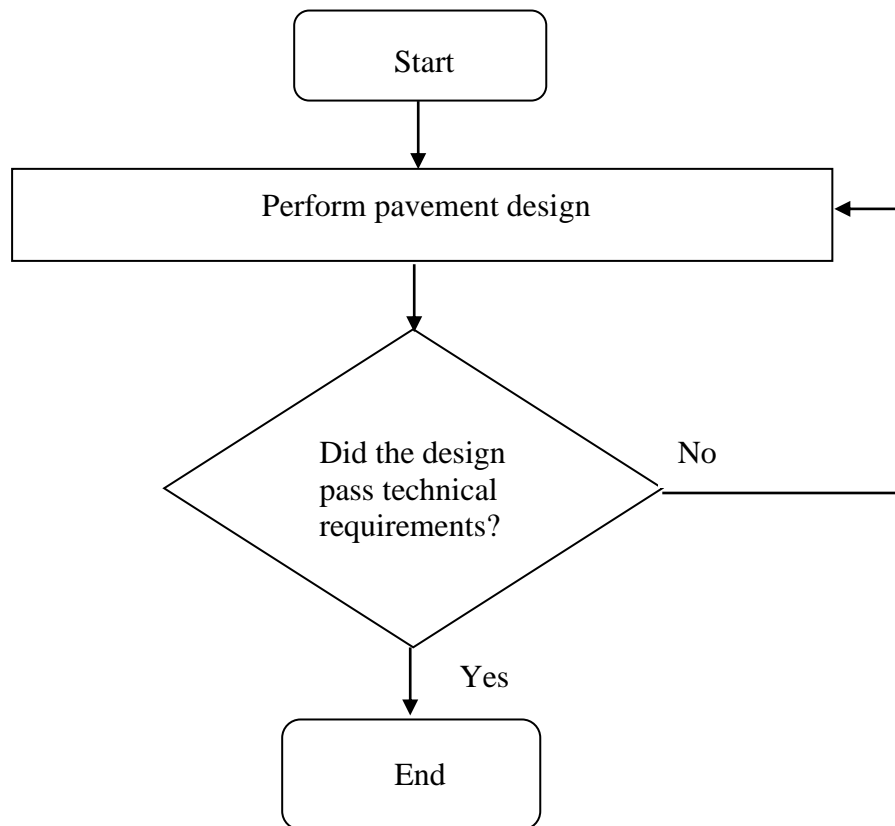


Figure 20. Old pavement design framework (FHWA 2015)

The modified pavement design framework is illustrated in Figure 21. As can be seen, the innovative pavement design incorporates a new sustainability factor (environmental and economic impacts). Therefore, pavement design will first be evaluated for technical performance (outside the scope of this work). Having satisfied the technical performance, the design is then evaluated for environmental and economic impacts, respectively. Iterations should be performed until the design satisfies both sustainability criteria. When the sustainability criteria is satisfied, the iterations stop and the design is finalized

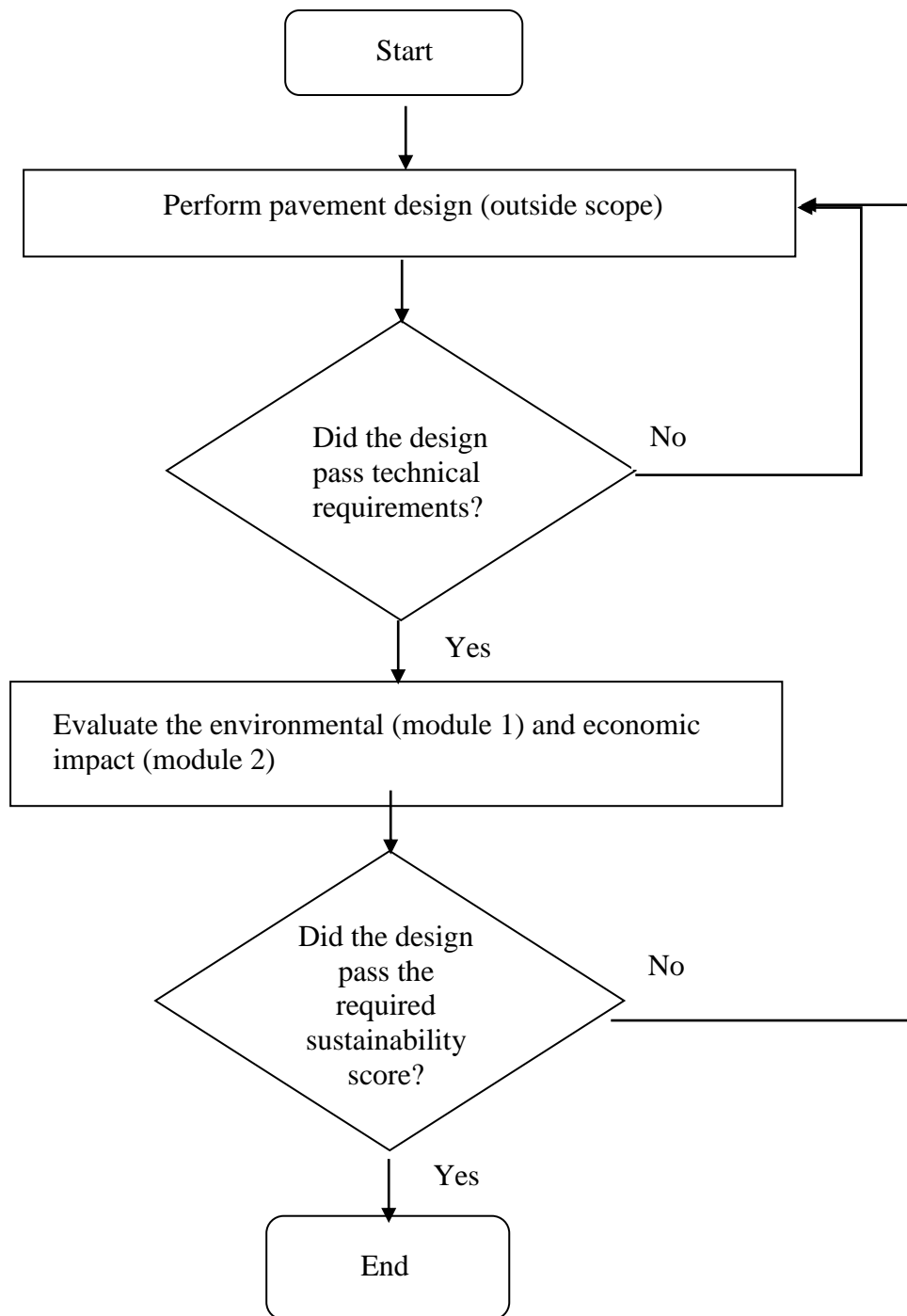


Figure 21. New pavement design framework

There are various ways to check whether the design satisfies the environmental and economic criteria. For example:

- The study performed by the National Ready Mix Concrete Association for the industry wide average can be used to benchmark the environmental impacts. In this case, the

benchmarking criteria will be performed with respect to each region, since the study was performed for each region. For example, the user might benchmark his product with respect to GWP for the Eastern region or U.S national average. In this case, the user would compare the GWP produced by his product to the GWP produced by the Eastern region, to discover whether the GWP of his product is below or above the average.

- In the event that individual Environmental Product Declarations are available, these also can be averaged for a certain compressive strength value or mix design breakdown. For competitive reasons, the stakeholder then can benchmark his product with respect to the average.
- Moreover, other benchmarking criteria can include emission regulations assigned by a certain law or mandate. As previously illustrated in literature review for example, various laws/mandates, such as the California Policy No. 262, will authorize certain emissions requirements that should not be exceeded.
- For an economic impact, the benchmarking criteria can include a certain project budget that should not be exceeded, and based on history, can be determined by the stakeholder. In case the design does not pass the sustainability criteria, a redesign should be performed. This can be accomplished through various ways:
 - A change in the mix design used will, in turn, change the environmental impact as well as the cost (since each mix design has a specific environmental impact, coupled with the associated cost).
 - A change of manufacturer will alter the transportation distance as well, and therefore will reshape the environmental impact associated with the transportation module. This will also rework the cost of the mixes and the environmental impact of the mix itself, since each manufacturer has a different manufacturing technology. Therefore, the resulting emissions will be different.

As previously described, the sustainability factor includes environmental and economic impacts, and therefore the data is divided into environmental and economic sections. The environmental impact section is divided into EPD, which covers the extraction of raw material, as well as transportation from raw material extraction to manufacturing and manufacturing phases. The process is inclusive of a lifecycle inventory data collection to perform LCA, which covers the transportation impact from the manufacturer to the project location.

The economic impact is composed of two sections of initial cost (cost occurring at the present time), and involves the maintenance and rehabilitation section (future cost through the entire lifecycle of the project). The initial cost involves two sections: the material cost collected from the manufacturer, and the initial cost including equipment, profits and overheads used (collected from the Louisiana Department of Transportation and Development).

The initial maintenance and rehabilitation costs were collected to perform a lifecycle cost analysis for the pavement during its entire lifetime (cradle to grave). Figure 22 illustrates the data breakdown structure, as well as the data description, which will be explained by module.

Figure 23 illustrates the data use process per lifecycle, as per the scope of the study. As previously described, the environmental impact section will cover impacts from raw material extraction to manufacturing, as well as the transportation impact from the manufacturer to the project location. EPD will cover a) the raw material extraction, b) the transportation from the raw material extraction to the manufacturing phase, and c) the manufacturing phase. LCA then will be performed in order to cover the transportation impact from the manufacturing to project location. The economic impact scope will serve to cover all of the pavement lifecycle from cradle to grave end of life options. Not evaluating the

environmental impact from cradle to grave emanates from time limitation; in addition, EPD only covers a cradle to gate analysis.

3.3 MODULE 1: ENVIRONMENTAL DATA COLLECTION PROCESS

The environmental data presented two data categories: The first data category contained individual Environmental Product Declarations; the second data category contained inventory data for the transportation impact module.

3.3.1 MODULE 1A :INDIVIDUAL ENVIRONMENTAL PRODUCT DECLARATIONS DATA

Individual Environmental Product Declarations are the declarations submitted by a certain company to reflect the environmental performance of its products. The collection process of these EPD was through: a) internet websites, b) communication with the industry, and c) product data sheets from companies. These data were stored in an Excel sheet with the following columns:

1. Company name
2. Location of the company, indicated by the zip code city and state
3. Compressive strength value in psi units
4. Environmental impact columns divided into: Global Warming Potential (kg CO₂ eq), Ozone Depletion Potential (kg CFC-11 eq), Acidification Potential (kg SO₂ eq), Eutrophication Potential (kg N eq), and Photochemical Ozone Creation Potential (kg O₃ eq).
5. Lifecycle inventory columns are divided into categories of a) total primary energy consumption (MJ), b) concrete batching water consumption (yd³), c) concrete washing water consumption (yd³), d) total water consumption (yd³), e) depletion of non-renewable energy resources (MJ), f) depletion of non-renewable material resources (kg), g) use of renewable material resources (kg), h) use of renewable primary energy (MJ), i) hazardous waste (kg), and j) non-hazardous waste (kg).

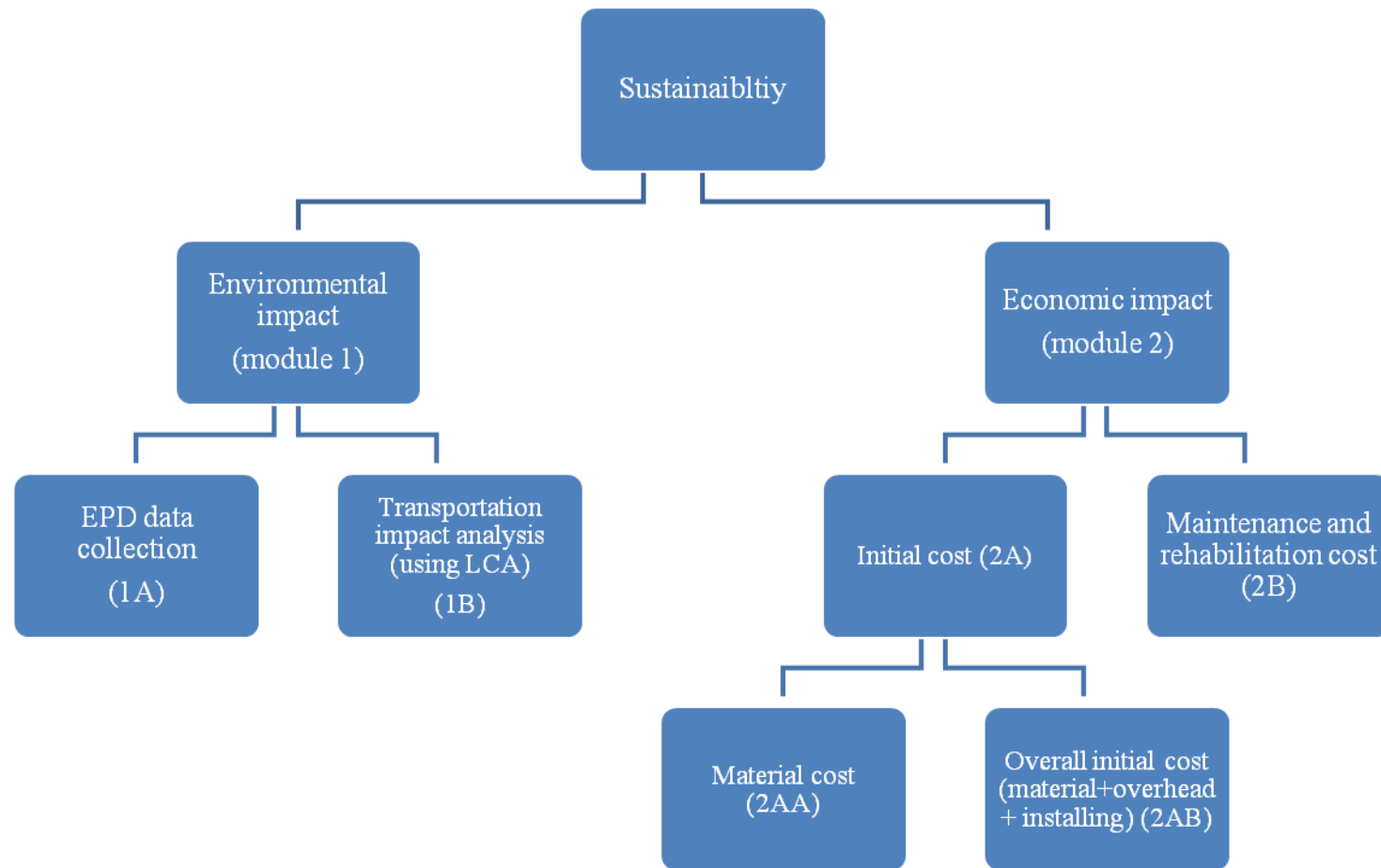


Figure 22. Data breakdown

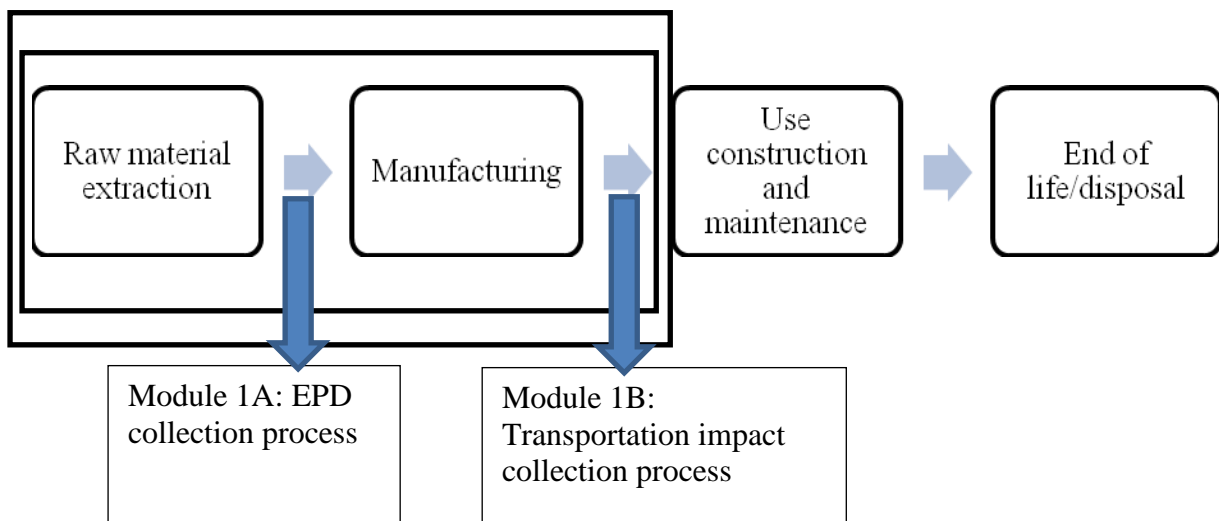


Figure 23. Data use per lifecycle phase

6. A column indicating the validity/end date of Environmental Product Declarations. This indicates the expiration date of the Environmental Product Declaration. The validity of any Environmental Product Declarations is usually five years; these are issued from the date.
7. Mix composition: the mix design composition is divided into the following columns: a) Portland cement (lb), b) fly ash (lb), c) slag (lb), d) mixing water (gallons), e) water to cement ratio, f) coarse aggregates (lb), g) fine aggregates (lb), and h) air (%). This information was collected from a products data sheet. Also, these are the search criteria for locating a mix design
8. Mix design total weight (lb) and density

Although parts 1 to 6 are normally found in most EPDs, the mix design breakdown is not usually found in EPD. To collect a mix design breakdown, companies were contacted for data sheets. Some EPD columns are illustrated in Tables 16 and 17. The search criteria becomes the mix design breakdown, as illustrated in Tables 16; the output should display the environmental impact as indicated in Table 17.

Table 16. Sample of EPD

Cement (lb)	Water cement ratio	Mixing water (gallons)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate (lb)
492	0.5	246	118	1309	1875
411	0.45	262	176	1346	1840
451	0.43	257	141	1193	1875
441	0.44	261	147	1353	1840
367	0.42	254	244	1202	1840
489	0.41	263	153	1108	1900
526	0.39	267	165	1079	1875
376	0.53	249	94	1433	1900
276	0.43	242	288	1340	1900

Table 17. Mix design breakdown

Product ID	Zip code	Compressive strength (Psi)	GWP (kg CO ₂ eq)
1597	75149	3000	264.54
1734	75149	4500	288.24
1735	75149	4000	312.71
1738	75149	4400	305.83
1811	75149	4500	259.95
1841	75149	4500	336.41
1899	75149	5000	360.88

3.3.1.1 Data statistics

This section provides an overview of the environmental data used through several statistical numbers. The EPD data contains products from Texas, Florida, Oklahoma, California, Washington, and Louisiana. The data is divided into three levels: the Louisiana Level (includes only the State of Louisiana), the South Regional Level (Louisiana, Texas, Florida, and Oklahoma), and the National Level (includes all States: Texas, Florida, Oklahoma, California, Washington, and Louisiana). The search range for each region is illustrated in Table 18, and the total number of products for each state is illustrated in Table 19.

Table 18. Search criteria

Region	Boundary	Cement (lb)	Water (gallons)	Fly ash (lb)	Slag (lb)	Fine aggregate (lb)	Coarse aggregate (lb)	Air (%)
South region	Lower	276	207	0	0	1047	1652	0
	upper	725	444	336	0	1840	1920	7.5
Louisiana	Lower	311	131.43	0	0	689	321	3
	Upper	950	316.08	122	0	1737	2006	7
National	Lower	253	160	0	0	1047	1652	0
	Upper	752	444	336	0	1840	1920	7.5

Data statistics are illustrated in Table 19, indicating the number of products per state. The total items/products are 2,267 products. As illustrated in Table 19, the highest number of products is produced by the State of California, followed by the states of Texas, Louisiana, Oklahoma, Washington, and Florida. The complete data is attached in Appendix A.

Table 19. Number of products per State

Number of products	Location
328	Texas
3	Florida
28	Oklahoma
1598	California
253	Louisiana
57	Washington
2267	Total

Table 20 illustrates the number of products produced for each compressive strength value per state. As illustrated, the State of California is the lone state that produces compressive strength values of 2000, 2500, 6500, and 7500 psi. The State of Texas is the only State that produces compressive strength values of 3600, 4400, and 9000 psi. All states produce compressive strength values of 3000, 4000 and 5000 psi.

Table 20. Number of products produced for each State per compressive strength value

Compressive strength (psi)	State	Number of products produced per State
2000	California	17
2500	California	119
3000	California	264
	Texas	35
	Florida	1
	Washington	1
	Oklahoma	3
3500	California	257
	Oklahoma	4
	Texas	3
3600	Texas	17
4000	California	227
	Florida	1
	Oklahoma	8
	Texas	35
	Washington	18
4400	Texas	18
4500	California	217
	Oklahoma	7
	Texas	72
	Washington	1
5000	California	214
	Florida	1
	Oklahoma	4
	Texas	37
	Washington	12
5500	California	126
	Oklahoma	2
6000	California	76
	Texas	36
	Washington	21
6500	California	40
7000	California	30
	Washington	2
7500	California	12
8000	Texas	34
	Washington	2
9000	Texas	39

3.3.2 ENVIRONMENTAL PRODUCT DECLARATION FOR THE STATE OF LOUISIANA

The process of issuing an individual Environment Product Declaration is both time consuming and very expensive. The cost mostly comes from two processes (NRMCA, 2016):

- Conducting an LCA and producing an LCA report, and
- Having the LCA report critically reviewed and verified.

Most companies do not have the expertise to perform an LCA inside the company and consequently, must hire a consultant (NRMCA, 2016). To date, companies that did not develop their own Environmental Product Declaration therefore participated in an industry wide, average Environmental Product Declaration study (NRMCA, 2016).

A survey was performed and distributed to concrete companies in Louisiana to assess the situation. The survey is attached in Appendix C. Companies were asked to report whether they had measured an environmental impact or inventory for their products. The results showed that some five companies participated in the industry wide average study, because an absence of expertise existed within each company to perform a lifecycle assessment. These five companies, with a total of 16 plants, are presented in Appendix D.

The attached survey was conducted and the results were analyzed. The findings are described (company names were omitted) as follows. All five companies stated that the sustainability concept is innovative in Louisiana, and that the essential cause for their participation in the survey is the LEED credit.

- Company 1. Provided the actual survey they submitted to the National Ready Mix Concrete Association. They were “very interested in further understanding about this sustainability concept and the direction that DOTD is trying to go.” The company also noted that they “would love to be a part of this endeavor” and wanted to “provide further assistance to this matter.”
- Company 2. Explained that they might issue an individual EPD in a year or so, since “EPDs are very expensive, time-consuming, and there ... is currently no demand for them.” However, this company also showed interest in the project, but provided no specific/individual data for data sensitivity issues relating to the company.

- Company 3. Stated that there are many sensitivity issues involved with providing company specific data; and that there is “no single entity responsible for handling this matter, and [so] ... many legal issues are involved.”
- Company 4. Explained that the company cannot provide any specific information regarding their data, due to data sensitivity issues. However, the company highly encouraged the notion of first issuing an industry wide average study for the State of Louisiana, “Before going into individual companies’ specific data, you should first start with an industry wide average study.” The company also stated that they will be issuing an individual EPD for the company soon (time frame is unknown).
- Company 5. The owner of this company did not reveal any specific data related to the company. Moreover, the owner’s assistant (who prepared the survey and submitted it to NRMCA), stated that the company only participated in the survey for the LEED credit and that the information therein should be kept private.

By analyzing all the previous responses, the survey showed clearly that not only were many companies concerned about data sensitivity issues, but that also all of the companies had participated in the industry wide average, solely for the LEED credit.

Furthermore, the consultant (Athena Institute) revealed that the data for the State of Louisiana was compiled together with other states in the Southern region to produce the industry wide EPD study. Yet, there exists no environmental impact data/inventory matrix solely for the State of Louisiana.

To issue an EPD for the state of Louisiana, Portland cement concrete mix designs were gathered from different LaDOTD districts, in order to assess the environmental impact per mix design. Each district has a set of plants, serving by geographic location. To ensure that all the mix designs of the companies participating in the industry wide average are included in the LCA study, all districts were visited. The nine districts are: 2) Bridge

City/New Orleans, 3) Lafayette, 4) Bossier/Shreveport City, 5) Monroe, 7) Lake Charles, 8) Alexandria, 58) Chase, 61) Baton Rouge, and 62) Hammond. The various districts are illustrated in Figure 24.

Mix design breakdown data were compiled in an Excel sheet to form a database, specific for Louisiana, with various search criteria. The scope included mix designs for highways and roadways projects for the past five years (2012 till 2017). The mix designs included the following classes B, D, and E (associated with rigid pavement design) and other classes such as A, AA, AA(M), P, R, S, and M, categorized as structural mixes.

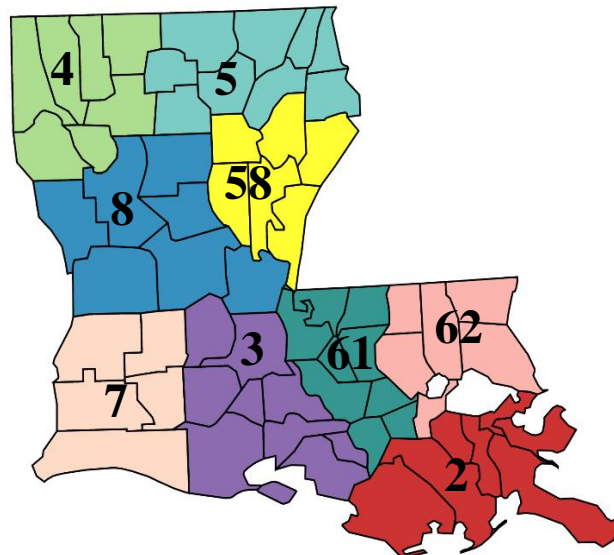


Figure 24. LaDOTD districts (LaDOTD)

These mix designs have no soft copies, are found in hard copies in the districts, and had to be entered manually into the Excel sheet). The mix design sheets collected from the districts contain the following information:

- Mix design breakdown
- Type of concrete (or class type): Indicates the type of job in which this concrete product can be used.

- Parish name: Indicates the parish in which the project took place. The study input this information into the data sheet to illustrate the project location for the user.
- Proposal number: The proposal number is used to link the mix design with the actual project/specifications. This proposal number was kept in the data sheet for future reference. In the event the user seeks to track the project, the LaDOTD intranet, as well as the Falcon website, can provide the data needed.
- Project name: The project name, added into the data sheet, should reflect the name of the project in which the mix design was used.
- Mix design number: The mix design number is to determine/locate a certain mix design in a certain project. The rationale indicates that a certain project can have more than one mix design with the same class type.
- Plant code: The plant code is unique for each plant. For example, a company can have two plants in the same parish; however, each plant has its own plant code.

The database displays 253 products. The database is provided in Appendix D. Table 21 illustrates some statistics about the number of mix designs per each concrete type, as well as the intended use, based on the Louisiana Department of Transportation and Development specifications. Class A, with 29 mixes, presents an intended use for box headwalls and culverts. Class AA has 14 mixes, with an intended use for bridge repairs. Class AA(M) has a total of 5 mixes, with an intended use for concrete special finishes. Class B has 104 products, with an intended use for pavement. Class D has 7 mixes, and an intended use for pavement. Class E has 21 products, with an intended use also for pavement. Class F has 10 products, with an intended use for culverts and storm drains. Class M, with 43 products has an intended use for culverts and drainage structures. Class R incorporates 11 mixes, with an intended use for stubbing and plugging pipes. Class S shows 4 products, with an intended use for shaft foundations.

Table 21. Concrete classes in the database

Concrete Class	Intended use	Number of mixes
A	Box headwalls culverts	29
AA	Bridge repairs	14
AA(M)	Special finishes for concrete	5
B	Pavement	104
D	Pavement	7
E	Pavement	21
F	Culverts/ storm drains	10
M	Culverts/ drainage structures	43
P	Precast/concrete roadway barriers	4
R	Stubbing and pugging pipes	11
S	Shaft foundations	4

3.3.2.1 Compressive strength value

Certain minimum compressive strength values are required for each class type, as per the Louisiana Department of Transportation and Development standard specification for the Roads and Bridges manual, found on the LaDOTD website. These specifications are illustrated in Table 22 for each class type. For example:

- The minimum compressive strength value for Class A is 3800 psi,
- The minimum compressive strength value for class AA is 4200 psi,
- The minimum compressive strength value for Class AA(M) is 4400 psi,
- The minimum compressive strength value for Classes B, D, and E are 4000 psi,
- The minimum compressive strength value for Class M is 3000 psi,
- The minimum compressive strength value for Class P is 5000 psi,
- The minimum compressive strength value for Class R is 1800 psi,
- The minimum compressive strength value for Class S is 3800 psi.

Table 22. Concrete classes in the database (LaDOTD)

Concrete Class	Minimum compressive strength value (psi)
A	3800
AA	4200
AA(M)	4400
B	4000
D	4000
E	4000
F	3400
M	3000
P	5000
R	1800
S	3800

However, the actual compressive strength value of these mixes should be higher, depending on project specifications. An intensive search was performed to collect the compressive strength value of these mix designs. This process included contacting the LaDOTD various districts and inquiring about the compressive strength values per proposal number, as well as contacting the industry/concrete companies and inquiring about the compressive strength values, either by proposal number or by the mix design breakdown and project year. The data collection process showing various compressive strength values is illustrated in Figure 25. Figure 25 also presents the data collection process for compressive strength values on the Louisiana level. Figure 26 illustrates the compressive strength values for the collected mixes, as well as the compressive strength distribution. The mixes mostly fall in compressive strength values of 4230 to 4740 psi and from 5250 to 5760 psi.

Furthermore, Athena Institute was asked to provide the breakdown of the environmental impact in the Environmental Product Declaration. Results of the environmental impacts, as well as the inventory data, were divided into three parts:

- A1: Raw material acquisition
- A2: Transportation from the raw material acquisition to the manufacturing phase

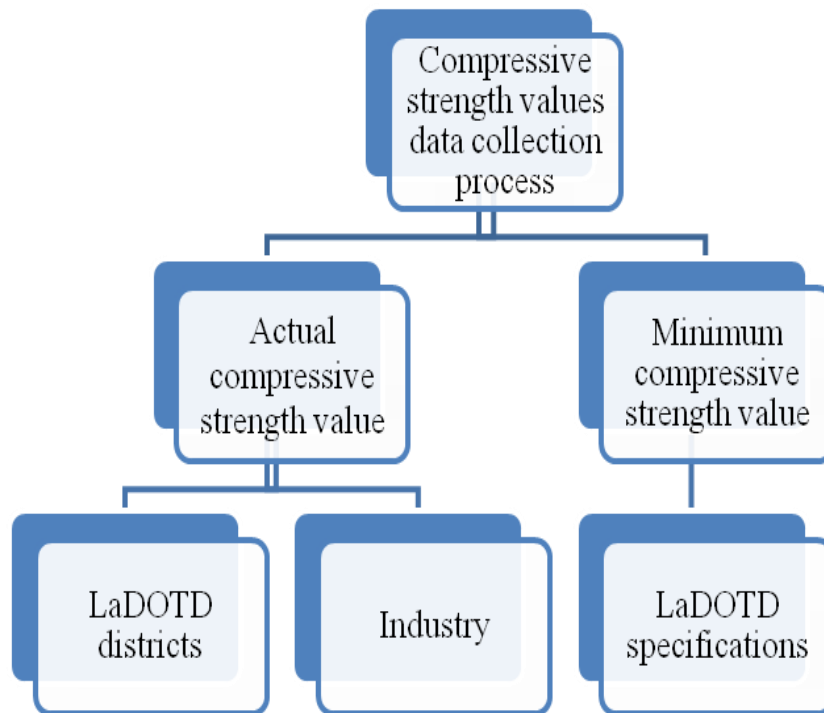


Figure 25. Data collection process for compressive strength values on Louisiana level

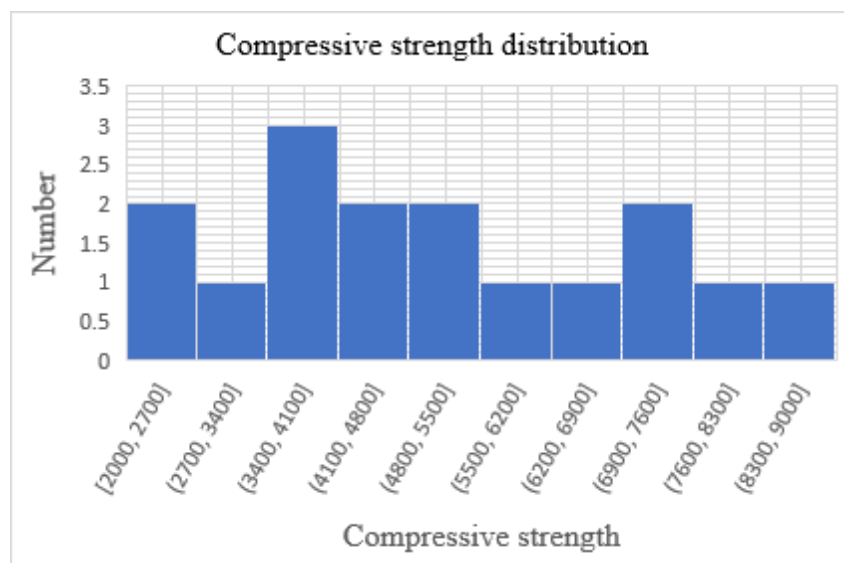


Figure 26. Compressive strength distribution

- A3: Manufacturing

A sample from the Environmental Product Declaration provided by Athena Institute is illustrated in Table 23. Three parts are shown: A1, A2, and A3 for each mix design. The total environmental impact is the sum of the parts A1, A2, and A3.

Table 23. Environmental Product Declaration sample provided by Athena

GWP A1 kg CO ₂ eq/yd ³	GWP A2 kg CO ₂ eq/yd ³	GWP A3 kg CO ₂ eq/yd ³	GWP Total kg CO ₂ eq/yd ³
187.02	23.34	7.2	217.56
335.01	27.39	7.2	369.6
204.84	24.07	7.2	236.11
204.82	24.06	7.2	236.08
215.63	25.04	7.2	247.87
314.29	26.55	7.2	348.04
172.1	23.2	7.2	202.5
213.82	23.45	7.2	244.47
204.85	24.07	7.2	236.12
187.34	24.32	7.2	218.86

3.3.2.2 MODULE 1B : TRANSPORTATION IMPACT ANALYSIS DATA COLLECTION (MANUFACTURER TO PROJECT LOCATION)

An increasing awareness of the importance of the transportation sector for achieving sustainable development goals becomes evident (Gorham, 2002). Although the transportation sector is crucial for economic and social development, that development imposes risks on the environment, such as environmental degradation and air pollution (Gorham, 2002). The transportation sector consumes 25% of the total commercial energy consumed worldwide, as well as one half of the total oil produced. Moreover, the demand for transportation services is expected to increase as economic growth increases and income rises. The growth is expected to increase by 1.5% in industrialized countries (Gorham, 2002).

In the United States, the transportation sector accounts for 72% of the total GHG leading to an increase in the average surface temperature. This increasing temperature leads to climate change such as precipitation patterns, storm severity, and rising sea levels. In addition, this climate change leads to an increase in the number of glacial lakes, a higher risk of plant and animal extinction, and a death increase from water floods (Najafi et al., 2010).

Statistics show that Texas emits more GHG than France, and California emits more GHG than Brazil. To mitigate the GHG impact, some states have adopted local plans to

reduce GHG inside their borders. It should be stated that while the federal government is slow in developing a national policy, there still are states that continue to adopt and redefine plans (Najafi et al., 2010).

Moreover, the transportation sector accounts for Acidification Potential, mostly from the sulfur emitted from vehicles (Sulphur Levels in Gasoline and Diesel, 2014). This results in acid gases, which when released to air cause acid rain, which in turn is absorbed by the plants, soil, and surface water (Acidification, 2017).

Also, Particulate Matters such as PM_{2.5} and PM₁₀ are released from the transportation sector. These Particulate Matters are air pollutants composed of liquid and solid particles suspended in the air. Particulate Matters, referred to as PM_{2.5}, have a diameter of less than 2.5 micrometer, while PM₁₀ are Particulate Matters that show a diameter of less than 10 micrometers. Particulate Matters pose significant health impacts, because these small particles have the capability to penetrate the respiratory system, thereby causing respiratory and cardiovascular problems such as asthma and lung cancer (Health Effect of Particulate Matter, 2013).

As a strategy to mitigate the environmental impact of transportation, this section will present a methodology to quantify the environmental impact resulting from product transportation from manufacturer location to project location. The environmental impact of concrete transportation from the manufacturer to the project location will be evaluated using three types of trucks: a light duty truck (light commercial truck), a medium duty truck (single unit truck), and a heavy duty truck (combination truck). Two types of fuel will be evaluated for each truck type: diesel and gasoline.

Inventory values were collected from United States lifecycle inventory free database. Corresponding inventory data for each truck type and fuel are illustrated in Table 24 for the combination truck diesel power (light duty truck). Other inventory values for other truck/fuel

types are attached in Appendix E. Detailed calculations for the transportation module are discussed in Chapter 4

Table 24. Combination truck, diesel power (light duty truck)

Details for Transport, combination truck, diesel powered				
Flow	Category	Flow Type	Unit	Amount
Outputs				
Carbon dioxide, fossil	air/unspecified	Elementary	kg	7.99E-02
Carbon monoxide, fossil	air/unspecified	Elementary	kg	1.27E-04
Methane, fossil	air/unspecified	Elementary	kg	1.29E-06
Nitrogen oxides	air/unspecified	Elementary	kg	5.32E-04
Particulates, < 10 um	air/unspecified	Elementary	kg	9.19E-06
Sulfur oxides	air/unspecified	Elementary	kg	1.76E-05
VOC, volatile organic compounds	air/unspecified	Elementary	kg	2.63E-05

3.4 MODULE 2: ECONOMIC IMPACT

This section will provide an overview of the data collection process for module 2AA, the cost associated with the mix design only, as well as for module 2AB, associated with the material price, the construction price, and the installation price. Figure 27 presents the breakdown to follow up with this section.

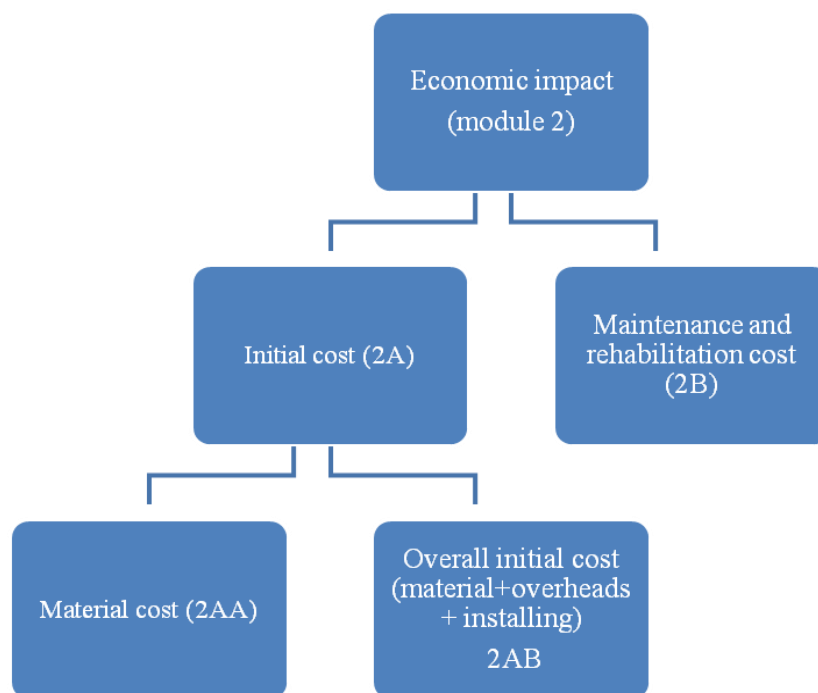


Figure 27. Economic analysis database

3.4.1 MODULE 2AA: MATERIAL COST

The material price was collected from the manufacturer. Prices were given in terms of 1yd³. A sample is illustrated in Table 25. As evident, each mix design has an associated cost per yd³.

Table 25. Module 2AA material cost

Product ID	Zip code	Compressive strength (psi)	GWP (kg CO ₂ eq)	Cost (\$/yd ³)
1597	75149	3000	264.5462	212
1734	75149	4500	288.2483	242
1735	75149	4000	312.715	219
1738	75149	4400	305.8338	230
1811	75149	4500	259.9587	217
1841	75149	4500	336.4172	220
1899	75149	5000	360.8839	243

3.4.1.1 Statistics for module 2AA

As previously described, this database contains pavement items in addition to structural items (non-pavement items). The total number of items is illustrated in Figure 28. The total initial cost items for the pavement items shows to be 121, whereas the total initial cost items for the structural elements show a sum total of 154.

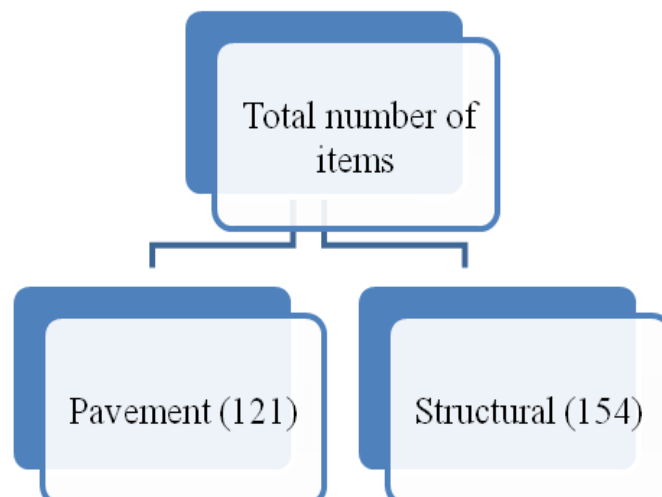


Figure 28. Initial cost database data statistics

For the paving items, Table 26 illustrates the number of initial cost items per layer thickness. As illustrated in Figure 29, most of the layer thickness falls in the 8, 9, and 10 inch categories (three highest values).

Table 26. Number of items in each layer thickness category

Layer thickness (inch)	Number of items
10	31
11	6
12	9
13	7
14.5	1
14	2
6	1
8.5	1
8	32
9	31

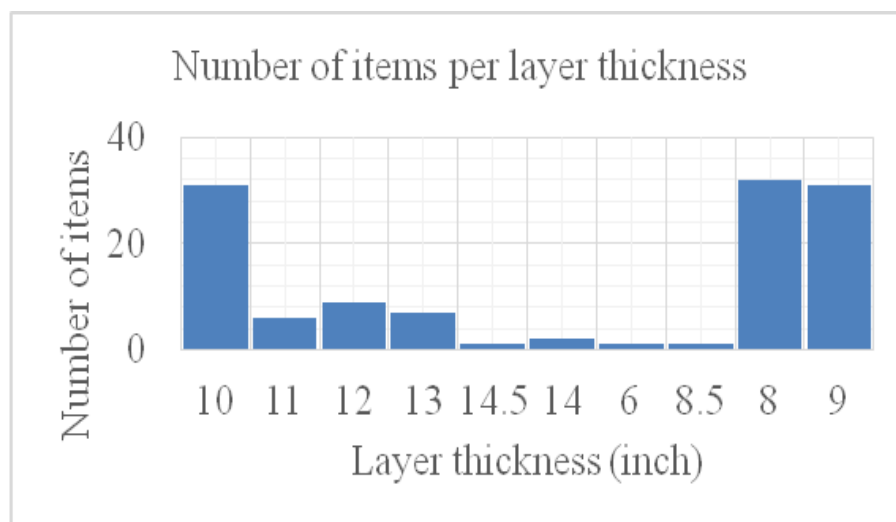


Figure 29. Number of items per layer thickness

3.4.2 MODULE 2AB: OVERALL MATERIAL COST AS PER BID ITEM

This module contains information about bid items (or material cost) including construction cost, profits, and installation cost. Data for the cost analysis database were gathered from the Louisiana Department of Transportation and Development. The data are found online in an Access database format. However, the only database published represents the past 11 years. Special arrangements were made to get older databases, through specialized

personnel working in the Louisiana Department of Transportation and Development. The data created contains the following information:

- Item number/ID is the same as the item number in the Louisiana Department of Transportation specifications. This number ID is composed of 11 digits. For the PCC layer items, the first three digits are 601, while for patching items, the first three digits are 602, etc. A full description of items is detailed in the LaDOTD specification manual.
- Item description: shows, as an example, whether this item is a PCC layer, patching item, etc.
- Proposal number: uses the proposal number to allow the user to obtain more project details. This may be accomplished by tracking this proposal number on the LaDOTD intranet, through the Falcon website.
- Items are categorized based on whether these are initial items, or maintenance and rehabilitation items. For example, PCC layers were categorized as initial items, as these are normally the material/mix designs bought at the start of the project. Other items, such as patching, were categorized as maintenance and rehabilitation items. The classification process is illustrated in Figure 28. The costs in this database include material price, profits, overhead, and equipment.
- The cost database was also divided by districts and parishes. The associated cost is made specific to each district and parish. Since the cost varies based on location, this procedure guarantees the use of a precise cost, based on the selected parish and district.
- Final column containing costs per corresponding unit of measurement. Various units of measurements are displayed in the database provided online by LaDOTD, such as ton, square yards, cubic yards, etc. A special unit conversion was performed to guarantee that a comparison between items would be performed based on the same unit; for example, the unit of yd^3 for volume. PCC maintenance and rehabilitation items are provided in

terms of yd^2 , while the layer thickness is given separately. The area was multiplied by the thickness, and the overall cost was adjusted to reflect the cost/ yd^3 .

Tables 27 and 28 illustrate several columns of the cost analysis database. This will be explained for the reader for replication. For example, Table 27 indicates the proposal ID, as well as the project name associated with this proposal ID. This will enable the user in reading the specifications. Then a letting date is illustrated in order to perform the lifecycle cost analysis later, and to account for the time value of money using the net present value. Then the parish and district names are provided as well. The cost items for these projects are illustrated in Table 28. The initial items for these projects consist of Portland cement concrete with various thicknesses, depending on the design and specifications. The final cost is then given for per yd^3 for consistency, to further enable a comparison between products.

Table 27. Initial cost items (project information)

Number	Proposal ID	Proposal description	Letting date	District	Parish name
1	H.000466.6	U.S 190: roundabout at Eden church road	5/13/2015	Hammond	Livingston
2	H.001205.6	LA 39: la 47-lake Borgne Canal Bridge	4/24/2013	New Orleans	St. Bernard

Table 28. Initial cost items information (cost items)

Number	Item	Item description	Type	Bid unit price per (yd^3)
1	601-01-00700	Portland Cement Concrete Pavement (11" Thick)	Initial	\$376.36
2	601-01-00300	Portland Cement Concrete Pavement (9" Thick)	Initial	\$380.00

3.4.3 MODULE 2B: MAINTENANCE AND REHABILITATION COST DATA

The maintenance and rehabilitation activities occur during the whole pavement lifecycle. For the State of Louisiana, the maintenance and rehabilitation cost activities for a certain road are stored in a database which can be accessed through LaDOTD internet. This database contains

all the maintenance and rehabilitation activities accomplished on a certain road since the initial construction.

Tables 29 and 30 illustrate a sample of the maintenance and rehabilitation cost data (the data was split into two tables, due to space limitation). Table 29 contains project information, such as the proposal description, the proposal ID in case the stakeholder wants to check the specifications, and the letting date, used at a later time to perform the lifecycle cost analysis. Table 30 contains an items description, and presents the actual maintenance and rehabilitation items and associated costs.

Table 29. Project information

Number	Proposal Id	Proposal description	Letting date
1	H.000466.6	U.S. 190: Roundabout at Eden Church Road	5/13/2015
2	H.001205.6	LA 39: LA 47-Lake Borgne Canal Bridge	4/24/2013

Table 30. Items description

Number	Item	Item description	Unit price per (yd ³)
1	602-05-01160	Full Depth Patching of Jointed Concrete Pavement (16.0 square yards and under) (9" Thick)	\$580.00
2	602-05-02160	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (9" Thick)	\$500.00

Once retrieved, maintenance and rehabilitation items should be linked to the initial cost items within a full lifecycle cost analysis. In other words, when the user selects a specific mix design, the user should be able to perform an analysis of the full lifecycle cost based on that mix design, which entails listing the initial cost, as well as the maintenance and rehabilitation costs of items.

As previously discussed, the initial cost items already exist in the database. However, since the projects selected are drawn from the past five years, these projects show no

maintenance and rehabilitation activities. To solve this problem, the compressive strength value of pavement sections will be matched with the compressive strength value of other pavement sections from past years. The pavement sections will also have corresponding maintenance and rehabilitation items, with the assumption that the earlier projects would have undergone similar maintenance and rehabilitation activities. To be more specific, after matching the compressive strength value, a similar match can be performed using mix design. The old database to be matched with the new items contains projects, show various compressive strength values (covering all the compressive strength values in the recent database) as well as mix designs associated with these projects. Consequently, the first filtering criteria could be the compressive strength value and the second one could be the mix design breakdown. This is to guarantee that the matched compressive strength value is equal or greater than the recent ones, and therefore is easy to use. The compressive strength value can be controlled using a tolerance level.

There are various scenarios here when matching the compressive strength values and/or the mix design breakdown (all depend on data availability):

- Scenario 1. Recent projects are matched with the compressive strength values of older projects (there is a tolerance value), as well as with the associated mix design. This is considered the best scenario (with a tolerance as well).
- Scenario 2. Recent projects get matched with the compressive strength value of older projects, yet the associated mix designs of the older projects do not exist. In this case, the compressive strength value is the only criteria. This should work as well, but will not be as specific as Scenario 1.

For example, if the user selected a mix design (mix design A) and an associated compressive strength of 5383 psi from the EPD database, the initial cost will be drawn automatically from the database, as previously discussed. However, the project will show no

maintenance and rehabilitation cost activities. Using the compressive strength value of 5383 psi, similar projects with the same compressive strength value (including a tolerance) may be identified, and thus the maintenance and rehabilitation activities may be found. For example, Table 31 illustrates the projects matching the required compressive strength value of 5383.

All the scenarios are illustrated. For example, when exactly matching the compressive strength value with the value of 5383, the associated projects do not have a mix design breakdown in the database. This is the case for various projects as well, such as: H.009572.6, H.009341.6, H.007265.6, H.006622.6, and H.010396.6. It should be noted that the selected alternatives will vary based on the tolerance level, and that these values are illustrated as a guide. Also, the selection will vary, depending on selected projects and data availability.

These projects are matched with a compressive strength value and a mix design breakdown. All the mix designs are illustrated for Table 32, and range from a cement content of 414 lb to 437 lb (this range can change, depending on available mix designs). The user can then select the required mix design breakdown and track the corresponding maintenance and rehabilitation items. The maintenance and rehabilitation items are illustrated in Table 33.

Table 31. Projects associated with the selected compressive strength value

Number	Compressive strength value (psi)	Project ID	Mix design available?
8	5383	H.000792.6	No
9	5560	H.010486.6	No
10	5540	H.009572.6	No
11	5540	H.009341.6	No
12	5540	H.007265.6	No
13	5560	H.006622.6	No
14	5560	H.010396.6	No
15	5555.10	450-91-0077	No
16	5548.5	742-17-0153	No
17	5620.51	455-09-0024	Yes
18	5638	H.007116.6	Yes
19	5893.8	013-06-0034	Yes
20	5947.10	025-06-0027	Yes
21	5821.24	808-07-0035	Yes

Number	Compressive strength value (psi)	Project ID	Mix design available?
22	5707.93	742-06-0016	Yes
23	5532.5	742-06-0074	Yes

As illustrated, various projects can show the same maintenance and rehabilitation items. Depending on data availability, this study recommends comparison/assumption of maintenance and rehabilitation activities occurring in the same district and parish, since the cost varies by location.

3.5 DISCOUNT RATE FOR LIFECYCLYE COST ANALYSIS

To perform a lifecycle cost analysis, the net present value is used. This will involve calculating the real discount rate, which is composed of the real interest rate and real inflation rate. Future values for real discount rates were forecast, using interest rates and inflation rates, using Equation 5 Real Discount Rate (D)

$$D = [(1 + I_{int}) / (1 + I_{inf})] - 1 \quad (5)$$

Where

- D = Real discount rate;
- I_{int} = Real interest rate, %
- I_{inf} = Real inflation rate, %

In regard to this equation, the Federal Highway Administration recommends the use of a discount rate without regard to the individual values of interest or inflation rate. Neither the interest rate nor the inflation rate values matter, but rather the differences between the two. This difference has remained constant (LCCA in pavement design 1998; Economic Analysis Primer 2003, Guide for the Design of Pavement Structures 1993; Guide for the MEPDG 2004). Therefore, this study will focus on using the discount rate, rather than a consideration of individual values of interest or inflation rate.

Table 32. Matching compressive strength value

Alternative	Proposal ID	Compressive strength value (psi)	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Air entertainer (%)
17	455-09-0024	5620.51	420	74	1437	1300	415	26	1.5
18	H.007116.6	5638	424	106	1018	1242	600	31.6	3.5
19	013-06-0034	5893.8	429	107	1275	1599	0	32	4
20	025-06-0027	5947.10	445	110	1589	1400	0	31.9	3.5
21	808-07-0035	5821.24	437	109	1119	1875	0	31.3	4.91
22	742-06-0016	5707.93	437	109	1158	1850	0	30	5
23	742-06-0074	5532.5	414	103	1407	1850	0	29.7	0

Table 33. Maintenance and rehabilitation activities for matching compressive strength (example)

Proposal ID	Letting date	Item	Item description	Unit	Quantity	Bid unit price (\$ per unit)
H.000792.6	6/24/2015	NS-805-00027	Structural Concrete Patching	Ft ²	445	365
H.000792.6	6/24/2015	NS-600-00220	Saw Cutting Portland Cement Concrete Pavement	Ft	2800	5
H.010486.6	9/10/2014	602-02-00300	Cleaning and Resealing Existing Transverse Pavements Joints	Ft	668607	0.69
H.010486.6	9/10/2014	602-05-02200	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards)	Yd ²	5151	105
H.010486.6	9/10/2014	NS-600-00220	Saw Cutting Portland Cement Concrete Pavement	Ft	29440	0.5

3.6 DATA OUTPUT FROM CHAPTER 3

The purpose of this section is to summarize the output for each module. These data will be used in Chapter 4, together with detailed equations.

For example, the output of module 1 (environmental impact module) has two different forms: inventory values reported in terms of kg/ton.km coming from the transportation module and environmental impacts coming from EPD (kg eq/yd³). Consider that a single environmental score is required for the environmental impact. Therefore, the data should be converted into the same units, before summing these together. Therefore, the data will need some modifications, which will be explained in Chapter 4.

Another example can be seen in module 2 (economic module). The output of this module is the maintenance and rehabilitation cost value given in the future, as well as the initial cost given at present. These two values are given in different amounts of time, and therefore cannot be compared. However, some modifications should be performed to make the data comparable, with the comparison considered at the same point in time. This process will be explained in Chapter 4. The requirement means that both scores should be summed together. Given the fact that these scores are not comparable, some modifications must be performed. The data output per module is illustrated in Figure 30.

3.7 SUMMARY

This chapter presented data concerning the development of the new framework and a data compilation process to be used later. The data consist of two modules (module 1 and module 2).

- Environmental data containing a compilation of Environmental Product Declarations.

The database included individual product declarations for those states that had produced their own Environmental Product Declarations. For the State of Louisiana, based on survey results performed to date, no company exists which has issued an individual EPD, and only a few

companies participated in the industry wide average EPD, with the National Ready Mix Concrete Association.

- An Environmental Product Declaration was produced for the State of Louisiana with the aid of Athena Institute, through the use of mix designs data from various districts of the Louisiana Department of Transportation and Development.
- The EPD was inclusive of transportation data containing substance content and an evaluation of the environmental impact of the transportation stage, incorporating the manufacturer to use phase. Vehicles were categorized based on their weights in three categories: light industry truck, medium duty truck, and heavy duty truck. Also, two fuel types were included: diesel and gasoline.
- Module 2: Economic data containing the cost data for initial costs and for the costs of maintenance and rehabilitation items.

All the data previously collected are not in the same format, such as units. Moreover, they pertain to different points in time. For this reason, the data should be modified to ensure that the data is equivalent. This will be performed in Chapter 4.

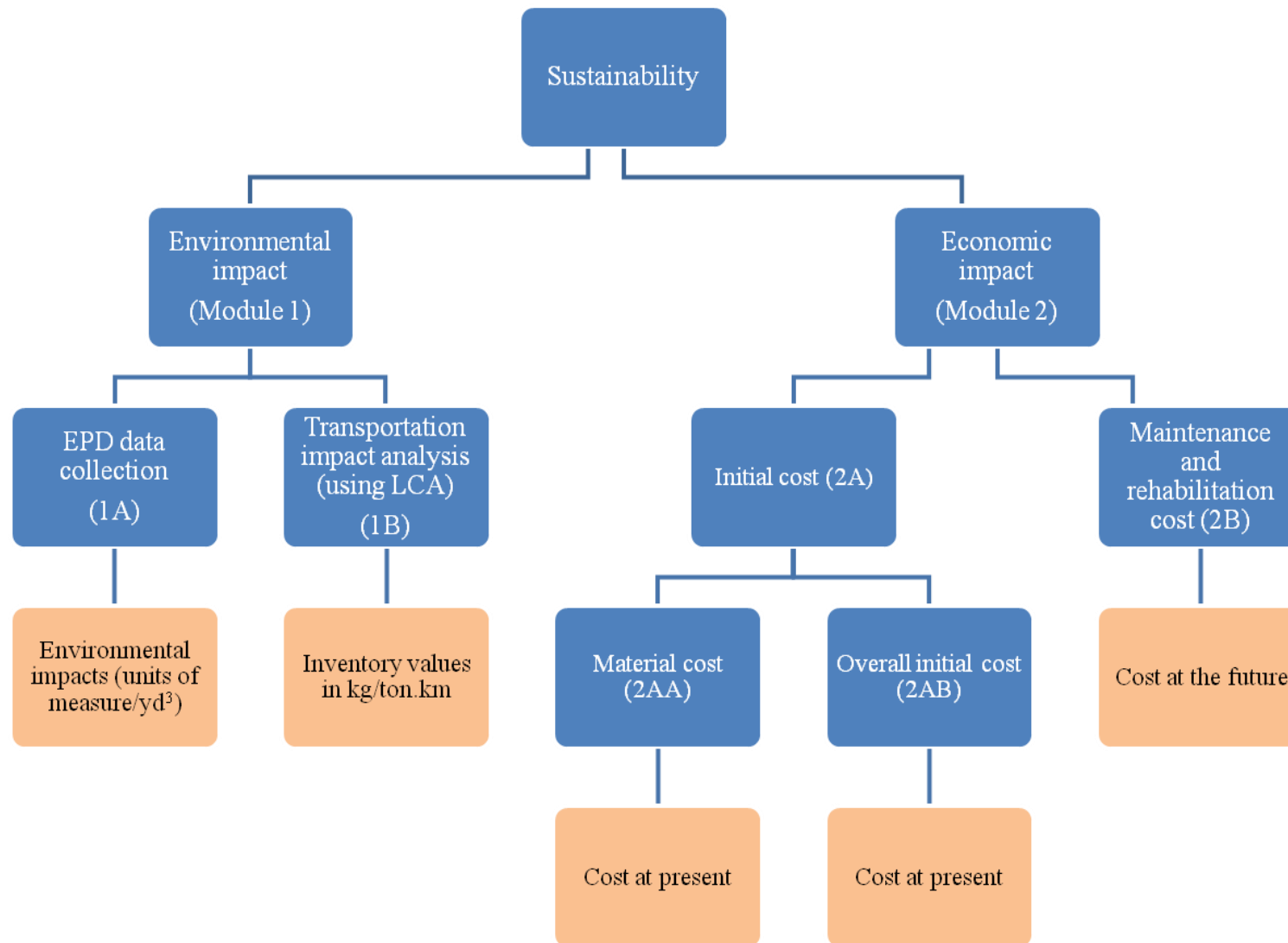


Figure 30. Data output per each module

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CHAPTER 4. IMPLEMENTATION

4.1 INTRODUCTION

This section will describe the incorporation process of sustainability data into the newly developed framework. To accomplish this process, the following steps should be performed:

- Adjusting data from module 1 (environmental impact): The purpose of this section is to guarantee that the inventory values from the transportation impact, as well as the environmental data coming from EPD, are comparable. Also, the data coming from the EPD should be adjusted to accommodate the total design volume.
- Adjusting data from module 2 (economic impact): The purpose of this section is to guarantee the costs data are comparable at the same point in time.
- Obtaining a final score: In this step the environmental score, as well as the economic score, should be comparable in order to obtain one final single score.

To perform data modification, the following procedure/background should be recalled from the literature review section: 1) the framework for pavement design, 2) the lifecycle inventory and lifecycle impact assessment from the overall LCA procedure, 3) the net present value for the cost analysis.

The new framework should enable product comparison, as well as benchmarking. For this reason, Chapter 4 will be divided into two sections: data adjustment for alternative design comparison, and data adjustment for benchmarking section

4.2 ALTERNATIVE DESIGN COMPARISON MODULE

The purpose of this section is to describe the modification procedure, in the event the stakeholder wants to compare the environmental/economic impact of more than one alternative. First the data will be adjusted to guarantee the data is equivalent (has the same units, and are evaluated at the same point in time, etc.) and finally, alternatives are compared relative to one another’.

The importance of the environmental and economic impacts varies, depending on stakeholder preference (Lippiatt, 2007). For this reason, the user can assign weights for economic (EcoW) and environmental impacts (EnvW), depending on their importance. The sum of both weights should sum to 100. The higher the score may be, the higher the importance.

4.2.1 MODULE 1: THE ENVIRONMENTAL IMPACT

The purpose of this section is to adjust the environmental data from Chapter 3, as well as to explain the concept, equations, and science behind the procedure.

4.2.1.1 Part 1A: Adjusting data from EPD

As previously discussed in Chapter 3, the output of Part 1A, or the data coming from EPD, is the environmental impact. These values are reported in terms of the following unit kg eq/yd³ (or per 1 yd³). However, in case of pavement design, these environmental impacts should be adjusted to account for the total design layer volume. The total design volume for the pavement layer is illustrated in Equation 6:

$$L_V = L_T \times L_w \times L_L \quad (6)$$

Where:

- L_V = layer volume
- L_T = layer thickness
- L_w = layer width. The design width in this study is: 12 feet which is the standard road width
- L_L = layer length. The design length taken in this study is: 1 mile

Please note the units in Equation 6, to make certain the units are consistent. This study recommends having the final layer volume in terms of yd³, since the impacts in EPD are reported in terms of 1yd³. However, the user might also use units of 1m³ as long as

calculations are consistent throughout the study. The conversions used are illustrated in Table 34

Table 34. Unit conversion

Unit	Conversion to yard
1 mile	1760
1 inch	1/36
1 feet	0.33

To obtain the total environmental impact per design layer volume, Equation 7 should be used to convert impacts in EPD, given per unit of volume (1yd³) or (1m³), depending on the manufacturer, to the total environmental impacts result for the total layer volume.

$$\text{Environmental impact reported from EPD} \times L_v \quad (7)$$

The output of Equation 7 should be the environmental impact adjusted per volume. One more thing to note here, the environmental impact/inventory values are reported in terms of compressive strength value in EPD. In other words, to find the environmental impact of any mix design, the search criteria should be in terms of compressive strength value.

Sometimes, the design is given in other properties, such as the modulus of rupture (this will be discussed later in case studies; for example, rigid pavement design in the State of Louisiana is reported in terms of modulus of rupture). In this case, the modulus of rupture should be converted to compressive strength value, to find the impacts from EPD. Various equations were reported in literature to convert from modulus of rupture to compressive strength value. For example, the American Concrete Institute Committee (ACI 330), as a guide for design and construction of concrete, presented Equation 8, relating the modulus of rupture to compressive strength value.

$$\text{MOR (psi)} = 2.3 f_c^{2/3} \quad (8)$$

Where:

- MOR: is the modulus of rupture
- f_c : compressive strength value

4.2.1.2 Normalization

Normalization is used to express the impact indicators in a manner that can be compared among impact categories (EPA, 2006). This process occurs by dividing the indicators by a selected reference value. Various reference values can be used such as:

- The total emissions or resource use for a given area. These emissions can be either global, regional, or local
- The total emissions or resource use given for a certain area per capita
- The ratio of one alternative to the other
- The highest value between all alternatives

This study uses the total emissions given per capita. Normalization values are illustrated in Table 35. All values are extracted from TRACI, except for the fossil fuel depletion and the renewable energy consumption values, extracted from the Statista database.

Table 35. Normalization value used (Traci and Statista database)

Name (units)	Value (impact per person per year)
Global Warming Potential (kg CO ₂ eq)	24000
Ozone Depletion Potential (kg CFC-11 eq)	0.16
Acidification Potential (kg SO ₂ eq)	91
Eutrophication Potential (kg N eq)	22
Photochemical Ozone Creation Potential (kg O ₃ eq)	1400
Fossil fuel depletion (MJ surplus)	288572.50
Renewable energy consumption (MJ)	24874.5

Values can be normalized using Equation 2 (Stranddorf et al., 2005).

Equation for normalization (previously described as Equation 2):

$$\text{Normalized value} = \text{ImpactA} / (\text{Normalization value for impactA})$$

By analyzing values in EPD for a random mix design (for a total volume of 1 yd³), the corresponding GWP = 346 kg CO₂ eq and the ODP = 3.99E-06 kg CFC-11 eq, which means these are not on the same scale or units. However, by normalizing them and using corresponding values given in Table 35, the values then become:

Normalized value for GWP = $346 \text{ kg CO}_2 \text{ eq} / 24000 \text{ kg CO}_2 \text{ eq} = 0.0144$

Normalized value for ODP = $3.99 \times 10^{-6} \text{ CFC-11 eq} / 0.16 \text{ kg CFC-11 eq} = 2.49 \times 10^{-5}$

(Stranddorf et al., 2005) Also, the values become unitless, which facilitates the process of adding them together later, since the objective is to get one final sustainability score at the end.

4.2.1.3 Weighting

The weighting process for LCA is the process of assigning weights to various impact categories, based on their importance (EPA, 2006). This weighting procedure is important, since it reflects the stakeholder preference. The weighting procedure could be different depending on stakeholders, and therefore, the reason for assigning any weights should be documented (EPA, 2006). The weighting criteria used in this study will be based on the EPA's weights, as well as the BEES model weights. It should be noted that this study does not evaluate all the impacts evaluated in the EPA, and only uses the following values: GWP, ODP, AP, EP, POCP, non-renewable energy consumption, and renewable energy consumption. Therefore, the weights were scaled to sum up to 100. Table 36 illustrates the weights assigned by the EPA's Science Advisory Board criteria, and Table 37 illustrates the weights used in the study, based on the EPA's weights.

Table 36. EPA's Science Advisory Board weighting criteria (EPA, 2006)

Impact category	Relative importance (weight) in %
Global Warming	16
Acidification	5
Eutrophication	5
Fossil Fuel Depletion	5
Indoor Air Quality	11
Habitat Alteration	16
Water Intake	3
Criteria Air Pollutants	6
Smog	6
Ecological Toxicity	11
Ozone Depletion	5
Human Health	11

Table 37. Adjusted weights based on EPA's Science Advisory Board

Weights	EPA Science Advisory Board Based
GWP	35%
ODP	10%
AP	11%
EP	10%
POCP	12%
NRE	11%
RE	11%
Total	100%

Moreover, the weights for the BEES are illustrated in Table 38; Table 39 illustrates the weights used in the study based on the BEES model.

Table 38. BEES stakeholder panel judgement (Lippiatt 2007)

Impact category	Relative importance (weight) in %
Global Warming	29
Acidification	3
Eutrophication	6
Fossil Fuel Depletion	10
Indoor Air Quality	3
Habitat Alteration	6
Water Intake	8
Criteria Air Pollutants	9
Smog	4
Ecological Toxicity	7
Ozone Depletion	2
Human health (Cancerous Effects)	8
Human health (Noncancerous Effects)	5

Table 39. Adjusted weight based on BEES

Weights	BEES stakeholder panel
GWP	45%
ODP	3%
AP	5%
EP	10%
POCP	5%
NRE	16%
RE	16%
Total	100%

This weighting process is performed after values are normalized. The equation used for weighting was previously illustrated as Equation 3 (Stranddorf et al., 2005). The reason for repeating the equation here is to display where to use the assigned weights.

$$\text{Weighted impact} = \text{assigned weights} \times \text{normalized value}$$

Where:

- The assigned weights are illustrated in Tables 37 and 39.

Example, to weight the previous normalized value for the GWP, using the EPA weight, this will lead to the following value, and the final value become unitless.

$$\text{Weighted impact} = 0.29 \times 0.0144 = 4.176 \times 10^{-3}$$

4.2.1.4 Part 1B: Adjusting data: Transportation impact module (Manufacturing to project location)

As previously discussed, data for the transportation module was extracted from U.S lifecycle inventory database, a free database available online. These values, illustrated in Table 40, are the inventory values reported in terms of kg/ton.km, and therefore need to be transformed into environmental impacts by means of the following: 1) multiplying by the total weight transported, 2) multiplying by the total distance traveled, 3) characterization of the results.

Table 40. Re-analyzing values for combination truck diesel power for light duty truck (TRACI)

Details for Transport, combination truck, diesel powered				
Flow	Category	Flow Type	Unit	Amount
Outputs				
Carbon Dioxide, fossil	air/unspecified	Elementary	kg	7.99E-02
Carbon Monoxide, fossil	air/unspecified	Elementary	kg	1.27E-04
Methane, fossil	air/unspecified	Elementary	kg	1.29E-06
Nitrogen Oxides	air/unspecified	Elementary	kg	5.32E-04
Particulates, < 10 um	air/unspecified	Elementary	kg	9.19E-06
Sulfur Oxides	air/unspecified	Elementary	kg	1.76E-05
VOC, volatile organic compounds	air/unspecified	Elementary	kg	2.63E-05

The total weight transported consists of two components: truck weight, as well as the transported concrete. Truck weights for various truck types are illustrated in Table 41.

Table 41. Truck weight by class type (Caltrans 2017)

Type of truck	Weight (lb)	Weight (ton)	Categorization
Light	8000	3.62	Light duty truck
Single unit	20000	9.07	Medium duty truck
Combination	80000	36.28	Heavy duty truck

As for the transported concrete, the total weight of concrete transported should be calculated. The EPD database previously described contains the density for each mix design, given in units of mass/volume (lb/yd³). To convert these values into units of mass, the density values should be multiplied by the total volume of concrete transported/designed. Equation 9 should be used to convert density to mass:

$$M = D \times Lv \quad (9)$$

Where:

- M = Mass (mass of concrete transported)
- D = Density of concrete transported (lb/yd³)
- Lv = Volume. This should be the total volume to be designed, previously calculated in Equation 6

To get the total number of loads required, per total job, the weight of concrete should be divided by the maximum truck loading capacity. This can be performed by using Equation 10.

$$\text{Total number of loads} = \text{total weight concrete designed} / \text{truck carrying capacity} \quad (10)$$

The loading capacity for each truck type is illustrated in Table 42.

Table 42. Maximum loading capacity per truck type (Technologies and approaches to reducing the fuel consumption of medium and heavy duty vehicles 2010)

Vehicle Type	Light duty truck	Medium duty truck	Heavy duty truck
Maximum loading capacity(lb)	3700	11500	54000

Equation 11 should then be used to get the total emissions after adjusting per distance traveled, total weight to be transported, and total number of loads.

$$2 \times \text{Emissions of each truck} \left(\frac{\text{kg}}{\text{ton.km}} \right) \times \text{total weight transported (truck weight (ton) + weight of concrete transported (ton))} \times \text{total distance (km)} \times \text{total number of loads} \quad (11)$$

Where:

- The factor of 2 accounts for the backhaul distance.
- Emission of each truck should be taken from Table 40, depending on truck type and fuel used.
- For truck weight and concrete weight, the truck weight should be taken from Table 41 and the weight of the concrete transported should be added from Equation 9 (density values are already in the database for each mix design).
- The total distance: is the distance from the manufacturer to the project location, calculated using the distance between the two zip codes (using Google maps).

The output of Equation 11 remains as inventory values that should be transformed into environmental impacts. To convert inventory values into environmental impact, these values should be characterized.

4.2.1.5 Characterization

The characterization step is one of the steps in performing LCA. The purpose of the characterization process is to convert lifecycle inventory into comparable impact indicators. For example, characterization can provide the relative terrestrial toxicity between Lead, Chromium and Zinc. To convert the inventory data into an impact indicator, characterization previously described as Equation 1 should be performed.

$$\text{Impact category} = \text{Adjusted inventory values} \times \text{characterization factor}$$

Where:

- Adjusted inventory values: These were already calculated in Equation 11.

- Characterization factor: The values for characterization are illustrated in Table 43, which were extracted from TRACI.

As may be seen from Table 43, inventory datum such as Nitrogen Dioxide contribute to Acidification Potential, Eutrophication Potential, and Smog Formation respectively, by the following values (7.00E-01 kg SO₂ eq /kg substance), (2.91E-01 kg N eq /kg substance), (1.68E+01 kg O₃ eq /kg substance). The example shown below will demonstrate how to use the characterization table (Table 43), using the combination truck (light duty truck), previously illustrated in Table 40 as an example.

Table 40 indicates that a combination truck emits Nitrogen Oxide In the amount of 0.000532 kg/ton.km. If the vehicle travels a distance of 1 km, and the total weight transported equals 1 ton, then the resulting inventory value from the Nitrogen Oxide is: 0.000532 kg/ton.km \times 1 km \times 1 ton = 0.000532 kg.

By using the characterization values in Table 43, this value should be multiplied by 7.00E-01 to convert to Acidification Potential, leading to a total value of 3.72E-04 kg SO₂ eq, and should be multiplied by a value of 2.91E-01 to convert to Eutrophication Potential, resulting in a value of 1.55E-04 kg N eq. This process should be repeated for all inventories; then the total impacts from all these inventories should be summed for each environmental impact category produced by the light duty truck. In Table 44, the final environmental impact calculation for the various types of trucks, using various fuel types coupled with a total weight transported, equals 1 ton; the total distance traveled equals 1 km.

Table 43. Characterization values used (TRACI)

Substance Name	Global Warming Air (kg CO ₂ eq / kg substance)	Acidification Air (kg SO ₂ eq / kg substance)	Eutrophication Water (kg N eq / kg substance)	Ozone Depletion Air (kg CFC-11 eq / kg substance)	Smog Air (kg O ₃ eq / kg substance)
Ammonia	0.00E+00	1.88E+00	7.79E-01	0.00E+00	0.00E+00
Nitrogen Dioxide	0.00E+00	7.00E-01	2.91E-01	0.00E+00	1.68E+01
Nitrogen Oxides	0.00E+00	7.00E-01	2.91E-01	0.00E+00	2.48E+01
Nitrous Oxide	2.98E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Methane	2.50E+01	0.00E+00	0.00E+00	0.00E+00	1.44E-02
Carbon Dioxide	1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Carbon Monoxide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.56E-02
Sulfur Dioxide	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00
PM10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PM2.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sulfur Oxides (SO _x)	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00
VOCs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.60E+00

Table 44. Final transportation impact per vehicle and fuel type (1 ton and 1 km)

Truck/fuel type	Global Warming Air (kg CO ₂ eq / kg substance)	Acidification Air (kg SO ₂ eq / kg substance)	Eutrophication Water (kg N eq / kg substance)	Ozone Depletion Air (kg CFC-11 eq / kg substance)	Smog Air (kg O ₃ eq / kg substance)	Fossil fuel depletion (MJ/ kg substance)
Light duty/diesel	7.99E-02	3.90E-04	1.55E-04	0.00E+00	1.33E-02	2.00E-02
Medium duty/diesel	1.71E-01	2.63E-05	3.55E-04	0.00E+00	3.06E-02	4.28E-02
Heavy duty/diesel	3.24E-01	1.34E-03	5.55E-04	0.00E+00	4.62E-02	8.09E-02
Light duty/gasoline	6.20E-02	2.68E-04	9.84E-05	0.00E+00	8.65E-03	1.55E-02
Medium duty/gasoline	1.33E-01	5.74E-04	2.26E-04	0.00E+00	2.00E-02	3.32E-02
Heavy duty/gasoline	3.16E-01	8.35E-04	3.47E-04	0.00E+00	3.02E-02	7.89E-02

4.2.1.6 Total transportation impact

The total transportation impact is accomplished for all states in the EPD database as simply the output of Equation 11, which is the environmental impact from the manufacturer to the project location. However, the situation differs for the State of Louisiana, since the values of EPD for transportation from the raw material extraction to the manufacturing phase were provided separately by Athena Institute. Therefore, the total transportation impact is the sum of the transportation impacts of two stages: from the raw material extraction to the manufacturing (provided by Athena) and from the manufacturer to the project location. The sum of both transportation modules is illustrated in Equation 12.

$$\begin{aligned} \text{Total transportation impact for the State of Louisiana} = \\ [\text{Transportation impact from raw material extraction to manufacturing} \times (L_v)] + \\ \text{Transportation impact from the manufacturer to project location} \end{aligned} \quad (12)$$

Where:

- The transportation impact from the raw material extraction to manufacturing was provided by Athena Institute separately. However, the impacts are given per 1 yd³ for each mix design, which means these values should be adjusted by multiplying each impact by total concrete volume (L_v), as calculated earlier.
- The transportation impact from the manufacturer to the project location was previously calculated (Equation 11) and characterized.

As an example, the total GWP for a certain mix design for the transportation impact from the manufacturer to project location = (GWP from EPD) \times (Total volume) + GWP previously calculated and characterized in Equation 11, etc... The same concept applies to other environmental impact values. After getting the total environmental impact of transportation, the values should then be normalized and weighted as previously described.

4.2.1.7 Overall environmental impact

After adjusting the environmental data coming from EPD, as well as the data coming from the transportation module, both data should be added together per alternative, to obtain one final environmental score for each alternative. This can be accomplished through Equation 13

$$\text{Total environmental impact from the transportation module (Equation 11)} + \text{The environmental impact resulting from concrete layer design (Equation 7)} \quad (13)$$

Where:

- The total transportation impact from the transportation module is the one previously calculated in Equation 11. In addition, the transportation impact for the State of Louisiana differs from all other states, since the transportation impact from the raw material extraction to the manufacturing was provided separately; this value should be normalized and weighted.

Finally, to obtain one single, relative, and comparable environmental score for each alternative, the overall environmental score for each alternative is divided by the total environmental score, or by all other alternatives. The result should be a unitless score, as illustrated in Equation 14

Score for environmental impact alternative i=

$$\frac{\text{Total environmental score for alternative i}}{\sum \text{Environmental impact of all alternatives a}} \quad (14)$$

The total environmental score is defined as the sum of the GWP, ODP, EP, AP, POCP, NRE, followed by deduction of the value of the RE, which leads to GWP+ODP+EP+POCP+NRE-RE. When the score rises, this means a higher environmental impact (emissions), and when the score lowers, this means the alternative has a lower environmental impact as a better alternative. In the event the user is assigned a weight for the environmental score, the environmental score for alternative i becomes

$$\text{EnvW} \times \text{Score for environmental impact alternative } i \quad (15)$$

4.2.2 MODULE 2: ECONOMIC PERFORMANCE

At that point, the design alternatives are evaluated for cost analysis. The cost analysis uses the net present value for evaluating different design alternatives. This includes factors such as initial cost (or current costs), and maintenance and rehabilitation costs (future costs). As previously discussed, the economic analysis has values at the present and values in the future. For this reason, the values should be compared at the same point in time. This will be performed using the net present value. The equation used to obtain the net present value, using current costs and future costs, was previously illustrated as Equation 4.

$$\text{NPV} = \text{initial costs} + \sum \text{Rehab Cost} \left[\frac{1}{(1+i)^n} \right]$$

Where:

i = discount rate, n = year of expenditure, $\left[\frac{1}{(1+i)^n} \right]$ = present value factor

Alternatively, in case the future value is to be expected, this will lead to

Future value = Present value $(1+i)^n$; where present value is the cost at current year, and the future value is the expected amount in the future.

The final economic score that should be assigned to each alternative can be calculated using Equation 16 (Lippiatt, 2007), where the net present value for the intended alternative is divided by the sum of the net present value for all other alternatives. The output of this equation should be a relative single score to compare between various alternatives.

$$\text{Score for Economic impact alternative } i = \frac{\text{NPV}_i}{\sum \text{NPV}_a} \quad (16)$$

Where:

- NPV_i : This is the net present value for the alternative required. This should have been calculated previously by Equation 4.
- The NPV_a : This is the net present value for all alternatives to be evaluated.

Moreover, in the event the user has assigned a weight for the economic impact (EconW), the final equation thus becomes:

$$\text{EconW} \times \text{Score for Economic impact alternative } i \quad (17)$$

Where:

- EconW is the economic score assigned by the user.
- Score for economic impact, which was previously calculated using Equation 16.

4.2.3 THE OVERALL/ TOTAL PERFORMANCE

The final scoring criteria is simplified in Figure 31. The environmental performance score includes GWP, ODP, AP, EP, renewable energy consumption, and non renewable energy consumption. The economic scoring criteria includes initial cost (costs occurring at the present and maintenance and rehabilitation items (occurring in the future).

Therefore, after all the previous calculations, the final sustainability score for the environmental (module 1) and economic impact (module 2) is illustrated in Equation 18.

Overall final sustainability score = Weighted economic score per alternative + Weighted environmental score per alternative (18)

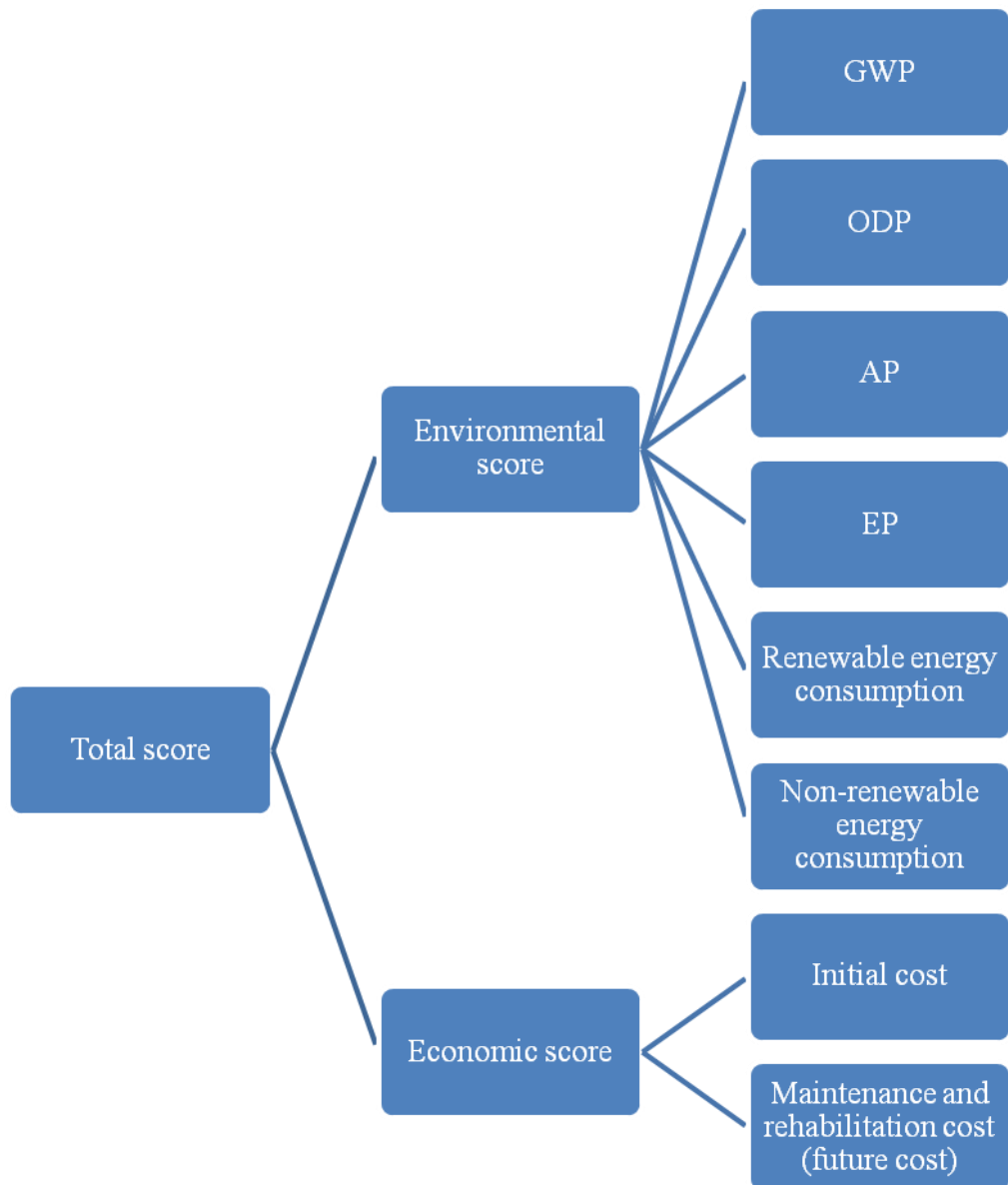


Figure 31. Final scoring criteria

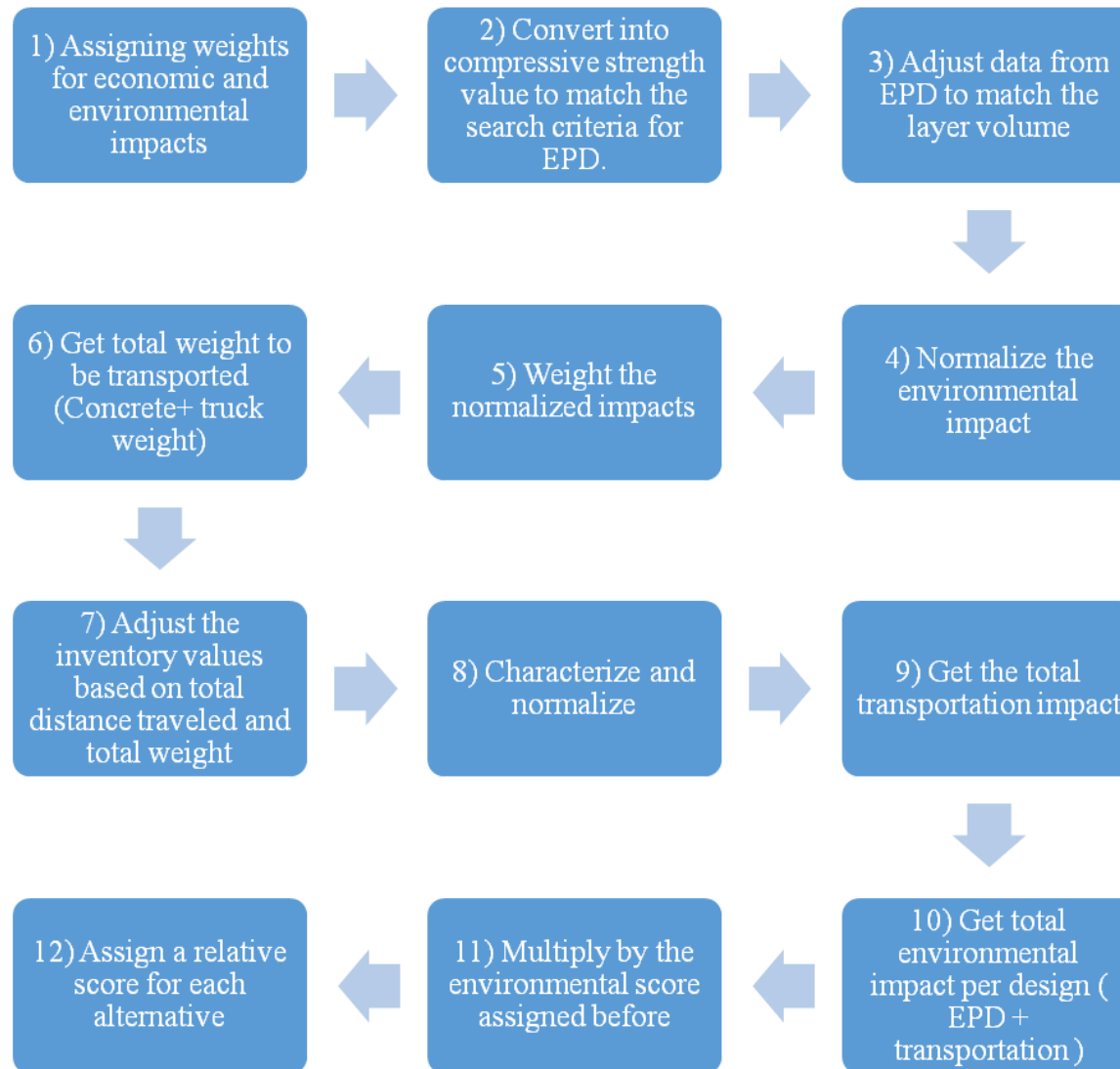


Figure 32. Environmental impact module

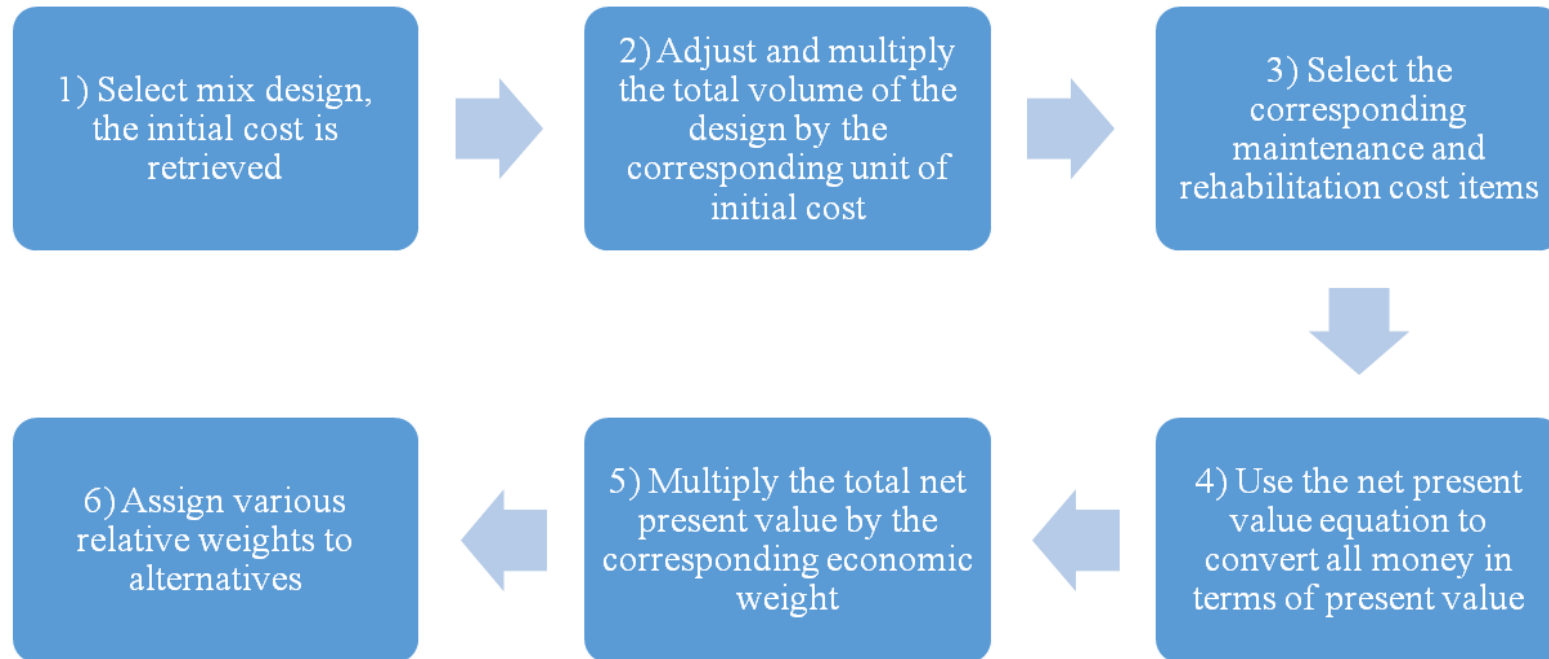


Figure 33. Economic impact module

BENCHMARKING MODULE

In addition to alternative design comparison, the sustainability data previously collected (modules 1 and 2), may also be used to benchmark

products in order to evaluate whether the products are above or below average. The benchmarking criteria can occur with respect to various criteria, such as benchmarking with respect to a certain district/region/location/mix design breakdown, etc. The benchmarking flowchart is illustrated in Figure 34, and the benchmarking equation is illustrated in Equation 19.

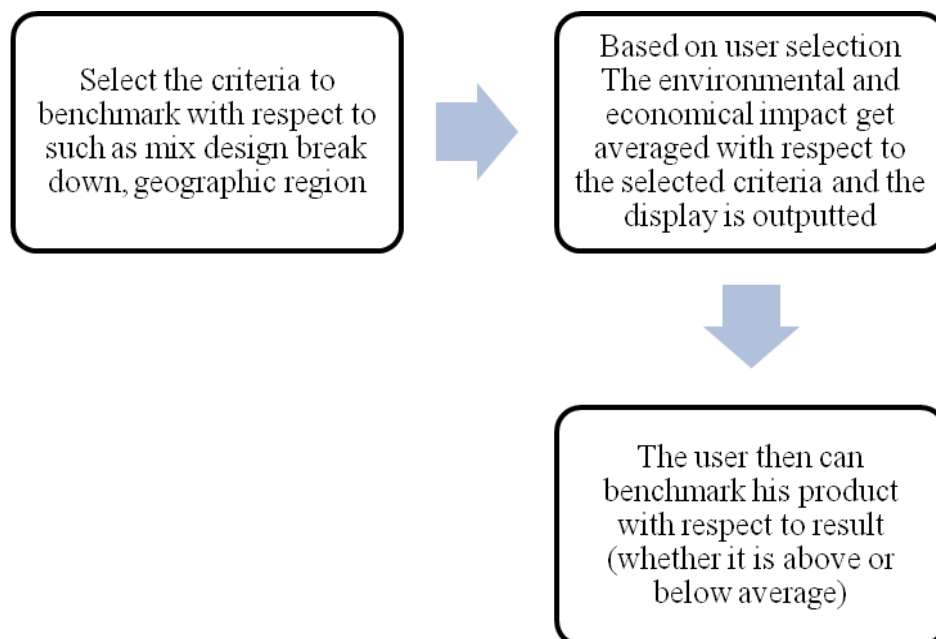


Figure 34. Benchmarking criteria flowchart diagram

$$\text{Benchmarking} = \frac{\sum \text{Each environmental impact or each inventory}}{\text{Number of mixes}} \quad (19)$$

The benchmarking can occur with respect to various criteria, such as:

- A specific mix design breakdown, as for example, mix designs with a cement content of 400 lb.
- A specific location such as a district, in the case of the State of Louisiana, i.e., at a State or National level.

In addition, the user has an option to select the mix designs that should be entered into the benchmarking module. For example, if the user selected some benchmarking criteria (such as geographic location, mix design breakdown, etc.) and the output is 10 mix designs, the user still can select the mixes that need to be averaged from these 10 mixes. After user selection the environmental impact, such as GWP values, are summed together and averaged over the selected mixes, with the same procedure for AP values, etc. As for the cost items, the entire cost of the mix designs is summed together as well, then divided by the number of selected mixes. Once the average result is displayed, the user can then average/benchmark the product.

All the equations previously described will hold, except for the fact that the environmental impact, as well as the economic impacts, will be averaged across all selected alternatives and finally treated as one single value. The equations previously described in the alternative design module are illustrated in Table 45, and the differences are indicated to be used in the benchmarking module.

Table 45. Benchmarking module equations

Equations/step previously used in the alternative design comparison module	Application in the benchmarking module
Assigning weights for economic and environmental impacts	Yes, this equation still holds and the sum of both weights should sum to 100. No changes
Total layer volume calculation $L_V = L_T \times L_W \times L_T$	Yes, still holds.
Total environmental impacts per design layer = Environmental impact reported from EPD \times Lv	There is a slight change in this equation. The impacts reported from the EPD are averaged impacts based on the selection criteria by stakeholder and no longer individual impacts. For example, if the filtering criteria narrowed down to 10 options, the impacts from EPD corresponding to these options are averaged.

Table 45 (cont.)

Equations/step previously used in the alternative design comparison module	Application in the benchmarking module
$MOR (psi) = 2.3 f_c^{2/3}$	Yes, still holds. This is not affected by the benchmarking module
Weighted impact = assigned weights × normalized value	Yes, still holds. All the assigned weights are still the same: BEES, the EPA, the default value for the software and the custom weights. The normalized value is the average environmental impact
Weight for concrete transported $M = D \times L_v$	There is a slight change in this equation. The weight of the concrete transported is the average value for the selected mixes. There are no individual values anymore.
Adjusted inventory values = $2 \times \text{Emissions of each truck (kg/(ton.km))} \times \text{total weight transported (truck weight (ton) + weight of concrete transported (ton))} \times \text{total distance (km)} \times \text{number of trucks}$	There is a slight modification in this equation as well. The total weight of concrete transported should be an averaged value. The average distance is calculated as well and not individual ones.
Impact category = adjusted inventory values × characterization factor	There is a slight change in this equation. The inventory values are averaged inventory values and not individual ones.
Total number of loads = total weight concrete designed/ truck carrying capacity	The average number of trucks for the selected alternatives is used and not the individual ones.
Total transportation impact for the State of Louisiana $\left[\text{Transportation impact from raw material extraction to manufacturing} \times (L_v) \right] + \text{Transportation impact (manufacturer to project)}$	There is a slight change in the equation. The transportation impact are the average transportation distances and not individual ones.
Total environmental impact = total environmental impact from the transportation module + the environmental impact resulting from concrete layer design	There is a slight change. The environmental impact is the average value and the environmental impacts from concrete are average values as well
Score for environmental impact alternative i = $\frac{\text{Total environmental score for alternative i}}{\sum \text{Environmental impact of all alternatives a}}$	This equation does not hold anymore, since alternatives are no longer compared.

Table 45 (cont.)

Equations/step previously used in the alternative design comparison module	Application in the benchmarking module
Weighted Environmental score per alternative $\text{EnvW} \times \text{Score for environmental impact alternative } i$	There is a slight change. The environmental impact for alternative i is no longer valid, since the values are now averaged.
$\text{NPV} = \text{initial costs} + \sum \text{Rehab Cost} \left[\frac{1}{(1+i)^n} \right]$	Yes, this equation still holds to perform a lifecycle cost analysis. However, the values used are the average values for the selected mix designs
$\text{EconW} \times \text{Score for Economic impact alternative } i$	There is a slight change. The economic impact for alternative i is no longer valid, since the values are now averaged.
Overall sustainability score per alternative $\text{Overall final sustainability score} = \text{Weighted economic score per alternative} + \text{Weighted environmental score per alternative}$	The overall sustainability score is still the sum of the environmental and economic score for the average values and not individual values anymore

4.2.3.1 THE DEVELOPMENT OF A TOOL FOR DATA MANIPULATION

ENGINEERING EQUATIONS

A software was developed to use all the previous described data. Therefore, the objective of this section is to describe how to use and integrate the previous data into the newly developed software¹. Equations, as well as screenshots from the program, are provided for the user. The algorithm used in the software is also provided. This software, as a tool for the previously used data, will therefore utilize the same background for performing calculations. The software allows an analysis of multiple designs and layers. The software workflow is illustrated in Figure 35. The workflow is as follows:

- Input values: These are mostly related to project and design information, such as zip code, layer thickness, and discount rate for the economic analysis.

¹ Software credit should be given to Qinadong Nie, LSU graduate student, computer science department.

- Databases: 1) EPD database: contains environmental impacts and inventory matrix; 2) cost analysis database
- Documents: This section contains the product category rule (PCR) associated with the EPDs used in the program.
- The Output: The output provides information about the environmental impact/inventory values of each mix design, as well as the transportation stage. Also, the output displays economic analysis information for the design. The software also allows alternative design comparison and benchmarking by using the same equations previously illustrated.

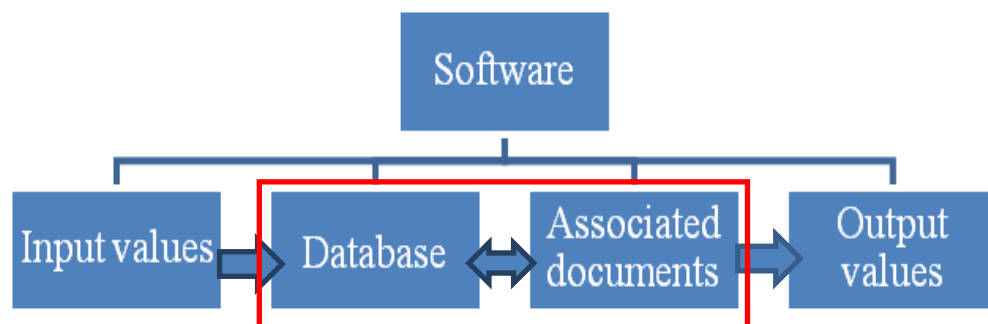


Figure 35. Software workflow

4.3 SOFTWARE DEMONSTRATION

There are five different tabs in the following order: layer information, weight tab, transportation tab, economic analysis tab, and summary/report tab.

1. Layer information tab: This tab enables the selection of analysis purpose (product design alternative vs. benchmarking), design type (new pavement), and pavement type (rigid). The user should input the layer thickness. The unit of measurement is given in both U.S. units (inch) and S.I. units (meters). The project zip code is a user input as well. The layer information tab is illustrated in Figure 36.

Layer Information | Weights | Transportation | EconAnalysis | Summary/Export

Purpose of Analysis: Select An Analysis Purpose | Project Location's Zip Code: | [Need a help?](#)

Design 1 +

Design type: New pavement | Pavement type: Rigid pavement

Layer 1

Layer Type: Portland Cement Concrete

Thickness: inch

Load Material

Figure 36. Layer information tab

2. Once the layer information is identified, corresponding materials are loaded from the database. As previously discussed, material selection criteria are inclusive of the: compressive strength value, geographic region and mix design description such as cement (lb), fly ash, coarse aggregates, and fine aggregates, etc. This is illustrated in Figure 37.
3. The selection criteria for the State of Louisiana are different. These were specifically designed to match the mix designs used by the Louisiana Department of Transportation districts. The criteria include: a) cement (lb), b) fly ash (lb), c) slag (lb), d) fine aggregates (lb), e) coarse aggregate 1 (lb), f) coarse aggregate 2 (lb), g) water (gallons), h) water reducer (oz), i) air (%), j) air entertainer (oz), k) set accelerator (oz), l) super plasticizer (oz), m) special additive A (oz), n) special additive B (oz), and o) special additive C (oz). This particular layout is illustrated in Figure 38

Compressive Strength (psi): psi

Analysis Geographic Region: South
 epds-LA,TX,FL,OK

Mix design	Value	Unit
Cement(lb) (276~725)	<input type="text"/>	lbs
FlyAsh(lb) (94~336)	<input type="text"/>	lbs
Water-Cement Ratio (0.31~1.11)	<input type="text"/>	ratio
CoarseAggregate(lb) (1750~1900)	<input type="text"/>	lbs
FineAggregate(lb) (1079~1840)	<input type="text"/>	lbs
Air(%) (0~7.5)	<input type="text"/>	%
Slag(lb) (0~0)	<input type="text"/>	lbs

Figure 37. Selection/filtering process

Select Concrete Mixes

Compressive Strength (psi): psi

Analysis Geographic Region: Louisiana
 epds-LA

Mix design	Value	Unit	Mix design	Value	Unit	Mix design	Value	Unit
Cement(lb) (65~950)	<input type="text"/>	lbs	Air(%) (3~7)	<input type="text"/>	%	SpecialAdditive_A(oz) (0~0)	<input type="text"/>	oz
FlyAsh(lb) (0~600)	<input type="text"/>	lbs	Slag(lb) (0~0)	<input type="text"/>	lbs	SpecialAdditive_B(oz) (0~0)	<input type="text"/>	oz
FineAggregate(lb) (756~2650)	<input type="text"/>	lbs	WaterReducer(oz) (0~733)	<input type="text"/>	oz	SpecialAdditive_C(oz) (0~17)	<input type="text"/>	oz
Water-Cement Ratio (0.24~0.79)	<input type="text"/>	ratio	AirEntrained(oz) (0~34)	<input type="text"/>	oz			
CoarseAggregate1(lb) (0~1987)	<input type="text"/>	lbs	SetAccelerator(oz) (0~95)	<input type="text"/>	oz			
CoarseAggregate2(lb) (0~424)	<input type="text"/>	lbs	SuperPlactidizer(oz) (0~85)	<input type="text"/>	oz			

82 Mixes

* Leave blank if it is not part of this design

Compressive Strength(psi)	District	Cement (lbs)	Water-Cement Ratio	FlyAsh (lbs)	Fine Aggregate (lbs)	Coarse Aggregate1 (lbs)	Coarse Aggregate2 (lbs)	Air(%)	Construction Type	Price (\$ per yd3)
4400.0	Baton Rouge	658.0	0.38	0.0	1,345.00	1,810.00	0.0	5±2	PCC Pavement	118.0
4400.0	Baton Rouge	510.0	0.46	100.0	1,354.00	1,866.00	0.0	5±2	PCC Pavement	112.0
4400.0	Baton Rouge	550.0	0.42	61.0	1,365.00	1,857.00	0.0	5±2	PCC Pavement	112.0
4283.0	Hammond	424.0	0.59	93.0	1,431.00	1,621.00	0.0	5±2	PCC Pavement	106.0
4173.0	New Orleans	408.0	0.62	102.0	1,388.00	1,748.00	98.0	5±2	PCC Pavement	122.0
4438.0	Shreveport	508.0	0.48	0.0	737.0	1,698.00	752.0	5±2	PCC Pavement	123.0

Search Save Finish

Figure 38. Selection criteria for the State of Louisiana

Once the user saves the selected options, the button turns into green, indicating that the options were saved, as illustrated in Figure 39.

Compressive Strength (psi): 4000.0 psi

Analysis Geographic Region: Louisiana

epds-LA

Mix design

Value	Unit	Value	Unit	Value	Unit
Cement(lb) (65~950)	lbs	Air(%) (3~7)	%	SpecialAdditive_A(oz) (0~0)	oz
FlyAsh(lb) (0~600)	lbs	Slag(lb) (0~0)	lbs	SpecialAdditive_B(oz) (0~0)	oz
FineAggregate(lb) (756~2650)	lbs	WaterReducer(oz) (0~733)	oz	SpecialAdditive_C(oz) (0~17)	oz
Water-Cement Ratio (0.24~0.79)	ratio	AirEntrained(oz) (0~34)	oz		
CoarseAggregate1(lb) (0~1987)	lbs	SetAccelerator(oz) (0~95)	oz		
CoarseAggregate2(lb) (0~424)	lbs	SuperPlasticizer(oz) (0~85)	oz		

82 Mixes

* Leave blank if it is not part of this design

Compressive Strength(psi)	District	Cement (lbs)	Water-Cement Ratio	FlyAsh (lbs)	Fine Aggregate (lbs)	Coarse Aggregate1 (lbs)	Coarse Aggregate2 (lbs)	Air(%)	Construction Type	Price (\$ per yd3)
4400.0	Baton Rouge	658.0	0.38	0.0	1,345.00	1,810.00	0.0	5±2	PCC Pavement	118.0
4400.0	Baton Rouge	510.0	0.46	100.0	1,354.00	1,866.00	0.0	5±2	PCC Pavement	112.0
4400.0	Baton Rouge	550.0	0.42	61.0	1,365.00	1,857.00	0.0	5±2	PCC Pavement	112.0
4283.0	Hammond	424.0	0.59	93.0	1,431.00	1,621.00	0.0	5±2	PCC Pavement	106.0
4173.0	New Orleans	408.0	0.62	102.0	1,388.00	1,748.00	98.0	5±2	PCC Pavement	122.0
4438.0	Shreveport	508.0	0.48	0.0	737.0	1,698.00	752.0	5±2	PCC Pavement	123.0

Search Save Finish

Figure 39. Saving process

4. **Weights tab:** This tab assigns weights for the environmental and economic impacts. The sum of both weights should equal 100. In addition, this tab assigns different weights for various environmental impacts/inventory matrix (GWP, ODP, AP, EP, POCP, and total primary energy consumption (or non renewable energy consumption and renewable energy consumption)). As discussed earlier, various weights may be used, depending on stakeholder preference. This includes the BEES weights, the EPA's weights, etc. Moreover, the software allows the user to input custom values. Also, in the event the user did not input values, the software also has default values. All existing weights provided by the software are illustrated in Table 46. The weight tab is illustrated in Figure 40 for the default software value.

Table 46. Various weights used by the software

Weights	Default value	BEES Stakeholder Panel	EPA Science Advisory Board based	Custom weight
GWP	20%	45%	35%	User input
ODP	15%	3%	10%	User input
AP	15%	5%	11%	User input
EP	15%	10%	10%	User input
POCP	15%	5%	12%	User input
NRE	10%	16%	11%	User input
RE	10%	16%	11%	User input
Total	100%	100%	100%	100%

The screenshot shows the 'Weights' tab in a software application. At the top, there are tabs for 'Layer Information', 'Weights', 'Transportation', 'EconAnalysis', and 'Summary/Export'. The 'Weights' tab is active. Below the tabs, the 'Performance Weights' section is visible, with 'Environmental Performance(%)' and 'Economic Performance(%)' both set to 50.0. Below this, the 'Predefined Weights' dropdown menu is set to 'EPA Science Advisory Board-based'. Underneath, several individual weight inputs are shown: Global Warming Potential(%) at 35.0, Ozone Depletion Potential(%) at 10.0, Acidification Potential(%) at 11.0, Photochemical Ozone Creation Potential(%) at 12.0, Eutrophication Potential(%) at 10.0, and Non-Renewable Energy Consumption(%) at 22.0. At the bottom, the 'Sum(%)' is displayed as 100.0.

Figure 40. Performance weight (environmental vs. economic)

5. Transportation tab: The transportation tab evaluates the environmental impact of transportation. Two types of fuels can be assigned (diesel and gasoline), and three categories of trucks are allowed (light duty truck, medium duty truck, and heavy duty truck). The transportation distance from the manufacturer to the project location is calculated as follows: The project location requires an input by the user; then the

manufacturer/plant location zip for each mix design is located in the software. The software then calculates the total distance between the two zip codes by connecting to Google. The user should be connected to the internet when using the distance calculator. As for the benchmarking module, the user can enter the manufacturer location. The transportation tab is illustrated in Figure 41 for the light duty truck and gasoline fuel.

Figure 41. Transportation impact tab

6. Economic analysis tab: The economic analysis tab uses the net present value to evaluate the economic impact of a design. The economic analysis tab is connected to the cost analysis database described previously. Cost items are first selected by checking them as illustrated in Figure 42.

lacyfx WIP

Layer Information Weights Transportation EconAnalysis Summary/Export

Start year: 2016 Analysis period: 50 Discount rate: 2.0

▼ Alternates

▼ Design 1: Rigid pavement(New pavement)

Product 1

Product 2

Product 3

Product 4

Initialization

Select maintenance activities in the following table

Check	Item Description	Quantity	Unit	Price	Occur year	Interval time	Num
-------	------------------	----------	------	-------	------------	---------------	-----

Figure 42. Economic analysis tab

Final cost analysis results for alternative design comparison module are illustrated in a graph format as shown in Figure 43.



Figure 43. Economic analysis and alternative design comparison

Additionally, the summary/export tab provides the breakdown of the output in terms of A1, A2, and A3 in regard to the environmental impact for the State of Louisiana, as illustrated in Figure 44.

As for the benchmarking module, the procedure is as follows. First, the user puts the software into the benchmarking module, and inputs the number of designs and layer thicknesses. Having selected the criteria, the user must benchmark with respect to the filtering criteria; the resulting mixes are then averaged and the design will proceed, using the averaged environmental impacts values. The user still can assign weights for environmental and economic impacts, as well as weights for various environmental impacts. Screenshots from the software are illustrated in Figure 45. The design will proceed normally as discussed earlier, before using the average value.

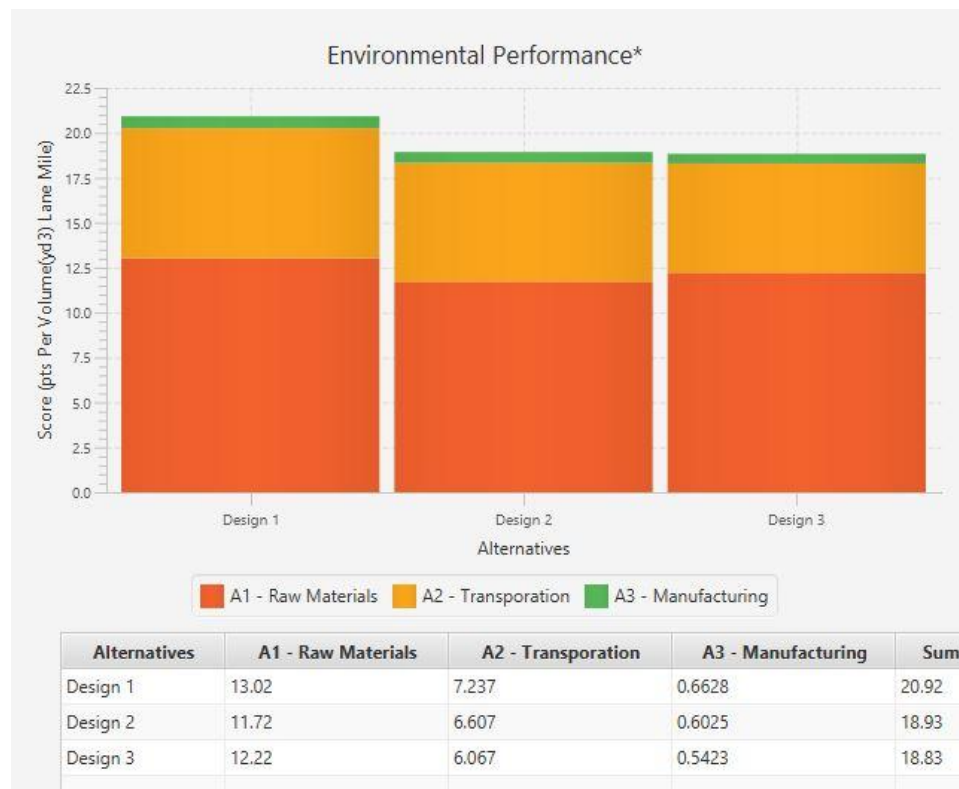


Figure 44. Environmental performance breakdown display

Figure 45. Benchmarking module

4.4 STUDY SIGNIFICANCE: THE BIGGER PICTURE. HOW CAN THIS FRAMEWORK BE USED IN THE REAL WORLD?

This methodology/framework/tool will quantify the sustainability of pavement design, using both an economic and environmental score. The application of this tool can be summarized into three categories: Accounting, decision making, and process improvement (FHWA, 2015)

4.4.1 ACCOUNTING

Accounting is the process of measuring only for the goal of quantification. This process is used in case of reporting emissions, such as GHG reporting. In fact, there exists no current rules for quantifying sustainability in the United States compared to Europe, where quantification methods are more advanced and required by various entities (FHWA, 2015).

In the United States, this tool would be most useful in mandates requiring quantifications of emissions, such as greenhouse gases. This measurement can be either on the State level or the National level (which the tool can currently handle, since it contains EPDs for other states). Some of the mandates associated with GHG emissions are as follows::

- The National Environmental Policy Act: This policy proposes that in the event there is a project emitting a huge amount of greenhouse gases (27500 tons or more of CO₂), stakeholders should perform a quantitative and qualitative analysis for these emissions (Sutley, 2010).
- Quantifying emissions for states mandates. Currently there is a minimum of thirty states that have issued GHG mandates (Center for Climate and Energy Solutions, 2012), which will require the assessment and quantification of GHG.

(FHWA, 2015)

4.4.2 CAP AND TRADE LEGISLATION

The government mandated a certain limit for industry's greenhouse gas emissions, which was known as the cap and trade policy. This policy was mandated to decrease pollution. Should the cap limit be exceeded, the industry must pay a penalty. This cap and trade legislation was passed in June 2009. The target of this registration is to decrease GHG by 3% in 2012, 20% by 2020, 42% by 2030 and 83% by 2050 (FHWA, 2015)

In a further analysis of past cap and trade legislation, a successful example may be noted for the reduction of Sulfur Dioxide, known as the Acid Rain Program, under Title IV of the 1990 Clean Air Act (CAA) Amendments. In 1995, the United States EPA become aware of high levels of acid rain in the Midwest and Northeast region; mostly resulting from coal burning plants. These plants emitted a significant amount of Sulfur Dioxide. The government then put a cap and every plant was held responsible for lowering their emissions to match the cap limit. The government then issued credits for the plants equal to one ton of emissions of Sulfur Dioxide (EPA, 2017). At the end of each year, plants had to report the number of credits used and whether the plants had sufficient credits. Plants under the cap could save the credits or emissions for future use, or sell it to other plants (EPA, 2017).

4.4.3 DECISION MAKING

Decision making is defined as measurement performed to assess the qualities and quantities that can help decision making in organizational or project levels (FHWA, 2015). Various alternatives can then be compared for the purpose of improvement. In some states, decision making tools are required (such as LCCA) and will be more required in the future (Senate and House of Representatives, 2012).

4.4.4 PROCESS IMPROVEMENT

The FHWA defined process improvement as” ... the measurements that provide feedback data to support the refining process and updating the overall methodology.” These measurements can then be compared to benchmarking or any other reference criteria to produce better results.

4.4.5 HOW DOES THE TOOL FIT?

By further analysis into the developed framework/tool, the tool can work for accounting as well as for laws and mandates requiring quantifications of emissions such as the cap and trade legislation. Both modules can aid the accounting method. For example, the product comparison module can help quantify the total emissions for concrete per total design volume, and to evaluate the impact of this specific design and whether the design exceeds the limits.

Moreover, the benchmarking module can help the user by measuring the impact of his product with respect to the market average. By comparison, the user can then lower his emissions, in case the emissions exceed the average limit. Also, the developed tool can help in the decision making process improvement processes. The product comparison module can help evaluate the environmental impact of the product as well as the economic impact, therefore, enabling the stakeholder to decide which alternative has higher/lower environmental score compared to the other.

For the process improvement, the benchmarking module allows the stakeholder to benchmark his product with respect to similar products (such as similar compressive strength value, mix design breakdown, or geographic location) to find whether the environmental impact of the product is below or above the average. In case it is above average, this means more process improvement should be performed in order to achieve a similar environmental impact.

4.5 SUMMARY

- This chapter presented methodology for the newly developed framework. Modification of the data provides a guarantee of equivalence and comparability.
- For the environmental module, the data from the transportation module, adjusted with data from the EPD, allowed both to be added together.
- For the cost analysis database, the initial cost as well as the maintenance and rehabilitation cost were first adjusted by using the net present value to ensure that the two costs are comparable; then the costs were added together.

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CHAPTER 5. DEMONSTRATION OF THE DEVELOPED FRAMEWORK IN CASE STUDIES

5.1 INTRODUCTION

As previously discussed, the pavement ME design approach is considered a highly temporary stage between the commonly used empirical design and the purely mechanistic design. The pavement ME design includes inputs such as material properties, traffic and climate. Climate has a powerful impact on the overall pavement performance. This is because material properties change with climatic impacts, such as temperature and moisture circumstances. The impact of climate can be seen in pavement distresses (Breakah et al., 2011).

Through climatic analysis in National Centers regarding environmental information, scientists have found nine climatically consistent regions in which to place current climate anomalies in a historic perspective. Therefore, to account for various climatic conditions, various case studies will be presented in different states. The following states will be considered for evaluation: Texas and Louisiana. Each case study will have a custom pavement design in regard to climate conditions and related data (EPD and cost data). In addition, the cost analysis performed in the State of Texas is extracted from literature review and is not part of the scope/cost analysis database of this study. However, for a complete demonstration of the new framework, cost data should be used. These case studies are already extant, which means these have satisfied the technical criteria.

5.2 CASE STUDIES IN TEXAS

The object of this study is to assess the use of ICC in the concrete pavement design in the State of Texas (Rao & Darter, 2003). Internally cured concrete (ICC) is a mix design type in which a percentage of coarse or fine aggregate is replaced with similarly sized, pre-wetted, lightweight aggregate (LWA). An internal curing process is a means to provide hydrating

concrete with enough moisture from within the mixture, which would serve to substitute water loss due to chemical shrinkage (Rao & Darter, 2003).

ICC has been used in several states, in applications such as bridge decks, toward decreasing the amount of plastic shrinkage, cracking, and other random cracks. ICC has also proven to have good constructability and excellent performance in many states, such as New York, Virginia, Utah, North Carolina, Georgia, and Ohio (Rao & Darter, 2003). ICC might display significant sustainability and durability benefits, such as longer life. Currently, there are many states interested in longer life pavement.

For example, some states have “long life pavement” programs. These long life pavements have design lives of 20, 30, 40, 50, and 60 years (Rao & Darter, 2003). States such as California have even reached a design life of 100 years, which has a great advantage over the environment and government of longer life pavement (Rao & Darter, 2003). When comparing the life of many concrete types with or without internal curing, such as conventional concrete and high performance concrete bridge decks, results demonstrated that service life tends to be 22 years for conventional concrete, 40 years for high performance concrete without internal curing, and 63 years for high performance curing.

The Pavement ME was used to evaluate the performance of the ICC; the developed tool was applied to evaluate associated environmental and economic impacts. Notably, the cost analysis was collected from project/literature review, because cost data does not exist in the database for states other than Louisiana. However, this example will be used as an illustration on how to use the framework/developed tool for states other than Louisiana.

5.2.1 PROJECT DESCRIPTION

The selected project is located in SH 121, west of I-75 and east of the Dallas North Tollway, falling in the Dallas Fort Worth weather station (Rao & Darter, 2003). The pavement is expected to serve moderate traffic volume with an average annual daily traffic

(AADT) of 23,400 and a linear traffic growth of 4%. The design analysis period was assumed to be 30 years for a CRCP design. The initial IRI limit is 63, together with a terminal IRI of 160 with a reliability level of 90%. The terminal thresholds for transverse cracking, longitudinal cracking, and corner cracking represented 10% of the slabs cracked (Rao & Darter, 2003). The project has a zip code of 75424.

5.2.2 INITIAL AND ALTERNATIVE DESIGNS

Details of the design and layers properties are illustrated in Table 47 for reproducibility. The original vs. the alternative trial designs are illustrated in Figure 46. Both alternatives have the same design and layers, with the exception of the top layer. The alternative design has a thinner concrete thickness, consisting of internally cured concrete (ICC).

Table 47. Design details and layers properties

Criteria	Conventional concrete design 1	Internally cured concrete design 2
Shoulder type	Tied PCC	Tied PCC
Steel content, percent	0.7	0.7
Bar diameter, inch	0.75	0.75
Steel depth, inch	6	6
Base/ slab friction	7.5	7.5
Compressive strength value (psi)	5200	6000

5.2.3 MATERIALS PROPERTIES AND LAYER DESIGN

The concrete mix designs used in this analysis were 6000 psi for ICC and 5200 psi for conventional concrete. The 5200 psi was extrapolated to 5500 psi to match the value in EPD's database, and the 6000 psi was used as listed.

11" CRCP (conventional concrete)	10" CRCP (ICC)
4 inch HMA, good quality base	4 inch HMA, good quality base
6.0" Aggregate Subbase	6.0" Aggregate Subbase
10" lime Subgrade	10" lime Subgrade
(a)	(b)

Figure 46. (a) Initial design vs. (b) Alternative design

5.2.4 ENVIRONMENTAL PERFORMANCE

To assess the environmental performance, the new framework developed in this study will evaluate the environmental impact of this project. The developed framework will be used, and the solution provided in detail for replication as follows:

1. Select the state you want to evaluate mix designs: The state is Texas.
2. The purpose of the design is to provide an alternative design comparison. The stakeholder is interested in evaluating the environmental impact of various alternatives. These various alternatives are presented as various mixes for each design.
3. Select the number of designs to evaluate: two designs (ICC vs. conventional concrete).
4. Select the number of mixes to evaluate: 3 PCC mix designs for both alternatives, if possible.
5. Assign weights for the environmental and economic impacts. Both impacts will be assigned a weight of 0.5.
6. In this example, there is no need to convert modulus of rupture to compressive strength value, since the compressive strength value is already given.
7. Select alternative mixes from the EPD data to evaluate the environmental impact. The user enters a specific mix design: to look for an environmental impact and/or look for the compressive strength value

By further considering the available compressive strength in the database for the State of Texas, there is no compressive strength value of 5200 or 5500 psi. Therefore, this value will be rounded out to 6000 psi for both designs. Table 48 summarizes the compressive strength value, as well as the mix design breakdown required by the user.

Table 48. Mix design breakdown required and compressive strength value

Compressive strength value (psi)	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Mixing water (lb)	Air %
6000	500	130	1200	1700	230	1

This exact mix design breakdown is not in the database and therefore, the nearest mix design breakdown will be used. Available mix designs for the compressive strength value of 6000 psi are illustrated in Table 49. The nearest mix design for the one required by the user is mix design number 4, when comparing the amount of cement. Therefore, this mix design will be selected.

There are not many mix designs from which to select, since a limited number of companies have published their EPDs to date. This will be discussed later in the study limitations and future work. The user intended to select three mix designs to evaluate. However, due to data limitation, only one mix design is available. The other option is to select the mix design with a cement content of 564 lb. Nevertheless, this mix design will show a higher environmental impact and is more expensive than the mix design required by the user. The next step is to find the nearest manufacturer selling the selected mix design. The following manufacturers sell this product (same product, but different locations). Four manufacturers in four different locations sell this product, accounting for a total of $4 \times 4 = 16$ locations/manufacturers.

The project zip code is 75424. The total distance between each zip code and the project zip code is illustrated in Table 50. In this case, the nearest manufacturer to the project location is manufacturer 9, with a total transportation distance of 30.3 miles. The manufacturer zip code exists in the database.

The environmental impact of mix 4 is illustrated in Table 51. The environmental impact varies by each manufacturer, since each one uses a different technology. Both alternatives, produced by different manufacturers, will be evaluated, since not many products exist in the database. These are the values extracted from EPD, with no modifications. As illustrated, the values are given per 1 yd³. The sum of the impacts for A1 are: raw material, for A2: transportation from raw material extraction to manufacturing, and for A3: manufacturing stage. These values are given as a sum; no breakdown is given for each phase.

These values are given per 1 yd³; some adjustments need to be performed to adjust the environmental impacts per the total design volume. The unit conversions for use in this case study are illustrated in Table 52. The table converts all other units to units of yd. Accordingly, the final volume for each design is illustrated in Table 53. The calculation was performed using Equation 6:

$$L_V = L_T \times L_w \times L_L$$

Finally, the total environmental impact for the design should be adjusted according to the overall design volume, using Equation 7.

$$\text{Environmental impact reported from EPD} \times L_v \quad (7)$$

For example, the total adjusted GWP, for design 1 =

The volume $2151.09 \text{ yd}^3 \times 353.238 \text{ kg CO}_2 \text{ eq/yd}^3 = 759849.427 \text{ kg CO}_2 \text{ eq}$

The environmental impact will be adjusted accordingly for each alternative. Final results are indicated in Table 54.

Table 49. Available mix design breakdown for the State of Texas

Mix number	Cement weight (lb)	Water cement ratio	Mixing water (lb)	Fly ash weight (lb)	Slag weight (lb)	Fine aggregate (lb)	Coarse aggregate (lb)
1	322	0.36	240	336	0	1256	1900
2	564	0.35	250	141	0	1285	1840
3	635	0.31	260	212	0	1256	1750
4	526	0.42	275	132	0	1200	1900

Table 50. Total distance

Number	Project zip code	Manufacturer's zip code	Total distance (mile)
1	75424	75212	58
2	75424	75038	56
3	75424	76106	79
4	75424	75081	39.9
5	75424	75035	30.8
6	75424	75019	49
7	75424	75067	48.5
8	75424	76118	72.3
9	75424	75078	30.3
10	75424	76134	85
11	75424	76247	79.5
12	75424	75165	85
13	75424	75160	44.1
14	75424	76092	66
15	75424	76177	73
16	75424	76179	78

Table 51. Environmental impact extracted from EPD (A1, A2, and A3)

Mix design	GWP kg CO ₂ eq/yd ³	ODP kg CFC-11 eq/yd ³	AP kg SO ₂ eq/yd ³	EP kg N eq/yd ³	POCP kg O ₃ eq/yd ³	NRE MJ/yd ³	RE MJ/yd ³
1	353.238	3.99E-06	1.935	0.0550	27.142	1865.586	13.984
2	352.473	3.98E-06	1.924	0.0542	26.836	1851.823	13.961

Table 52. Conversion table to yards

Original unit	Factor to convert to yd
1 inch	1/36
1 foot	0.33
1 mile	1760.006

Table 53. Final layer volume

Dimension	Design 1	Design 2
Layer thickness (inch)	11	10
Length (mile)	1	1
Width (feet)	12	12
Total volume (yd ³)	2151.09	1955.54

Table 54. Adjusted environmental impact per volume for each design

Design	GWP kg CO ₂ eq	ODP kg CFC- 11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
1	759849.42	0.009	4162.72	118.41	58386.69	4013057.58	30081.48
1B	758204.73	0.009	4139.69	116.77	57728.82	3983453.05	30032.14
2	690772.20	0.008	3784.29	107.65	53078.81	3648234.16	27346.80
2B	689277.02	0.008	3763.36	106.15	52480.74	3621320.96	27301.94

As illustrated, the values have different units. Therefore, they should be normalized to be consistent and unitless, to be summed altogether later. The normalization values used are illustrated in Table 55.

Table 55. Normalization values used

GWP (kg CO ₂ eq/ yd ³)	24000
ODP (kg CFC-11 eq/ yd ³)	0.160
AP (kg SO ₂ eq/ yd ³)	91
EP (kg N eq/ yd ³)	22
POCP (kg O ₃ eq/ yd ³)	1400
NRE (MJ/ yd ³)	288572.509
RE (MJ/ yd ³)	24874.54785

The normalization can be performed by dividing the environmental impact per the normalization value. This may be accomplished by following Equation 2.

$$\text{Normalized value} = \text{ImpactA} / (\text{Normalization value for impactA})$$

For example, the normalization value for the GWP for design 1 =

759849.427 kg CO₂ eq/24000 kg CO₂ eq = 31.660. Final results are illustrated in Table 56

Table 56. Normalized value for adjusted environmental impact per total volume

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
1	31.660	0.054	45.744	5.383	41.705	13.907	1.209
1B	31.592	0.053	45.491	5.308	41.235	13.804	1.207
2	28.782	0.049	41.586	4.893	37.913	12.642	1.099
2B	28.720	0.049	41.356	4.825	37.486	12.549	1.098

5.2.5 TRANSPORTATION MODULE

The two parts of the transportation module are as follows: a) Part 1: Transportation from the raw material extraction to the manufacturing phase. This does not exist for states other than Louisiana; b) Part 2: Transportation impact from the raw material extraction to the project location. In order to calculate the transportation impact from the raw material extraction to the project location, the distance between the manufacturer to the project location first should be determined. This can be accomplished by calculating the distance between the two zip codes of the project location, as well as the manufacturer's location. The zip code of the project location is 75424, while the manufacturer zip codes are presented in the EPD for each mix design. Table 57 illustrates the project zip code, the manufacturer zip code, the distance between the project, and the manufacturer's location (calculated through Google maps).

Table 57. Total transportation distance (manufacturer to project location)

Design	Project location	Manufacturer location	Total distance (miles)	Total distance (km)
1	75424	75035	30.8	49.280
1B	75424	75035	30.8	49.280
2	75424	75078	30.3	48.480
2B	75424	75078	30.3	48.480

Moreover, the type of truck used to transport concrete is a heavy duty truck (80,000 lbs or 36.28 tons), and diesel fuel. The total weight of concrete to be transported is illustrated in Table 58. To obtain the total weight of the concrete to be transported, Equation 9 should be used. This can be accomplished through the use of Equation 9:

$$M = D \times Lv$$

Where: M is the total mass to be transported, D is mix design density (in the database as collected by the manufacturer, with Lv as the total design volume, based on corresponding dimensions). For example, the density for design 1 = 4033 lb/yd³ and the total design volume = 2151.09 yd³; therefore, the total design weight = 4033 lb/yd³ × 2151.09 yd³ = 8675376.396 lb. This weight value then should be converted to metric ton, which will be accomplished by multiplying the value by 0.00045359.

This is to ensure the units are consistent, since the transportation equation will be used. The total weight is the weight of concrete transported + weight of truck = 8675376.396 lb + 80000 lb = 8755376.4 lb. Total weight conversion to ton = 8755376.4 lb × 0.00045359 = 3971.35 ton. Final values are illustrated in Table 58.

To get the total number of loads required, Equation 10 should be applied:

$$\text{Total number of loads} = \text{total weight concrete designed} / \text{truck carrying capacity}$$

For example, for design 1 = 8675376.39/54000 = 160.65 loads.

Values are illustrated in Table 58 as seen below:

Table 58. Weight of concrete to transport

Design	Density (lb/yd ³)	Total weight per design volume of concrete (lb)	Total number of loads	Total weight (truck+ concrete) (ton)
1	4033	8675376.39	160.65	3971.35
1B	4033	8675376.39	160.65	3971.35
2	4033	7886705.81	146.05	3613.61
2B	4033	7886705.81	146.05	3613.61

To adjust the inventory values coming from the transportation module, Equation 11 should be used:

$$2 \times \text{Emissions of each truck} \left(\frac{\text{kg}}{\text{ton.km}} \right) \times \text{total weight transported (truck weight (ton) + weight of concrete transported (ton))} \times \text{total distance (km)} \\ \times \text{total number of loads}$$

The emissions/ inventory for the heavy duty truck is illustrated in Table 59.

Table 59. Heavy duty truck emissions

GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ
3.24E-01	0.00E+00	1.34E-03	5.55E-04	4.62E-02	8.09E-02

For example, to calculate the transportation impact from the manufacturing to the project location for GWP for Design 1, the Adjusted inventory values = $2 \times 3.24\text{E-}01 \text{ kg CO}_2/\text{ton.km}$ $3971.35118\text{ton} \times 49.280 \text{ km} \times 160.655 \text{ loads} = 20374106.14 \text{ kg CO}_2 \text{ eq}$. All values are illustrated in Table 60.

5.2.6 TOTAL ENVIRONMENTAL IMPACT

The total environmental impact consists of the total environmental impact coming from concrete design (EPD) as well as the total transportation impact. This will result for the values given in Table 61. For example, the environmental impact extracted from EPD and as adjusted based on design volume, was previously described. An example is provided for Design 1 and Alternative 1. Environmental impact from EPD (adjusted per volume) + total transportation impact = $759849.42 \text{ kg CO}_2 \text{ eq} + 20374106.14 \text{ kg CO}_2 \text{ eq} = 21133955.57 \text{ kg CO}_2 \text{ eq}$

Table 60. Transportation impact from the manufacturer to project location

Alternative	GWP kg CO ₂ eq	ODP kg CFC- 11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
1	20374106.14	0.00	84263.27	34900.08	2905196.61	5087238.23	0.00
1B	20043357.66	0.00	82895.36	34333.52	2858034.33	5004653.19	0.00
2	16853489.63	0.00	69702.70	28869.40	2403182.78	4208170.71	0.00
2B	16579894.02	0.00	68571.16	28400.74	2364170.07	4139856.25	0.00

Table 61. Total environmental impact per alternative

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
1	21133955.57	0.009	88426.00	35018.50	2963583.31	9100295.81	30081.48
1B	20801562.39	0.009	87035.06	34450.30	2915763.15	8988106.25	30032.14
2	17544261.84	0.008	73486.99	28977.05	2456261.59	7856404.87	27346.80
2B	17269171.05	0.008	72334.53	28506.90	2416650.81	7761177.21	27301.94

These total environmental impacts must be normalized. Values after normalization are illustrated in Table 62 for each alternative.

Table 62. Normalized values for total environmental impact

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
1	880.58	0.054	971.71	1591.75	2116.84	31.53	1.20
1B	866.73	0.053	956.42	1565.92	2082.68	31.14	1.20
2	731.01	0.049	807.54	1317.13	1754.47	27.22	1.09
2B	719.54	0.049	794.88	1295.76	1726.17	26.89	1.09

5.2.7 WEIGHTING THE ENVIRONMENTAL IMPACT

Based on stakeholder preference, weighting can be assigned to the impacts. The weighting procedure will be used here for demonstration. Default weights were used for this case. The weights are illustrated in Table 63.

Table 63. Weights used in the study

GWP	ODP	AP	EP	POCP	NRE	RE	Total
0.200	0.150	0.150	0.150	0.150	0.100	0.100	1

The total environmental impact after the weighting process is illustrated in Table 64.

Equation 3 can be used to convert the environmental impacts into weighted environmental impacts: For example, for Design 1, the weighted value = $880.58 \times 0.200 = 176.116$

The total environmental score is the sum of all the environmental values together and then the RE value is deducted: Total environmental score = GWP+ODP+AP+POCP+NRE-RE

For example, for Design 1, the total environmental score =

$$176.11+0.008+145.75+238.76+317.52+3.15-0.12=881.20$$

The relative score is the environmental impact score compared for each alternative, with respect to the other alternatives. This can be accomplished through Equation 14.

Score for environmental impact for each alternative =

Total environmental score for alternative i/ \sum Environmental impact for all alternatives

For example, in the score for Design 1, there are two alternatives (or mix designs). This will lead to the following equation: $= 881.20 / (881.20+867.10+730.69+719.02) = 0.276$

This equation was repeated for all other alternatives. Values are illustrated in Table 64. In this case, the alternative having the lowest score is the one that has the lowest environmental impact. In this case, alternative 1B for Design 1 is the best alternative, as is alternative 2B for Design 2.

Should the stakeholder assign a weight for the environmental score (which is presented in this study, since the assigned weight is 0.5), the final environmental score after adjusting per the weight can be calculated, using Equation 15.

Weighted environmental score per alternative = EnvW \times score for environmental impact for the alternative. For example, for Design 1 and Alternative 1, the weighted score = $0.5 \times 0.272=0.138$. In the instance of Design 2, the overall layer thickness for Design 2 is lower than Design 1. Final weights are illustrated in Table 65

Table 64. Total environmental impact after normalizing and weighting

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE	Total
1	176.11	0.008	145.75	238.76	317.52	3.15	0.12	881.20
1B	173.34	0.008	143.46	234.88	312.40	3.11	0.12	867.10
2	146.20	0.007	121.13	197.57	263.17	2.72	0.11	730.69
2B	143.91	0.007	119.23	194.36	258.92	2.69	0.11	719.02

Table 65. Relative score and environmental score

Alternative	Total	Relative score	Assigning environmental score
1	881.201	0.276	0.138
1B	867.101	0.271	0.136
2	730.692	0.228	0.114
2B	719.023	0.225	0.112

5.2.8 ECONOMIC IMPACT

As previously described, the economic analysis will be performed by performing a lifecycle cost analysis for each alternative. This lifecycle cost analysis consists of the initial cost (occurring at present), and the maintenance and rehabilitation cost (occurring in the future). Notably, the cost database in this study contains no cost analysis for the State of Texas. The cost information was collected from the actual project in Texas. However, the initial cost for each mix design exists in the database, and was used in the study.

The initial cost for the selected mix designs is extracted from the database. Both alternatives have the same price, except that the internally cured concrete is \$10/yd³ more expensive than the conventional concrete. Values are illustrated in Table 66. To get the total costs adjusted per volume, the initial cost is multiplied by the total design volume. For example, for Design 1, the material cost is given in 1yd³, which means the cost should be adjusted to account for the total design volume. Total cost = 213 (\$/yd³) × 2151.09 yd³ = \$458183.77. The initial cost items were previously collected at the current year (2017), so there exists no need to discount the values or to use the net present value equation.

Table 66. Initial material price for each alternative

Design	Initial material cost (\$/yd ³)	Design volume (yd ³)	Total initial cost adjusted per volume (\$)
1	213	2151.09	458183.77
1A	213	2151.09	458183.77
2	223	1955.54	436086.13
2B	223	1955.54	436086.13

As for the overall initial construction cost, the project assigns a percentage for maintenance over time (5%), design cost (10%), and construction inspection services (10%). The maintenance and rehabilitation items breakdown are illustrated in Table 67.

Table 67. Initial cost item overall

Criteria	Design 1 (conventional concrete)		Design 2 (internally cured concrete)	
	Alternative 1 (\$)	Alternative 1B (\$)	Alternative 1 (\$)	Alternative 1B (\$)
Initial material price	213	213	223	223
Initial material price adjusted per total volume	458183.77	458183.77	436086.1385	436086.1385
Maintenance over time (MOT) at 5%	22909.188	22909.188	21804.30693	21804.30693
Design cost at 10%	45818.3776	45818.3776	43608.61385	43608.61385
Construction inspection services at 10%	45818.37769	45818.37769	43608.61385	43608.61385
Total at year 2017	572729.7212	572729.7212	545107.6732	545107.6732

Notably, the unit cost varies from one location to the other and from one project to the other, based on total quantity. Therefore, the values used in this study are specific for this project. The total maintenance and rehabilitation schedule for this project is illustrated in Table 68. A total analysis period of 60 years is presented. The study used a discount rate of 3% (Rao & Darter, 2003). The project occurred at year 2013. Therefore, the values were discounted one more time to the year 2017 to evaluate the net present value. As illustrated in Table 68, the maintenance and rehabilitation items are different for both alternatives; since the deterioration rate is different.

Table 68. Maintenance and rehabilitation activities schedule for both alternatives (Rao & Darter, 2003)

Conventional concrete 11 inch			Internally cured concrete 10 inch		
Age	Actual year	# of punchout repair	Age	Actual year	# of punchout repair
15	2028	4	15	2028	4
25*	2038	5	25*	2038	5
42	2055	19	40	2053	6
50**	2063	50	60**	2073	17
*The maintenance activity includes diamond grinding					
**The maintenance activity includes repair and structural rehabilitation with HMA overlay					

A detailed example for the maintenance and rehabilitation activities is illustrated in Table 69 and will be examined step by step. The maintenance and rehabilitation cost items are given along with the associated year. To get the total price for a certain activity for full depth pavement design, the total quantity is multiplied by the unit price: $32 \text{ yd}^2 \times 200 \text{ $/yd}^2 = \$6400$. Moreover, an additional cost will be added, such as maintenance over time (MOT) at 5%, which is calculated as $(5/100) \times \$6400 = \320 ; and design cost for 10%, which is calculated as $(10/100) \times \$6400 = \640 . Also, there are construction and inspection services, which account for 10% and may be calculated as $(10/100) \times \$6400 = \640 . The total value is \$8000 at year 2028 (or at year 15). By discounting this value to the current year (2017), using a discount rate of 3%, the resulting value is $\$8000/(1+0.03)^{11} = \5779.4 . The final maintenance and rehabilitation activity for Alternative 1 (conventional concrete) is illustrated in Table 69. This accounts for \$676,431 over a design life of 60 years at the year 2013 (Rao & Darter, 2003).

Table 69. Detailed maintenance and rehabilitation activities for conventional concrete

Age from project start year	Activity	Quantity	Unit	Unit price (\$)	Total (\$)
15	Diamond grinding existing surface	0	yd ²	5.60	0
15	Full depth pavement design	32	yd ²	200	6400
15	MOT at 5%				320
15	Design cost at 10%				640
15	Construction inspection services at 10%				640
	Total				8000
25	Diamond grinding existing surface	22293	yd ²	5.60	124843
25	Full depth pavement repair	4	yd ²	200	800
25	MOT at 5%				6282
25	Design cost at 10%				12564
25	Construction inspection services at 10%				12564
25	Total				157053
42	Diamond grinding existing surface	0	yd ²	5.60	0
42	Full depth pavement repair	20	yd ²	200	4000
42	MOT at 5%				200
42	Design cost at 10%				400
42	Construction inspection services at 10%				400
	Total				5000
50	Milling	0	yd ²	3.50	0
50	Full depth pavement repairs	528	yd ²	150	79200
50	Place asphalt tack coat (9 yd ² /gal)	2477	gallon	1.70	4211
50	2 inch HMA binder	2475	tons	1.70	160846
50	2 inch HMA surface	2475	tons	65	160846
50	MOT at 5%			65	20255
50	Design cost at 10%				40510
	Construction inspection services at 10%				40510
	Total				506378
	Overall Total (all items) at year 2013				676,431

Detailed analysis for the maintenance and rehabilitation activities for conventional concrete are attached in Appendix F. The use of internally cured concrete resulted in a lower lifecycle cost analysis and higher savings. This is due to the better qualities and higher

durability of internally cured concrete, resulting in lower maintenance and rehabilitation as well as a higher salvage value, compared to conventional concrete. The total lifecycle cost analysis for each alternative is illustrated in Table 70.

Table 70. Final lifecycle cost analysis for both alternatives

Cost item	Control section 11 inch CRCP		Internally cured concrete 10 inch CRCP	
	Total cost at 2013	Net present worth (2017)	Total cost at 2013	Net present worth (2017)
Total initial cost		572729.7212		545107.6732
Total M&R cost (1-60 years)	676433	761331.3009	608133	684459.0492
Salvage value at year 60	-57754	-65002.63581	-75002	-84415.411
Net present value (year 2017)		1269058.386		1145151.311

To get a final total score for each alternative, Equation 16 should be used.

Score for economic impact alternative $i = NPVi / (\sum NPVa)$

The score is the net present value for the alternative, divided by all the net present value for all alternatives. For example, for Design 1 and Alternative 1, the economic score =

$1269058.386 / (1269058.386 + 1269058.386 + 1145151.311 + 1145151.311) = 0.2628$. In this case study, the user assigned a weight of 0.5 for the economic impact vs. the environmental impact. Therefore, the values for the economic impact must be adjusted.

This can be performed using Equation 17.

$EconW \times \text{Score for Economic impact alternative } i$

For example, for Design 1 and Alternative 1, the final economic score = $0.2628 \times 0.5 =$

0.134. The final economic values are illustrated in Table 71. From this analysis, Design 2 is

more economic than Design 1. This is because Design 2 has a lower thickness and higher durability; these attributes were converted into a lower maintenance and rehabilitation cost in the long term.

Table 71. Total lifecycle cost analysis per design and alternative

Design 1 conventional concrete		Design 2 internally cured concrete	
Alternative 1	Alternative 1B	Alternative 2	Alternative 2B
1269058.38	1269058.38	1145151.31	1145151.31

Table 72. Final economic score per alternative

	Design 1		Design 2	
	Alternative 1	Alternative 1B	Alternative 2	Alternative 2B
Economic	0.2628	0.2628	0.2371	0.2371
Weighted economic score	0.1314	0.1314	0.1185	0.1185

5.2.9 TOTAL SUSTAINABILITY SCORE

Overall final sustainability score = Weighted economic score per alternative + Weighted environmental score per alternative

The total score is illustrated in Table 73. As illustrated, Design 2 and Alternative 2B is the best alternative, due to the lower total score (environmental and economic).

Table 73. Total sustainability score

Required score	Design 1		Design 2	
	Alternative 1	Alternative 1B	Alternative 2	Alternative 2B
Weighted economic score	0.131	0.131	0.118	0.118
Weighted environmental score	0.138	0.136	0.114	0.112
Total score	0.269	0.267	0.233	0.231

5.2.10 STATISTICAL ANALYSIS

To be able to compare statistical significance of the results, another EPD will be used to assess the environmental impact. Note that the economic impact cannot be compared because cost data does not exist for states other than Louisiana. A compressive strength value

of 7000 psi will be used to evaluate the following environmental impact/inventory values: GWP, ODP, AP, EP, POCP, RE and NRE.

The scope will include the following stages: raw material extraction, transportation from raw material extraction to manufacturing, manufacturing, and transportation from manufacturing to project location. The total environmental score will be compared, since the breakdown for EPD is not available for states other than Louisiana. The same procedure will be followed to evaluate the total environmental impact with the same assumptions, only raw data from EPD will change. The raw data used, extracted from EPD, for compressive strength value of 7000 psi are illustrated in Table 74 as a sample.

Table 74. Total environmental impact per alternative

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
1	256.44	4.49E-06	5.67	0.55	82.61	2191.03	35.28
1B	230.47	4.43E-06	3.71	0.42	56.64	1813.35	32.28
2	346.35	4.29E-06	2.59	0.09	38.38	2190.03	34.26
2B	347.88	4.38E-06	2.59	0.09	38.61	1812.35	31.25
Average	295.28	4.3975E-06	3.64	0.28	54.06	2001.69	33.26

Final results for the environmental score are illustrated in Table 75. To better understand the data used, descriptive statistics is illustrated in Table 76, including the mean, the standard deviation, and confidence interval. To evaluate results significance, analysis of variance (ANOVA) is performed with a confidence interval of 95%. Results are illustrated in Table 77. The resulting P value =1 (> 0.001 indicating insignificance of the results).

Table 75. Environmental impact comparison

Alternative	Environmental score (Texas)	Environmental score (7000 psi)
1	0.138	0.139
1B	0.136	0.134
2	0.114	0.115
2B	0.112	0.112
Mean	0.125	0.125
Standard deviation	0.013491	0.013491

Table 76. Descriptive statistics for the environmental impact values

Criteria	Texas data	7000 psi
Mean	0.125	0.125
Standard Error	0.006745	0.006745
Median	0.1245	0.1245
Standard Deviation	0.013491	0.013491
Sample Variance	0.000182	0.000182
Kurtosis	-5.09341	-5.09341
Skewness	0.074939	0.074939
Range	0.027	0.027
Minimum	0.112	0.112
Maximum	0.139	0.139
Sum	0.5	0.5
Count	4	4
Confidence Level(95.0%)	0.021467	0.021467

Table 77. Analysis of variance results

Source of Variation	SS	Degrees of freedom (df)	MS	F	P-value	F critical
Between Groups	0	1	0	0	1	5.987378
Within Groups	0.001126	6	0.000188			
Total	0.001126	7				

5.3 CASE STUDIES IN LOUISIANA

The Louisiana Department of Transportation and Development (LaDOTD) is responsible for maintaining more than 17,000 miles of state U.S. and interstate highway pavement structure (Wu & Xiao, 2016). This study was supported by the Louisiana Transportation and Research Center (LTRC) and the Louisiana Department of Transportation and Development (LaDOTD). The study will analyze various projects previously performed by LaDOTD. Case studies were extracted from LaDOTD past and current projects. This section will provide a step by step demonstration of the case studies performed from the moment the case study was extracted for analysis, until the final decision making criteria.

5.3.1 CASE STUDY 1 : ALTERNATIVE DESIGN COMPARAISON

5.3.1.1 Project description

This project falls under a proposal number of H.003432. The project is titled Interchange Improvements @ I-12 & U.S 51 Bus. The project is in Tangipahoa Parish, Hammond district, with a zip code of 70454.

5.3.1.2 Project properties

Project properties such as a) traffic data, b) directional distribution, c) truck distribution, d) design speed, e) average daily traffic, and f) K factor are illustrated in Table 78. The project is divided into two roads: The U.S 51 bus and the I-12 Westbound exit ramp. The directional distribution, the K factor, and the design speeds are the same in both roads. However, other factors, such as the 2012 average daily traffic and the 2032 average daily traffic, are different.

Table 78. Traffic data criteria (LaDOTD)

Criteria	U.S 51 bus	I-12 Westbound exit ramp
D (Directional distribution)	55%	55%
K	10%	10%
T (truck distribution)	8%	18%
Design speed (MPH)	40	40
2012 Average Daily Traffic (A.D.T.)	22300	7000
2032 A.D.T	29900	11300

5.3.1.3 Design properties

The design and thicknesses are illustrated in Figure 48. The layers input are as follows: Portland cement concrete layer, a class 2 Base course (crushed stone, recycled PCC, or blended calcium sulfate, and a Subbase layer of lime treatment type E. The PCC modulus of rupture is 600 psi.

Portland cement concrete 11 inch
Class 2 Base Course 8 inch
Lime Treatment 12 inch

Figure 47. Design layers

5.3.1.4 Environmental impact

To evaluate the environmental impact of this project, a developed framework will be used. The solution will be provided in detail, step by step.

1. Select the state you want to search for the mix design: The state is Louisiana.

2. The purpose of the design is to present an alternative design comparison. The stakeholder is interested in evaluating the environmental impact of various alternatives. These different alternatives consist of various mix designs.
3. Select the number of designs to evaluate: only one design.
4. Select the number of mixes to evaluate: 3 PCC mix designs.
5. Assign weights for the environmental and economic impacts. Both impacts will be assigned a weight of 0.5.
6. Convert the modulus of rupture to compressive strength value, using Equation 8, where:

$$\text{MOR (psi)} = 2.3 (\text{fc})^{2/3} \text{ or } \text{fc} = (\text{MOR}/2.3)^{3/2}$$
This results in a compressive strength value of $(600/2.3)^{3/2} = 4213$ psi
7. Select alternative mixes from the EPD data to evaluate the environmental impact. The user enters a specific mix design (required by the design) to look for the environmental impact in the database. This mix design is illustrated in Table 79. Normally, the paving mix designs have a cement content ranging from 400 to 550 lbs. The input value for the cement content should be in this range.

Table 79. Required mix design

Compressive strength value (psi)	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Air entertainer (%)
4213	412	102	1400	1600	1420	32	1

This exact mix design is not in the database; therefore, the stakeholder may select from among the existing mixes. The nearest mixes, based on the cement and fly ash contents, are illustrated in Table 80. All these mixes have a compressive strength value above 4213 psi. As illustrated in Table 80, there are various mix designs, but there should be some filtering criteria

For example, the stakeholder can select one of the filtering criteria to be the proximity to the project location (providing less environmental impact and less time for transportation).

The manufacturers in Hammond can provide a good selection criteria, since the project is in Hammond. The selection of the Hammond district would narrow the mixes to options 6, 7, 8, 9, and 10. The new selections are illustrated in Table 80.

Another filtering criteria can be the initial cost. For example, the user can select the top three mixes with the least cost. This will narrow down the search criteria to mixes 6, 7, and 9, as illustrated in Table 81. These are the mixes which will proceed to the environmental impact evaluation.

The environmental impact of the mixes 6, 7, and 9 are illustrated in Table 83. These are the values extracted from EPD with no modifications. As illustrated, the values are given per 1 yd³. These are the impacts for A1: raw material extraction and A3: manufacturing.

These values are given per 1 yd³; some adjustments must be performed to adjust the environmental impacts per the total design volume. The total design volume calculation is illustrated in Table 84, for the 11 inch thickness.

The calculation was performed using Equation 6: $L_v = L_T \times L_W \times L_L$. The total environmental impact for the design then should be adjusted according to the overall design volume, using Equation 7:

Environmental impact reported from EPD \times L_v

For example, the total adjusted GWP, for alternative 6 = the volume 2151.09 yd³ \times 194.079 kg CO₂ eq/yd³ = 417482.804 kg CO₂ eq

The environmental impact will be adjusted accordingly for each alternative. Final results are indicated in Table 85. As illustrated, the values have different units. Therefore, these should be normalized to present consistent, unitless units, that can be summed up altogether in the end. The normalization values used are illustrated in Table 86.

Table 80. Corresponding mix design

Alternative	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water	Water reducer (oz)	District	Initial cost (\$/yd ³)
1	414	103	1,180.00	1,481.00	413	29.6	20.7	Baton Rouge	123
2	414	103	1,291.00	1,559.00	413	31	20.7	Baton Rouge	123
3	414	103	1,092.00	1,353.00	846	30.3	15.51	Baton Rouge	123
4	414	103	1,285.00	1,379.00	607	31	20.7	Baton Rouge	117
5	414	103	1,281.00	1,376.00	604	31	20.7	Baton Rouge	117
6	413	104	1,483.00	1,421.00	320	31	15.51	Hammond	106
7	414	103	1,399.00	1,652.00	0	30	20.68	Hammond	120
8	414	103	1,092.00	1,475.00	715	30.3	15.51	Hammond	123
9	414	103	1,362.00	1,682.00	0	30	20.68	Hammond	106
10	413	104	1,483.00	1,438.00	320	31	20.68	Hammond	220
11	414	103	1,000.00	1,483.00	550	29.7	30.2	Lafayette	116
12	414	103	1,521.00	1,521.00	0	29.5	31.2	New Orleans	106

Table 81. Filtering criteria based on manufacturer location

Alternative	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Water reducer (oz)	Initial cost (\$/yd ³)
6	413	104	1,483.00	1,421.00	320	31	15.51	106
7	414	103	1,399.00	1,652.00	0	30	20.68	120
8	414	103	1,092.00	1,475.00	715	30.3	15.51	123
9	414	103	1,362.00	1,682.00	0	30	20.68	106
10	413	104	1,483.00	1,438.00	320	31	20.68	220

Table 82. Filtering criteria based on cost

Alternative	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Water reducer (oz)	Initial cost (\$/yd ³)
6	413	104	1,483.00	1,421.00	320	31	15.51	106
7	414	103	1,399.00	1,652.00	0	30	20.68	120
9	414	103	1,362.00	1,682.00	0	30	20.68	106

Table 83. Environmental impact extracted from EPD (A1 and A3)

Alternative	GWP kg CO ₂ eq/yd ³	ODP kg CFC-11 eq/yd ³	AP kg SO ₂ eq/yd ³	EP kg N eq/yd ³	POCP kg O ₃ eq/yd ³	NRE MJ/yd ³	RE MJ/yd ³
6	194.079	3.23E-06	0.801	0.088	13.133	1399.590	157.365
7	194.076	3.34E-06	0.801	0.088	13.133	1399.522	157.344
9	193.893	3.23E-06	0.802	0.088	13.145	1400.768	157.492

Table 84. Final layer volume

Dimension	Value	Unit	Unit conversion	Final unit
Layer Thickness	11	Inch	1/36	Yd
Length	1	Mile	1760	Yd
Width	12	Feet	0.33	Yd
Total volume			2151.09	Yd ³

The normalization can be performed by dividing the environmental impact per the normalization value. This can be accomplished by following Equation 2

Normalized value = environmental impact/normalization value

For example, the normalization value for the GWP for alternative 6 =

417482.804 kg CO₂ eq/24000 kg CO₂eq = 17.39. Final values are illustrated in Table 87.

Table 85. Adjusted environmental impact per volume

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
6	417482.80	0.006	1723.97	189.39	28249.55	3010654.00	338507.89
7	417476.45	0.006	1723.95	189.39	28251.41	3010508.34	338463.66
9	417082.24	0.006	1724.60	189.51	28276.42	3013189.54	338780.86

Table 86. Normalization values used

GWP(kg CO ₂ eq/ yd ³)	24000
ODP(kg CFC-11 eq/ yd ³)	0.160
AP(kg SO ₂ eq/ yd ³)	91
EP(kg N eq/ yd ³)	22
POCP(kg O ₃ eq/ yd ³)	1400
NRE(MJ/ yd ³)	288572.509
RE(MJ/ yd ³)	24874.54785

Table 87. Normalized value for adjusted environmental impact per total volume

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
6	17.39	0.037	18.94	8.60	20.17	10.43	13.60
7	17.39	0.037	18.94	8.60	20.18	10.43	13.60
9	17.37	0.037	18.95	8.61	20.19	10.44	13.62

5.3.1.5 Transportation impact

Transportation from the raw material extraction to the manufacturing phase. These are given per Athena Institute for each mix design. The values are given per 1 yd³. The values are illustrated in Table 88. These values should be adjusted to total design volume.

Table 88. Transportation from raw material extraction to manufacturing phase (A2)

Alternative	GWP kg CO ₂ eq/ yd ³	ODP kg CFC-11 eq/ yd ³	AP kg SO ₂ eq/ yd ³	EP kg N eq/ yd ³	POCP kg O ₃ eq/ yd ³	NRE MJ/ yd ³	RE MJ/ yd ³
6	23.53	0.00	0.164	0.009	4.66	322.70	0.00
7	23.62	0.00	0.165	0.009	4.68	323.99	0.00
9	24.48	0.00	0.170	0.010	4.83	335.73	0.00

The adjustment process is illustrated in Table 89, which is performed by multiplying the values in Table 84 by the total design volume. For example, the adjusted GWP for alternative 6 = 23.535 kg CO₂ eq/ yd³ × 2151.09 yd³ = 50625.655 CO₂ eq

Table 89. Adjusted transportation impact per design volume

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
6	50625.65	0.00	352.75	19.73	10035.23	694178.65	0.00
7	50827.32	0.00	354.01	19.80	10070.86	696944.58	0.00
9	52669.24	0.00	365.63	20.45	10396.84	722204.51	0.00

Part 2: Transportation impact from the raw material extraction to project location

To calculate the transportation impact from the raw material extraction to project location, the distance between the manufacturers to project location should first be determined. This can be accomplished by calculating the distance between the two zip codes of the project location, as well as the manufacturer location. The zip code of the project location is 70454 and the manufacturer zip codes are presented in the EPD for each mix design. Table 90 illustrates the project zip code, the manufacturer zip code, and the distance between the project and the manufacturer location (calculated through Google maps). Results in Table 90 indicate that the transportation values are almost identical, since the manufacturer is in the Hammond area for all alternatives.

Table 90. Total transportation distance (manufacturer to project location)

Alternative number	Project location	Manufacturer location	Total distance (miles)	Total distance (km)
6	70454	70471	37	60
7	70454	70726	36	58
9	70454	70471	37	60

The transportation will be performed using a heavy duty truck with a weight of 80,000 lb and diesel fuel. The total weight of concrete to be transported is illustrated in Table 81. These values exist in the database and were gathered from the manufacturer. To obtain the total weight of the concrete transported, Equation 9 should be used: $M = D \times L_v$

For example, the density for alternative 6 = 4000.81lb/yd³ and the total design volume = 2151.09 yd³; therefore, the total design weight = 4000.81lb/yd³ × 2151.09 yd³ = 8606152.733 lb; then this weight value should be converted to metric ton, which will be accomplished through multiplying the value by 0.00045359. Total design weight = 8606152.733 lb × 0.00045359 = 3903.664818 ton. The total weight to be transported for each alternative is therefore the sum of truck weight as well as the transported concrete. Final values are illustrated in Table 91.

To obtain the total number of loads required, Equation 10 should be used.

Total number of loads = total weight concrete designed/ truck carrying capacity

For example, for alternative 6, the total number of loads = 8606152.73 lb/54000 lb = 159.37 loads

Table 91. Weight of concrete to transport

Alternative number	Density (lb/yd ³)	Total weight per design volume of concrete (lb)	Weight of concrete (ton)	Total number of loads	Total weight (truck+ concrete) (ton)
6	4000.81	8606152.73	3903.66	159.37	3939.95
7	3819.91	8217016.49	3727.15	152.16	3763.44
9	3812.92	8201966.88	3720.33	151.88	3756.61

To adjust the inventory values coming from the transportation module, Equation 11 should be used:

$$2 \times \text{Emissions of each truck} \left(\frac{\text{kg}}{\text{ton.km}} \right) \times \text{total weight transported (truck weight (ton) + weight of concrete transported (ton))} \times \text{total distance (km)} \\ \times \text{total number of loads}$$

The emissions/inventory for the heavy duty truck is illustrated in Table 92.

Table 92. Heavy duty truck emissions

GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
3.24E-01	0.00E+00	1.34E-03	5.55E-04	4.62E-02	8.09E-02	0.00

For example, to calculate the transportation impact from the manufacturing to the project location for GWP for alternative 6:

$$\text{Adjusted inventory values} = 2 \times 0.324 \text{ kg CO}_2/\text{ton.km} (3939.952\text{ton}) \times 60 \text{ km} \times 159.37$$

loads= 24088122.57kg CO₂ eq. The adjusted inventory per design alternative is indicated in Table 93.

Table 93. Transportation impact from the manufacturer to project location

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
6	24088122.57	0.00	99623.71	41262.06	3434787.84	6014596.03	0.00
7	21374862.61	0.00	88402.21	36614.34	3047897.07	5337118.47	0.00
9	21888597.91	0.00	90526.91	37494.35	3121151.92	5465393.73	0.00

Total transportation impact. The total transportation impact is the sum of Part 1 (transportation from raw material extraction to manufacturing), and Part 2 (transportation from the manufacturer to project location). Values are illustrated in Table 94. These values should be normalized.

To normalize the total transportation impact values, each value should be divided by the corresponding normalization value.

For example, alternative 6 will have the following value after normalization (for GWP) =
 $24138748.233 \text{ kg CO}_2 \text{ eq} / 24000 \text{ kg CO}_2 \text{ eq} = 1005.781$

The total transportation values are illustrated in Table 95 for the three alternatives.

5.3.1.6 Total environmental impact

The total environmental impact is the total of the environmental impact from concrete design (EPD), as well as the total transportation impact (from raw material extraction to manufacturing and from manufacturing to project location). This will result from the values given in Table 96.

For example, the environmental impact extracted from EPD and adjusted, based on design volume, was previously described:

Environmental impact from EPD (adjusted per volume) + total transportation impact. =
 $417482.80 \text{ kg CO}_2 \text{ eq} + 24138748.233 \text{ kg CO}_2 \text{ eq} = 24556231.037 \text{ kg CO}_2 \text{ eq}$. These total environmental impacts must be normalized. Values after normalization are illustrated in Table 97.

5.3.1.7 Weighing the environmental impact

Based on stakeholder preference, weighting can be assigned to the impacts. The weighting procedure will be used here for demonstration. Default weights were used for this case. The weights are illustrated in Table 98.

Equation 3 can be used to convert the environmental impacts into weighted environmental impacts: $\text{weighted impact} = \text{assigned weight} \times \text{normalized value}$

For example, for alternative 6 = $1023.176 \times 0.200 = 204.635$

Table 94. Total transportation impact per alternative

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
6	24138748.23	0.00	99976.46	41281.79	3444823.08	6708774.69	0.00
7	21425689.94	0.00	88756.22	36634.15	3057967.93	6034063.05	0.00
9	21941267.15	0.00	90892.55	37514.80	3131548.76	6187598.25	0.00

Table 95. Total transportation impact per alternative normalized

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
6	1005.781	0.000	1098.642	1876.445	2460.588	23.24	0.00
7	892.737	0.000	975.343	1665.189	2184.263	20.91	0.00
9	914.219	0.000	998.819	1705.219	2236.821	21.44	0.00

Table 96. Total environmental impact per alternative

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
6	24556231.03	0.006	101700.44	41471.19	3473072.63	9719428.69	338507.89
7	21843166.39	0.006	90480.17	36823.54	3086219.34	9044571.40	338463.66
9	22358349.40	0.006	92617.15	37704.32	3159825.18	9200787.80	338780.86

Table 97. Normalization values for the total environmental impacts

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
6	1023.17	0.037	1117.58	1885.05	2480.76	33.68	13.60
7	910.13	0.037	994.28	1673.79	2204.44	31.34	13.60
9	931.59	0.037	1017.77	1713.83	2257.01	31.88	13.62

Table 98. Weights used in the study

GWP	ODP	AP	EP	POCP	NRE	RE	Total
0.200	0.150	0.150	0.150	0.150	0.100	0.100	1

At this point in time, the values are on the same scale (because of normalization, which put all the values on the same scale as well as unitless). The total environmental score is the sum of all the environmental values together, then the RE value is deducted: Total environmental score = GWP+ODP+AP+POCP+NRE-RE = 1029.159

The relative score is the environmental impact score compared for each alternative with respect to other alternatives. This can be accomplished through Equation 14

Score for environmental impact for each alternative =

Total environmental score for alternative i/ \sum Environmental impact for all alternatives

For example, the score for alternative 6 = score for environmental 6 / sum of all scores

$$= 1029.159 / (1029.159 + 914.685 + 936.445) = 0.357$$

This equation was repeated for all other alternatives. Values are illustrated in Tables 99 and 100. In this case, the alternative having the lowest score is the one that has the lowest environmental impact. Alternative 7 is the alternative with the lowest environmental impact. Should the stakeholder be assigned a weight for the environmental score (the case in this study, since the assigned weight is 0.5), then the final environmental score after adjusting per the weight can be calculated, using Equation 15.

Weighted environmental score per alternative = EnvW \times score for environmental impact for alternative. For example, for alternative 7, the weighted score = $0.5 \times 0.357 = 0.179$. In this instance, alternative 7 has the lowest environmental impact

Table 99. Total environmental impact after normalizing and weighting

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE	Total
6	204.635	0.006	167.638	282.758	372.115	3.368	1.361	1029.159
7	182.026	0.006	149.143	251.070	330.666	3.134	1.361	914.685
9	186.320	0.006	152.666	257.075	338.553	3.188	1.362	936.445

Table 100. Relative score and environmental score

Alternative	Relative score	Assigning environmental score
6	0.357	0.179
7	0.317	0.159
9	0.325	0.163

5.3.1.8 Economic impact

As previously described, the economic analysis will be performed by completing a full lifecycle cost analysis for each alternative. This lifecycle cost analysis consists of an initial cost (occurring at the present) and a maintenance and rehabilitation cost occurring in the future. The economic analysis will follow the maintenance and rehabilitation schedule for the State of Louisiana, previously illustrated in the literature review. This schedule is illustrated in Table 101.

The total analysis period to study the project is 50 years; the project start year is 2017, for the maintenance and rehabilitation items. Based on this schedule at year 20, there are items such as cleaning and sealing joints and patching. In year 30; there is patching as well. This addresses the schedule and items that will be selected. At year 50, this is the end of life, and there is no salvage value. Also, in addition to this schedule, saw cutting will be added in years 20 and 30 of the project start year. This is to demonstrate the available items in the database.

Table 101. Maintenance and rehabilitation schedule for the State of Louisiana

Project Type	Alternate	Year 0	Year 15	Year 20	Year 30	Year 50
Interstate New Construction	Rigid	New JPC Pavement	No Action	Clean/Seal Joints Patch 1% of Joints	Retexture Patch 3% of Joints	End of life. No salvage value.

The initial material price (collected from the manufacturer) is illustrated in Table 102. Values are given per 1 yd³. To adjust the material price per total design volume, the price per 1 yd³ is multiplied by the total volume. For example, for alternative 6, this will equal $106\$/\text{yd}^3 \times 2151.09 \text{ yd}^3 = \228016.33

Table 102. Material price adjusted per volume

Alternative number	Material price \$/yd ³	Adjusted material price per total design volume
6	106	228016.33
7	120	258131.70
9	106	228016.33

The initial cost (from the bidding) exists for all the mix designs. The values are illustrated in Table 103. As may be seen, these mix designs were originally used in projects with various thicknesses. For example, alternative 6 was previously used in a project with a paving thickness of 9 inch. However, the unit price is given in terms of volume in order to fit various thicknesses. In the unit conversion for example, if the item is given in terms of area and the thickness is provided, the item is then converted to units of volume by multiplying the area \times thickness. The total bid cost for this item is divided by the total volume, to get the price per unit volume.

The letting date is provided, which may be used to calculate the time value of money for this mix design, as well as to compare them at the same point in time for example, at year 2017. This can be accomplished by using the net present value equation (Equation 4).

For example, for alternative 6: The total price = $\$328 \times (1+0.04)^4 = \383.713 ; to account for the total design volume, this cost should be multiplied by the total design volume. This will result in the following value: $383.713 \text{ \$/yd}^3 \times 2151.09 \text{ yd}^3 = \825401.2 . All adjusted values are illustrated in Table 104.

As for the maintenance and rehabilitation items, the compressive strength value of the selected mixes will be matched to the compressive strength value for past projects (applying a tolerance of 10%), and the maintenance and rehabilitation items will be matched accordingly. Depending on data availability, the perfect case would be to match the compressive strength value for recent projects, with the compressive strength value of older projects. Should the mix design of the past project be available, it would be advantageous to match both mix design breakdowns and select maintenance and rehabilitation activities based on both the compressive strength and mix design breakdowns.

The selected mixes have a compressive strength value of 5540, 4800, and 5530. Matched past projects with these compressive strength values are indicated in Table 105 for each alternative, and a detailed example is provided for alternative 6. As illustrated in Table 105, based on the selected tolerance, there are various compressive strengths as well as a mix design breakdown. All these compressive strengths are above the required compressive strength value, and therefore, any compressive strength value can be safe to use.

The next step is to match the mix design breakdown for available mixes. Table 106 illustrates the matching projects based on the compressive strength values and whether they have a mix design breakdown. For the projects that have a mix design breakdown and to match both mix designs (with a tolerance up to 10% for the cement value, the closer the match to the original mix, the better), the first step is to look at the cement content. As can be seen, project H.007116.6 has the closer cement content. In this case, project H.007116.6 will be selected based on a matched mix design breakdown.

Table 103. Initial cost items

Alternative number	Letting date	Parish name	Item Description	Bid unit price at letting date per yd ³	Compressive strength value (psi)
6	10/9/2013	Tangipahoa	Portland Cement Concrete Pavement (9" Thick)	\$328.00	5540
7	11/14/2012	Tangipahoa	Portland Cement Concrete Pavement (9" Thick)	\$460.00	4800
9	2/29/2012	St. Tammany	Portland Cement Concrete Pavement (12" Thick)	\$210.00	5530

Table 104. Initial cost items per alternative

Alternative number	Letting date	Parish name	Item Description	Bid unit price at letting date per yd ³	Net present value at year 2017 for the bid unit price (\$)	Bid unit price discounted to current year (2017) and adjusted per total design volume (\$/design)
6	10/9/2013	Tangipahoa	Portland Cement Concrete Pavement (9" Thick)	\$328.00	383.71	825405.399
7	11/14/2012	Tangipahoa	Portland Cement Concrete Pavement (9" Thick)	\$460.00	559.66	1203883.97
9	2/29/2012	St. Tammany	Portland Cement Concrete Pavement (12" Thick)	\$210.00	255.49	549599.20

Table 105. Projects associated with the selected compressive strength value alternative 6

Compressive strength value (psi)	Project ID	Mix design available?
5540	H.009572.6	No
5540	H.009342.6	No
5540	H.007265.6	No
5560	H.006622.6	No
5560	H.010486.6	No
5560	H.000466.6	No
5560	H.010396.6	No
5638	H.007116.6	Yes
5893.8	013-06-0034	Yes
5947.10	025-06-0027	Yes
5707.93	742-06-0016	Yes
5821.24	808-07-0035	Yes

Table 106. Matching mix design alternative 6

Proposal ID	Compressive strength value (psi)	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Air entertainer (%)
H.007116.6	5638	424	106	1018	1242	600	31.6	3.5
013-06-0034	5893.8	429	107	1275	1599	0	32	4
025-06-0027	5947.1	445	110	1589	1400	0	31.9	3.5
742-06-0016	5707.9	437	109	1158	1850	0	30	5
808-07-0035	5821.2	437	109	1119	1875	0	31.3	4.91

A detailed example is provided in Table 107 for the maintenance and rehabilitation activities. All the maintenance and rehabilitation activities for all matching projects are provided. As can be seen, the maintenance and rehabilitation projects occurred in various districts. Having compared all the items at the same point in time, the bid unit price will vary by location as well as by total quantity for the same activity. For example, the higher the total quantity, the lower the unit price. Since the cost varies by location, it is recommended to choose maintenance and rehabilitation activities occurring in the same district and parish. Also, it is recommended to select similar quantities. For example, if a project has an area of 16.1 yd² and a thickness of 11 inch, it is recommended to select matching projects with a similar area (16.1 yd²) and thicknesses (11 inch).

The selection depends on the user; for example, one scenario is to select maintenance and rehabilitation items that occurred in the same district or parish to guarantee similar price. Another scenario is to select the project with a matching mix design breakdown and assume that both mixes will behave similarly on the long term (in this case, project H.007116.6). In the event there are not many items for the selected mix design, the user might go further and select other projects with an available mix design breakdown. In this case, the cement content might rise. Another scenario would be to select the lowest maintenance and rehabilitation option, after discounting all alternatives at the same point in time.

All the maintenance and rehabilitation activities are converted to the year 2017, so that the user can compare. As can be seen, the data availability itself is of paramount importance and this is the main criteria to affect the user selection. Values discounted are presented in Table 107. The final user selection criteria are also illustrated. However, this cost only performs as a guide, so the final actual prices might vary by district and parish and layer thickness. As discussed, the selection criteria is also subject to data availability and will be discussed later in limitations and future work.

As for detailed calculations: The project starts at year 2017; the design life is 50 years; and the discount rate used is 4%. For example, for alternative 6 and project H.010486.6, the full depth patching JPCP (16.1 square yards to 48.0 square yards) (10" thick) has a value of \$377.96, which occurred at the year of 2014. To get the present value of this amount at current year 2017, this value is converted by $377.96 \times (1+0.04)^{(2017-2014)} = \425.164 , which is illustrated in Table 107. The same methodology was used for all the other activities and alternatives. All the values were converted from the letting date to the year 2017, for a strong comparison at the same point in time. The same discount rate was used in all cases.

The selection criteria here will be as follows: first, the items are going to be selected from Hammond district (since the project is already in Hammond). In case the Hammond district does not have all the maintenance and rehabilitation items required, the user might refer to other districts for guidance. Selected items have a year of occurrence in the table as a user input. In this case study, the user is interested in getting three maintenance and rehabilitation activities for all the three alternatives: full depth patching of jointed concrete pavement (16.1 square yards and over) occurring at years 20 and 30, cleaning and sealing random cracks occurring at year 20, and saw cutting Portland cement concrete pavement at years 20 and 30. Based on this assumption, the saw cutting was selected from Hammond district. However, since the other items do not exist in Hammond district, they will be selected from other districts based on the lowest cost. Final values are illustrated in Table 107 with the corresponding year of occurrence.

Table 107. Maintenance and rehabilitation item for alternative 6

Proposal number and district	Letting date	Item description	Price at letting date (\$)	Unit	Net present value, year 2017 (\$)	Year of occurrence	Cost at year of occurrence (\$)
H.010486.6 (Alexandria)	9/10/2014	Full Depth Patching of Jointed Concrete Pavement (16.0 square yards and under) (10" Thick)	485.9611	Yd ³	546.640		
	9/10/2014	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	377.9697	Yd ³	425.164	2047	1378.977
	9/10/2014	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	377.9697	Yd ³	425.164	2037	931.58
	9/10/2014	Full Depth Patching of Jointed Concrete Pavement (48.1 square yards and over) (10" Thick)	359.9712	Yd ³	404.918		
H.010396.6 (Monroe)	10/8/2014	Cleaning and Sealing Random Cracks	11879.619	Mile	13362.95	2037	29279.88
	10/8/2014	Full Depth Patching of Jointed Concrete Pavement (16.0 square yards and under) (9" Thick)	1199.9040	Yd ³	1349.72		
	10/8/2014	Full Depth Patching of Jointed Concrete Pavement (16.1	1139.9088	Yd ³	1282.24		

Table 107 (cont.)

Proposal number and district	Letting date	Item description	Price at letting date (\$)	Unit	Net present value, year 2017 (\$)	Year of occurrence	Cost at year of occurrence (\$)
		square yards to 48.0 square yards) (9" Thick)					
	10/8/2014	Full Depth Patching of Jointed Concrete Pavement (48.1 square yards and over) (9" Thick)	959.92	Yd ³	1079.78		
H.000466.6 (Hammond)	5/13/2015	Saw Cutting Portland Cement Concrete Pavement	1	INLF	1.08	2037	2.36
H.000466.6 (Hammond)	5/13/2015	Saw Cutting Portland Cement Concrete Pavement	1	INLF	1.08	2047	3.50
H.006622.6 (Hammond)	8/21/2014	Cleaning and Resealing Existing Longitudinal and Transverse Pavement Joints	17423.44	Mile	19599.00		
H.006622.6 (Hammond)	8/21/2014	Saw Cutting Portland Cement Concrete Pavement	1.5	INLF	1.68		
H.007265.6 (New Orleans)	10/12/2016	Cleaning and Resealing Existing Longitudinal Pavement Joints	5279.83	Mile	5491.02		
H.007265.6 (New Orleans)	10/12/2016	Cleaning and Resealing Existing Transverse Pavements Joints	5279.83	Mile	5491.02		

Table 107 (cont.)

Proposal number and district	Letting date	Item description	Price at letting date (\$)	Unit	Net present value, year 2017 (\$)	Year of occurrence	Cost at year of occurrence (\$)
H.007265.6 (New Orleans)	10/12/2016	Cleaning and Sealing Random Cracks	7919.74	Mile	8236.53		
H.007265.6 (New Orleans)	10/12/2016	Saw Cutting Portland Cement Concrete Pavement	1.5	INLF	1.56		
H.007116.6 (Alexandria)		Saw Cutting Portland Cement Concrete Pavement	1.5	INLF	1.75		
H.009572.6 (New Orleans)	11/18/2015	Saw Cutting Portland Cement Concrete Pavement	0.75	INLF	0.8112		
H.009342.6 (Hammond)	7/8/2015	Saw Cutting Portland Cement Concrete Pavement	1	INLF	1.0816		
Net present value					14215.4		

Following the same logic, all the matching projects based on compressive strength values and or mix design breakdown were collected for alternative 7. Table 108 illustrates the matching projects associated with the compressive strength value and whether these projects have associated mix design breakdown. Table 109 illustrates the mix design breakdown for the matched projects with mix design breakdown.

There are two projects with associated mix design breakdown (based on a tolerance level of 10% for the cement value). Depending on preference, the user might proceed with these alternatives. All the maintenance and rehabilitation activities for the projects in Table 110 are displayed. It should be noted that not all projects have maintenance and rehabilitation activities. For example, projects 077-04-0015 and 451-01-0108 have no maintenance and rehabilitation activities, only those costs associated with initial cost activities.

Maintenance and rehabilitation items from Hammond district will be selected first, since the project is in Hammond, and then the rest of maintenance and rehabilitation activities will be selected from other districts. Should two similar activities occur at the same parish, the lowest cost item would be selected. Selected values have the year of occurrence displayed. Values are illustrated in Table 110.

Table 108. Projects associated with the selected compressive strength value alternative 7

Compressive strength value (psi)	Project ID	Mix design available?
4800	H.003298.6	No
4800	H.009546.6-R1	No
4800	H.009539.6	No
4900	077-04-0015	Yes
4890.4	102-01-0034	No
5100	451-01-0108	Yes

Table 109. Matching compressive strength value alternative 7

Proposal ID	Compressive strength value (psi)	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Air entertainer (%)
077-04-0015	4900	436	109	1216	1769	0	31.3	4.09
451-01-0108	5100	482	120	1078	1426	357	35	5

Table 110. Maintenance and rehabilitation activities for alternative 7

Proposal number and district	Letting date	Item description	Price at letting date (\$)	Unit	Net present value, year 2017 (\$)	Year of occurrence	Cost at year of occurrence (\$)
H.003298.6 (Monroe)	2/8/2017	Saw Cutting Portland Cement Concrete Pavement	1.19	INLF	1.19	2037	2.60
H.003298.6 (Monroe)	2/8/2017	Saw Cutting Portland Cement Concrete Pavement	1.19	INLF	1.19	2047	3.85
H.009546.6-R1 (Monroe)	12/16/2015	Cleaning and Sealing Random Cracks	7655.75	Mile	8280.46	2037	18143.517
H.009539.6 (Alexandria)	3/12/2014	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	395.968	Yd ³	445.41	2047	1444.64

Table 110 (cont.)

Proposal number and district	Letting date	Item description	Price at letting date (\$)	Unit	Net present value, year 2017 (\$)	Year of occurrence	Cost at year of occurrence (\$)
H.009539.6 (Alexandria)	3/12/2014	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	395.968	Yd ³	445.41	2037	975.94
102-01-0034 (Shreveport)	7/22/2009	Saw Cutting Portland Cement Concrete Pavement	5	INLF	5.62		
Net Present Value					9173.66		

As illustrated, Table 111 illustrates the projects with matching compressive strength value and/or a mix design breakdown for alternative 9. After that, Table 112 displays the mix design breakdown for the projects having a matched mix design breakdown. Depending on data availability, maintenance and rehabilitation items are illustrated in Table 113. There are two projects matching the compressive strength value and with associated mix designs. However, the projects with associated mix design breakdown have no maintenance and rehabilitation activities. Therefore, the user must select the maintenance and rehabilitation items from the remaining projects.

Table 111. Projects associated with the selected compressive strength value alternative 9

Compressive strength value (psi)	Project ID	Mix design available?
5530	H.011678.6	No
5540	H.009341.6	No
5530	H.009598.6	No
5560	H.010486.6	No
5534	024-04-0013	Yes
5532	019-04-0036	Yes

The maintenance and rehabilitation items are illustrated in Table 113, for projects having maintenance and rehabilitation activities. For example, Project 024-04-0013, 019-04-0036 have no maintenance and rehabilitation activities. The selected items have the year of occurrence as a user input.

5.3.1.9 Final weight for the economic impact

The final weight for the economic impact will be performed using the sum of initial cost and maintenance and rehabilitation cost. Values for each alternative are illustrated in Tables 114 and 115. There are two scenarios here. The first scenario is to calculate the total cost with respect to the initial cost and pertaining to the material only.

Table 112. Matching compressive strength value alternative 9

Proposal ID	Compressive strength value (psi)	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Air entertainer (%)
024-04-0013	5534	436	109	1290	1887	0	32.9	0
019-04-0036	5532	476	0	1280	1052	359	27.2	2.5

Table 113. Maintenance and rehabilitation activities for alternative 9

Proposal number and district	Letting date	Item description	Price at letting date (\$)	Unit	Net present value, year 2017 (\$)	Year of occurrence	Cost at year of occurrence (\$)
H.011678.6 (Alexandria)	4/8/2015	Saw Cutting Portland Cement Concrete Pavement	1	INLF	1.08	2037	2.36
H.011678.6 (Alexandria)	4/8/2015	Saw Cutting Portland Cement Concrete Pavement	1	INLF	1.08	2047	3.50
H.011678.6 (Alexandria)	4/8/2015	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (11" Thick)	643.03	Yd ³	695.51		
H.011678.6 (Alexandria)	8/12/2015	Cleaning and Sealing Random cracks	29039.07	Mile	31408.65	2037	68820.23
H.010486.6		Full Depth Patching of Jointed Concrete			425.16		1378.97

Table 113 (cont.)

Proposal number and district	Letting date	Item description	Price at letting date (\$)	Unit	Net present value, year 2017 (\$)	Year of occurrence	Cost at year of occurrence (\$)
(Alexandria)	9/10/2014	Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	377.969	Yd ³		2047	
H.010486.6 (Alexandria)	9/10/2014	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	377.969	Yd ³	425.16	2037	931.58
H.010486.6 (Alexandria)	9/10/2014	Cleaning and Resealing Existing Transverse Pavements Joints	3643.08	Mile	4097.97		
Net present value at 2017					32261.151		

Add to that the maintenance and rehabilitation cost item. In this case, alternative 6 has the lowest cost. The other option is to add the initial overall cost (including design and overhead) to the maintenance and rehabilitation cost item. In this case, alternative 9 has the lowest economic cost. Assignment of the economic score can be accomplished through

Equation 16:
$$\frac{NPV_i}{\sum NPV_a}$$

For example, for alternative 6, the resulting score =

$$242231.77 / (242231.77 + 267305.36 + 260277.49) = 0.314$$

In assigning an economic score in this study, there is an economic score of 0.5; the final economic score after assigning the economic score may be calculated using Equation 17.

EconW × score for economic weight per alternative

$$\text{Economic score for alternative 6} = 0.314 \times 0.5 = 0.157$$

Table 114. Cost analysis for alternatives (scenario 1)

Alternative	Initial cost (material)	Maintenance and rehabilitation item	Total (\$/design)	Weighted	Assigning economic score
6	228016.33	14215.44	242231.77	0.314	0.157
7	258131.70	9173.66	267305.36	0.347	0.173
9	228016.33	32261.15128	260277.49	0.338	0.169

Table 115. Cost analysis for alternatives (scenario 2)

Alternative	Initial cost (overall)	Maintenance and rehabilitation item	Total (\$/design)	Weighted	Assigning economic score
6	825405.399	14215.44	839620.83	0.318	0.159
7	1203883.973	9173.66	1213057.63	0.460	0.230
9	549599.204	32261.15128	581860.35	0.220	0.110

5.3.1.10 Total sustainability score

The total score can then be calculated using Equation 18: overall final sustainability score = weighted economic score for alternative + weighted environmental impact for alternative. In the first scenario, considering only the material cost, alternatives 7 and 9 have

the lowest score. When the total initial cost is considered, alternative 9 has the lowest total score as well, and is considered the best choice. The final values are illustrated in Table 116.

Table 116. Total score

Alternative	Economic score		Environmental score	Total score	
	Scenario 1	Scenario 2		Scenario 1	Scenario 2
6	0.157	0.159	0.179	0.336	0.338
7	0.173	0.230	0.159	0.332	0.389
9	0.169	0.110	0.163	0.332	0.273

5.3.1.11 Statistical analysis

To be able to compare statistical significance of the results, another EPD will be used to assess the environmental impact. Note that the economic impact cannot be compared because cost data does not exist for states other than Louisiana. A compressive strength value of 4400, 5000 and 6000 psi will be used to evaluate the following environmental impact/inventory values: GWP, ODP, AP, EP, POCP, RE and NRE.

The scope will include the following stages: raw material extraction, transportation from raw material extraction to manufacturing, manufacturing, and transportation from manufacturing to project location. The total environmental score will be compared, since the breakdown for EPD is not available for states other than Louisiana. The same procedure will be followed to evaluate the total environmental impact with the same assumptions, only raw data from EPD will change. The raw data used, extracted from EPD, for compressive strength value of 4400 psi are illustrated in Table 117, as a sample.

Table 117. Total environmental impact per alternative

Alternative	GWP kg CO ₂ eq/ yd ³	ODP kg CFC-11 eq/ yd ³	AP kg SO ₂ eq/ yd ³	EP kg N eq/ yd ³	POCP kg O ₃ eq/ yd ³	NRE MJ/ yd ³	RE MJ/ yd ³
6A	305.83	3.51E-06	1.69	0.05	24.31	1673.67	12.54
7B	262.25	3.07E-06	1.48	0.04	21.48	1488.64	10.77
9C	255.37	2.97E-06	1.44	0.04	21.25	1433.59	10.57
Average	274.48	3.18E-06	1.54	0.04	22.35	1531.97	11.29

Final results for the environmental score are illustrated in Table 118. To better understand the data used, descriptive statistics is illustrated in Table 119, including the mean, the standard deviation, and confidence interval. To evaluate results significance, analysis of variance (ANOVA) is performed with a confidence interval of 95%. Results are illustrated in Table 120. The resulting P value =0.999462 (> 0.001 indicating insignificance of the results).

Table 118. Environmental impact comparison

Alternative	Environmental score (Louisiana)	Environmental score (4400 psi)	Environmental score (5000 psi)	Environmental score (6000 psi)
6	0.179	0.178	0.178	0.177
7	0.159	0.158	0.159	0.159
9	0.163	0.162	0.162	0.163
Mean	0.167	0.166	0.166	0.166
Standard deviation	0.0106	0.0106	0.0102	0.0095

Table 119. Descriptive statistics for the environmental impact values

Criteria	Louisiana data	4400 psi	5000 psi	6000 psi
Mean	0.167	0.166	0.166333	0.166333
Standard error	0.00611	0.00611	0.005897	0.005457
Median	0.163	0.162	0.162	0.163
Standard deviation	0.01058	0.010583	0.010214	0.009452
Sample variance	0.00011	0.000112	0.000104	8.93E-05
Skewness	1.45786	1.457863	1.565482	1.389636
Range	0.02	0.02	0.019	0.018
Minimum	0.159	0.158	0.159	0.159
Maximum	0.179	0.178	0.178	0.177
Sum	0.501	0.498	0.499	0.499
Count	3	3	3	3
Confidence level (95.0%)	0.02629	0.02629	0.025374	0.023479

Table 120. Analysis of variance results

Source of Variation	SS	df	MS	F	P-value	F critical
Between Groups	1.58E-06	3	5.28E-07	0.005055	0.999462	4.066181
Within Groups	0.000835	8	0.000104			
Total	0.000837	11				

5.3.1.12 Sensitivity analysis

Sensitivity analysis is an important criteria in decision making. Sensitivity analysis should determine the sensitivity of an output to a change in input, while keeping all the other alternatives constant. In this section, a sensitivity analysis will be performed to evaluate how the change in the following criteria affects the total environmental impact for each alternative

- 1) Environmental impact of raw material extraction and manufacturing (reported from EPD)
- 2) Environmental impact of transportation
 - a) From raw material extraction to manufacturing (from EPD)
 - b) From manufacturing to project location
 - c) Total environmental impact of transportation from raw material extraction to manufacturing and from manufacturing to project location
- 3) Impact of total distance traveled from raw material extraction to project location.

The sensitivity levels will be evaluated by an increase of 10% in the previous factors. Final results are illustrated in Table 121.

Table 121. Sensitivity analysis and final environmental impact

Criteria	Change on total environmental impact (%)
Environmental impact of raw material extraction and manufacturing (reported from EPD)	0.107
Environmental impact of transportation (from raw material extraction to manufacturing)	0.0259
Environmental impact of transportation (from manufacturing to project location), by changing the inventory values/environmental impact of heavy duty truck	9.86
Total distance traveled from manufacturing to project location	9.86
Environmental impact of total transportation module (transportation from raw material extraction to manufacturing and from manufacturing to project location)	9.86

In a further interpretation for the results illustrated in Table 121, the final environmental impacts are highly altered by changing criteria in the transportation module either in changing the environmental impact of the transportation stage from manufacturing to project location, or by changing the total distance traveled from manufacturing to project location, or by changing the total environmental impact of transportation (transportation from raw material extraction to manufacturing and from manufacturing to project location).

As for changing raw material extraction and manufacturing stages of concrete, changing these criteria did not change the total environmental impact compared to the transportation stages. This example illustrates the importance of the transportation module and proves it to be a sensitive criteria towards the total environmental impact.

5.3.2 CASE STUDY 2: BENCHMARKING MODULE

The same case study will be performed using the benchmarking module for illustration. A step by step procedure will be displayed. The same procedure and format will be followed in this module.

5.3.2.1 Environmental performance

1. Select the state you want to use the mix design: The state is Louisiana.
2. The purpose of the design is benchmarking. The stakeholder is interested in benchmarking the product, and wants to know whether the product is below or above the market average.
3. Select the number of products to benchmark: The stakeholder might want to benchmark the product with respect to various criteria, inclusive of a certain region, with respect to the Hammond district or with respect to a specific parish. Also, the user might want to measure the cost of the product to know whether the product is above or below the market average.
4. Assign weights for the environmental and economic impacts. Both impacts will be assigned a weight of 0.5
5. Convert the modulus of rupture to compressive strength value, using Equation 8, where:
$$\text{MOR (psi)} = 2.3 (f_c)^{2/3} \text{ or } f_c = (\text{MOR}/2.3)^{3/2}.$$
 This results in a compressive strength value of $(600/2.3)^{3/2} = 4213 \text{ psi}$
6. Select alternative mixes from the EPD data, to evaluate the environmental impact. The user enters a specific, required mix design to seek the environmental impact in the database. The stakeholder is interested in acquiring cement content around the 412 lb value. This mix design is illustrated in Table 122.

Table 122. Required mix design

Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Air entertainer (%)
412	102	1400	1600	1420	32	1

This exact mix design is not in the database and therefore, the stakeholder can select from among the existing mixes. The nearest mixes based on the cement and fly ash amount are illustrated in Table 123. As illustrated, there are various mix designs that appear. Yet there should be some filtering criteria for the stakeholder. For example, one of the filtering criteria could be the proximity to the project location. The user would select to benchmark the product with respect to all the mixes produced in the Hammond area.

The environmental impact of the mixes 6, 7, and 9 are illustrated in Table 125. These are the values extracted from EPD, with no modifications. Values of the environmental impact will be averaged, and the design will proceed with the average value. This is one of the differences between the alternative design module and the benchmarking module. As illustrated, the values are given per 1 yd³. These are the impacts for A1: raw material extraction and A3: manufacturing.

These values are given per 1 yd³. Some adjustments must be performed to adjust the environmental impacts per the total design volume. The total design volume calculation is illustrated in Table 126, for the 11 inch thickness. The calculation was performed using Equation 6: This step remains intact, since the design will not change. $L_v = L_T \times L_W \times L_L$

The total environmental impact for the design then should be adjusted according to the overall design volume, using Equation 7.

Equation 7 Total environmental impact per design layer

Environmental impact reported from EPD \times L_v

Table 123. Corresponding mix designs

Alternative	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Water reducer (oz)	District	Initial cost (\$/yd ³)
1	414	103	1,180.00	1,481.00	413	29.6	20.7	Baton Rouge	123
2	414	103	1,291.00	1,559.00	413	31	20.7	Baton Rouge	123
3	414	103	1,092.00	1,353.00	846	30.3	15.51	Baton Rouge	123
4	414	103	1,285.00	1,379.00	607	31	20.7	Baton Rouge	117
5	414	103	1,281.00	1,376.00	604	31	20.7	Baton Rouge	117
6	413	104	1,483.00	1,421.00	320	31	15.51	Hammond	106
7	414	103	1,399.00	1,652.00	0	30	20.68	Hammond	120
8	414	103	1,092.00	1,475.00	715	30.3	15.51	Hammond	123
9	414	103	1,362.00	1,682.00	0	30	20.68	Hammond	106
10	413	104	1,483.00	1,438.00	320	31	20.68	Hammond	220
11	414	103	1,000.00	1,483.00	550	29.7	30.2	Lafayette	116
12	414	103	1,521.00	1,521.00	0	29.5	31.2	New Orleans	106

Table 124. Filtering criteria based on manufacturer location

Alternative	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Water reducer (oz)	District	Initial cost (\$/yd ³)
6	413.66	103.33	0.00	1414.66	1585.00	106.66	30.33	Hammond	106
7	413.66	103.33	0.00	1414.66	1585.00	106.66	30.33	Hammond	120
9	413.66	103.33	0.00	1414.66	1585.00	106.66	30.33	Hammond	106
Average	413.66	103.33	0.00	1414.66	1585.00	106.66	30.33	Hammond	110.67

Table 125. Environmental impact extracted from EPD (A1 and A3)

Alternative	GWP kg CO ₂ eq/yd ³	ODP kg CFC-11 eq/yd ³	AP kg SO ₂ - eq/yd ³	EP kg N eq/yd ³	POCP kg O ₃ eq/yd ³	NRE MJ/ yd ³	RE MJ/ yd ³
6	193.89	2.78E-06	0.801	0.0881 0	13.14	1400.76	157.49
7	194.07	2.77E-06	0.801	0.0880 4	13.13	1399.52	157.34
9	194.08	2.77E-06	0.801	0.09	13.13	1399.59	157.37
Average	194.02	2.77E-06	0.80	0.09	13.14	1399.96	157.40

Table 126. Final layer volume

Dimension	Value	Unit	Unit conversion	Final unit
Layer Thickness	11	Inch	1/36	Yd
Length	1	Mile	1760	Yd
Width	12	Feet	0.33	Yd
Total volume			2151.09	Yd ³

For example, the total adjusted GWP for the average value is: The volume 2151.09 yd³ × 194.02 kg CO₂ eq/yd³ = 417347.167 kg CO₂ eq. The environmental impact will be adjusted accordingly to each alternative. Final results are indicated in Table 127.

Table 127. Adjusted environmental impact per volume

Alternative	GWP kg CO ₂ eq	ODP kg CFC- 11 eq	AP kg SO ₂ - eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
Average	417347.16	0.006	1724.17	189.43	28259.12	3011450.63	338584.14

As illustrated, the values have different units. Therefore, these should be normalized to have consistent, unitless units, which can be summed up altogether in the end. The normalization values used are illustrated in Table 128.

The normalization can be performed through dividing the environmental impact per the normalization value. This can be accomplished by following Equation 2.

$$\text{Normalized value} = \text{Impact}_A / \text{Normalization value for impact}_A$$

Table 128. Normalization values used

GWP (kg CO ₂ eq/ yd ³)	24000
ODP (kg CFC-11 eq/yd ³)	0.160
AP (kg SO ₂ -eq/yd ³)	91
EP (kg N eq/yd ³)	22
POCP (kg O ₃ eq/yd ³)	1400
NRE (MJ/yd ³)	288572.509
RE (MJ/yd ³)	24874.54785

For example, the normalization value for the GWP for the average value is:

417347.167 kg CO₂ eq/24000 kg CO₂eq = 17.38. Normalized values are illustrated in Table 129.

Table 129. Normalized value for adjusted environmental impact per total volume

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
Average	17.38	0.03	18.94	8.611	20.18	10.43	13.61

5.3.2.2 Transportation impact

Transportation from the raw material extraction to the manufacturing phase. These are given per Athena Institute for each mix design. The values are given per 1 yd³. The values are illustrated in Table 130. These values should be adjusted to total design volume. Since this is the benchmarking module, the average value is computed to work in tandem with the appropriate data.

Table 130. Transportation from raw material extraction to manufacturing (A2)

Alternative	GWP kg CO ₂ eq/ yd ³	ODP kg CFC-11 eq/yd ³	AP kg SO ₂ eq/yd ³	EP kg N eq/yd ³	POCP kg O ₃ eq/yd ³	NRE MJ/ yd ³	RE MJ/ yd ³
6	24.484	9.31E-10	0.169	0.009	4.833	335.737	0.00
7	23.628	8.98E-10	0.164	0.009	4.681	323.994	0.00
9	23.53	8.95E-10	0.16	0.01	4.67	322.71	0.00
Average	23.883	9.08 E-10	0.166	0.009	4.833	327.481	0.00

The adjustment process is illustrated in Table 131, which is performed by multiplying the average value in Table 130 by the total design volume. For example, the adjusted GWP for the average alternative = 23.883 kg CO₂ eq/ yd³ × 2151.09 yd³ = 51737.55 kg CO₂ eq.

Table 131. Adjusted transportation impact per design volume

GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
51374.07	0.00	357.46	19.99	10396.84	704442.58	0.00

Part 2 Transportation impact from the raw material extraction to project location

To calculate the transportation impact from the raw material extraction to the use phase, the distance between the manufacturers to the project location first should be determined. This can be accomplished by calculating the distance between the two zip codes: the zip code of the project location, as well as the manufacturer's zip code. The zip code of the project location is 70454 and the manufacturer zip codes are user input, as indicated in Table 132. The user input value is one difference between the benchmarking module and the alternative design comparison module. The distance can be calculated using Google maps. The average transportation distance is 36.66 miles or 58.66 kms. The average distance will be used.

Table 132. Total transportation distance (manufacturer to project location)

Alternative number	Project location	Manufacturer location	Total distance (miles)	Total distance (km)
6	70454	70471	37.000	59.200
7	70454	70726	36.000	57.600
9	70454	70471	37.000	59.200
Average			36.66	58.66

Also, the total weight to be transported should be identified. The transportation will be performed using a heavy duty truck with a weight of 80,000 lb and diesel fuel.

The total weight of concrete to be transported is illustrated in Table 133. These values exist in the database (originally gathered from the manufacturer). As previously described, the total weight to be transported is calculated by the vehicle weight and the total weight of concrete to be transported. This can be accomplished through using Equation 9: $M = D \times L_v$

For example, the density for the average alternative = 3877.89 lb/yd³ and the total design volume = 2151.09 yd³, therefore, the total average design weight = 3877.89 lb/yd³ × 2151.09 yd³ = 8341712.04 lb. This weight value should be converted to metric ton, which will be accomplished through multiplying the value by a factor of 0.00045359.

The average concrete weight to be transported = 8341712.04 lb × 0.00045359 = 3783.72 ton. The total weight to be transported for the average alternative is therefore the sum of truck weight (800000 lb or 36.28 ton + 3783.72) = 3820 ton. To find the total number of loads required, Equation 10 is used.

$$\text{Total number of loads} = \text{total weight concrete designed} / \text{truck carrying capacity}$$

In this case, the average weight will be used = 8374663.14 lb/ 54000 lb = 154.48 loads

Table 133. Weight of concrete to transport

Alternative number	Density (lb/yd ³)	Total weight per design volume of concrete (lb)	Weight of concrete (ton)	Truck weight (ton)	Total number of loads	Total weight (truck+ concrete) (ton)
Average	3877.89	8341712.04	3783.72	36.28	154.48	3820

To adjust the inventory values coming from the transportation module, Equation 11 should be used: Adjusted inventory values =

$$2 \times \text{Emissions of each truck} \left(\frac{\text{kg}}{\text{ton.km}} \right) \times \text{total weight transported (truck weight (ton) + weight of concrete transported (ton))} \times \text{total distance (km)} \times \text{total number of loads}$$

The emissions/ inventory for the heavy duty truck is illustrated in Table 134

Table 134. Heavy duty truck emissions (kg/ton.km)

GWP kg CO ₂ eq	ODP kg CFC- 11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
3.24E-01	0.00E+00	1.34E-03	5.55E-04	4.62E-02	8.09E-02	0.00

For example, to calculate the transportation impact from the manufacturing to the project location for GWP: Adjusted inventory values = $2 \times 0.324 \text{ kg CO}_2/\text{ton.km}$ (3820 ton) $\times 58.66 \text{ km} \times 154.48 = 22433226.08 \text{ kg CO}_2 \text{ eq}$. Values are illustrated in Table 135.

Table 135. Transportation impact from the manufacturer to project location

Alternative	GWP kg CO ₂ eq	ODP kg CFC- 11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
Average	22433226.08	0.00	92779.391	38427.28	3198811.86	5601382.68	0.00

Total transportation impact: The total transportation impact is the sum of Part 1 (transportation from raw material extraction to manufacturing) and Part 2 (transportation from the manufacturer to project location). For GWP, both values will lead to $51374.07 + 22433226.08 = 22484600.16 \text{ kg CO}_2 \text{ eq}$. Values are illustrated in Table 136. These values should be added and then normalized.

Table 136. Total transportation impact per alternative

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
Average	22484600.16	0.00	93136.85	38447.28	3209208.70	6305825.27	0.00

To normalize the total transportation impact values, each environmental impact should be divided by the corresponding normalization value. For example, the average mix design will have the following value after normalization (for GWP) = $22484600.16 \text{ kg CO}_2 \text{ eq} / 24000 \text{ kg CO}_2 \text{ eq} = 936.85$. The total transportation values are illustrated in Table 137 for the average.

Table 137. Total normalized transportation impact per alternative

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
Average	936.85	0.00	1023.48	1747.60	2292.29	21.85	0.00

5.3.2.3 Total environmental impact

The total environmental impact presents the total of the environmental impact coming from concrete design (EPD), as well as the total transportation impact (from raw material extraction to manufacturing and from manufacturing to project location). This results from the values displayed in Table 138. Based on design volume, the environmental impact extracted from EPD and adjusted, was previously described:

Environmental impact from EPD (adjusted per volume) + total transportation impact
 $= 417347.16 \text{ kg CO}_2 \text{ eq} + 22484600.16 \text{ kg CO}_2 \text{ eq} = 22901947.33 \text{ kg CO}_2$. These total environmental impacts must be normalized. Values after normalization are illustrated in Table 139.

Table 138. Total environmental impact per alternative

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
Average	22901947.33	0.006	94861.03	38636.71	3237467.83	9317275.90	338584.14

Table 139. Normalization values for the total environmental impacts

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
Average	954.248	0.037	1042.429	1756.214	2312.477	32.287	13.612

5.3.2.4 Weighing the environmental impact

Based on stakeholder preference, weighting can be assigned to the average environmental impacts. The weighting procedure will be used here for demonstration. The weights used are illustrated in Table 140.

Table 140. Weights used in the study

GWP	ODP	AP	EP	POCP	NRE	RE	Total
0.200	0.150	0.150	0.150	0.150	0.100	0.100	1

The total environmental impact after the weighting process is illustrated in Table 130. Equation 3 can be used to convert the environmental impacts into weighted environmental impacts: weighted impact = assigned weight \times normalized value

For example, for the weighted alternative = $0.20 \times 954.248 = 190.85$. At this point in time, the values are on the same scale due to normalization, which placed all the values on the same scale, as well as unitless).

The sum of all the environmental values together is the total environmental score for the average impact. $GWP + ODP + AP + POCP + NRE - RE = 959.391$. Here the relative score no longer exists, since the average value is taken. Values are illustrated in Table 141.

Table 141. Total environmental impact after normalization and weighting

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE	Total
Average	190.850	0.006	156.364	263.432	346.872	3.229	1.361	959.391

5.3.2.5 Economic impact

As previously described, the economic analysis will be accomplished though performing a complete lifecycle cost analysis for each alternative. This lifecycle cost analysis consists of an initial cost (occurring at the present) and a maintenance and rehabilitation cost (occurring in the future). The initial cost for the selected mix designs is extracted from the database. These values include the profits, overheads, installation fees, etc. The initial cost items of the selected alternatives (6, 7, and 9) are illustrated in Table 142. The letting date is provided, which can be used to calculate the net present value or the average price at the same point in time/at present as the year 2017. An analysis period of 50 years is used, with a discount rate of 4%. The calculation will be the same as the alternative design module, except for the fact that the values will be averaged to have a single number with which to deal.

The initial cost items are illustrated in Table 142. This is for the materials cost only; the average value is taken. The average value is $110.67 \text{ \$/yd}^3$ to be adjusted to total volume = $110.67 \text{ \$/yd}^3 \times 2151.09 \text{ yd}^3 = \238061.96 . The overall initial cost is illustrated in Table 143. This includes the overheads, profits, etc. and the cost is adjusted to volume.

Table 142. Average material price

Alternative	Initial cost ($\text{\$/yd}^3$)
-------------	-----------------------------------

6	106
7	120
9	106
Average	110.67
Adjusted per volume	238061.96

Table 143. Cost analysis for alternatives (scenario 2)

Alternative number	Bid unit price discounted to current year (2017) and adjusted per total design volume (\$/design)
6	825405.399
7	1203883.97
9	549599.204
Average	859629.52

The average maintenance and rehabilitation item for the average alternative is illustrated in Table 144, under the same assumptions previously illustrated in the alternative design module. The average value is taken as well, but in this case the average value is per each item and not for the overall design. As for the maintenance and rehabilitation items, the benchmark is taken per activity; as illustrated in Table 144.

Table 144. Average maintenance and rehabilitation activities

Item	Design 6 (\$)	Design 7 (\$)	Design 9 (\$)	Average (\$)
Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	425.1645	445.4105112	425.164	431.9/Yd ³
Cleaning and Sealing Random cracks	13362.95	8280.46	31408.658	17684.022//Mile
Saw Cutting Portland Cement Concrete Pavement	1.08	1.19	1.0816	1.116/ INLF

5.3.3 CASE STUDY 3 ALTERNATIVE DESIGN COMPARAISON

5.3.3.1 Project description

This project falls under a proposal number of H.003495. The project is titled I-49N, segment K - phase 2 -220 to Martin Luther King Drive. The project is in Caddo Parish, Shreveport district, with a zip code of 71107.

5.3.3.2 Design inputs

The project traffic information is illustrated in Table 145. The project is divided into two roads; each road has certain characteristics, such as directional distribution, K value, truck distribution, design speed, and average daily traffic.

Table 145. Project traffic data (LaDOTD)

Criteria	I 49 Traffic data	MLK drive
D (Directional distribution)	55.3%	7%
K	10.6%	11%
T (truck distribution)	14.7%	9.3%
Design speed (MPH)	60	40
2013 Average Daily Traffic (A.D.T.)	22869	6349
2032 A.D.T	33165	7388

5.3.3.3 Design properties

The design is illustrated in Figure 52. The layer inputs are as follows: PCC layer, class 2 Base course (recycled PCC or stone), subgrade layer (treated). Thicknesses are illustrated in Figure 52. The Modulus of rupture is 600 psi, resulting in a compressive strength value of 4213 psi

Portland cement concrete 11 inch
Class 2 Base Course 4 inch
Subgrade layer (treated) 12 inch

Figure 48. Design layers

5.3.3.4 Environmental impact

To evaluate the environmental impact of this project, the developed framework will be used. The solution will be provided in steps for replication.

1. Select the state you want to use the mix design: The state is Louisiana.
2. The purpose of the design is alternative design comparison. The stakeholder is interested in evaluating the environmental impact of various alternatives. These different alternatives are various mix designs, since the design cannot be changed.
3. Select the number of designs to evaluate: only one design.
4. Select the number of mixes to evaluate: 3 PCC mix designs
5. Assign weights for the environmental and economic impacts. Both impacts will be assigned a weight of 0.5
6. Convert the modulus of rupture to compressive strength value using Equation 8, where:
$$\text{MOR (psi)} = 2.3 (f_c)^{2/3} \text{ or } f_c = (\text{MOR}/2.3)^{3/2}.$$
 This results in a compressive strength value of $(600/2.3)^{3/2} = 4213 \text{ psi}$
7. Select alternative mixes from the EPD data to evaluate the environmental impact. The user enters a specific mix design (required by the design) to look for an environmental impact in the database. This mix design is illustrated in Table 146. Normally, the paving mix designs have a cement content ranging from 400 to 550 lbs. The input value for the cement content should be in this range.

Table 146. Required mix design

Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Air entertainer (%)
500	100	1501	1520	750	29	3

This exact mix design is not in the database; therefore, the stakeholder can select from among the existing mixes. As illustrated in Table 147, there are various mix designs that appear. There should be some filtering criteria for the stakeholder. For example, one of the

filtering criteria can be proximity to project location (and thereby provides less environmental impact for transportation). The mixes selected are the mixes manufactured in the Shreveport district.

For example, this project is in Shreveport and therefore, the manufacturers located in Shreveport can be the best alternatives. This narrows the choice of mixes to options 5, 6, and 7. The new selections are illustrated in Table 148.

The environmental impact of the mixes 5, 6 and 7 are illustrated in Table 149. These are the values extracted from EPD, with no modifications. As illustrated, the values are given per 1 yd³. These are the impacts for A1: raw material extraction and A3: manufacturing.

These values are given per 1 yd³, yet some adjustments must be performed to adjust the environmental impacts per the total design volume. The total design volume calculation is illustrated in Table 150, for an 11 inch thickness. The calculation was performed using Equation 6:

$$L_v = L_T \times L_W \times L_L$$

To get the total environmental impact per total design volume, Equation 7 is used:

Environmental impact reported from EPD \times L_v

For example, the total adjusted GWP, for alternative 5 = the volume 2151.09 yd³ \times 235.88 kg CO₂ eq/yd³ = 507413.993 kg CO₂ eq. The environmental impact will be adjusted accordingly for each alternative. Final results are indicated in Table 144. As illustrated, the values have different units. Therefore, these should be normalized to have consistent, unitless units that can be summed up altogether in the end. The normalization values used are illustrated in Table 152 .

The normalization can be performed through dividing the environmental impact per the normalization value. This can be accomplished by following Equation 2.

Normalized value = ImpactA/Normalization value for impactA

For example, the normalization value for the GWP for alternative 5 =

507413.993kg CO₂ eq/24000 kg CO₂eq = 21.14. All normalized values are illustrated in Table 152.

5.3.3.5 Transportation module

Transportation from the raw material extraction to the manufacturing phase. These are given per Athena Institute for each mix design. The values are given per 1 yd³. The values are illustrated in Table 153. These values should be adjusted to total design volume.

The adjustment process is illustrated in Table 148, which is performed by multiplying the values in Table 153 by the total design volume. For example, the adjusted GWP for alternative 5 = 23.040kg CO₂ eq/yd³×2151.09 yd³= 49562.32 CO₂ eq.

Part 2. Transportation impact from the raw material extraction to project location

To calculate the transportation impact from the raw material extraction to the project location, the distance between the manufacturers to project location first should be determined.

Table 147. Corresponding mix design

Alternative	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Water reducer (oz)	District	Initial cost (\$/yd ³)
1	517	0	1,235.00	1,332.00	450	30.9	23.23	Hammond	112
2	510	0	1,052.00	1,638.00	402	28.1	30.8	Lafayette	116
3	517	0	1,006.00	1,488.00	555	29.4	2.5	Lafayette	116
5	508	0	737	1,698.00	752	29.5	30.5	Shreveport	119
6	508	0	1,737.00	1,698.00	752	29.2	20.3	Shreveport	119
7	508	0	730	1,698.00	752	29.2	20.3	Shreveport	123

Table 148. Filtering criteria based on manufacturer location

Alternative	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Water reducer (oz)	Initial cost (\$/yd ³)
5	508	0	737	1,698.00	752	29.5	30.5	119
6	508	0	1,737.00	1,698.00	752	29.2	20.3	119
7	508	0	730	1,698.00	752	29.2	20.3	123

Table 149. Environmental impact extracted from EPD (A1 and A3)

Alternative	GWP kg CO ₂ eq/yd ³	ODP kg CFC-11 eq/yd ³	AP kg SO ₂ eq/yd ³	EP kg N eq/yd ³	POCP kg O ₃ eq/yd ³	NRE MJ/yd ³	RE MJ/yd ³
5	235.88	0.00	0.96	0.106	15.94	1681.57	190.54
6	237.33	0.00	0.97	0.107	16.18	1705.44	192.74
7	235.79	0.00	0.96	0.106	15.93	1679.69	190.53

Table 150. Adjusted environmental impact per volume

Alternative	GWP kg CO ₂ eq	ODP kg CFC- 11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
5	507413.99	0.007	2081.93	228.17	34300.04	3617239.26	409886.74
6	510531.18	0.007	2106.08	230.99	34807.80	3668574.88	414619.55
7	507207.73	0.007	2080.78	228.12	34285.62	3613183.16	409853.61

Table 151. Normalization values used

GWP (kg CO ₂ eq/ yd ³)	24000
ODP (kg CFC-11 eq/yd ³)	0.160
AP (kg SO ₂ eq/yd ³)	91
EP (kg N eq/yd ³)	22
POCP (kg O ₃ eq/yd ³)	1400
NRE (MJ/yd ³)	288572.509
RE (MJ/yd ³)	24874.54785

Table 152. Normalized value for adjusted environmental impact per total volume

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
5	21.14	0.043	22.87	10.37	24.50	12.53	16.47
6	21.27	0.045	23.14	10.50	24.86	12.71	16.66
7	21.13	0.043	22.86	10.36	24.49	12.52	16.47

Table 153. Transportation from raw material extraction to project location (A2)

Alternative	GWP kg CO ₂ eq/ yd ³	ODP kg CFC-11 eq/yd ³	AP kg SO ₂ eq/yd ³	EP kg N eq/yd ³	POCP kg O ₃ eq/yd ³	NRE MJ/ yd ³	RE MJ/ yd ³
5	23.04	0.00	0.16	0.009	4.64	315.90	0.00
6	28.94	0.00	0.20	0.011	5.69	396.93	0.00
7	22.98	0.00	0.16	0.009	4.63	315.10	0.00

Table 154. Adjusted transportation impact per design volume

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
5	49562.32	0.00	350.76	19.60	9985.03	679548.35	0.00
6	62271.30	0.00	431.08	24.08	12240.80	853839.53	0.00
7	49436.33	0.00	349.96	19.55	9962.74	677820.48	0.00

This can be accomplished by calculating the distance between the two zip codes of the project location, as well as the manufacturer location. The zip code of the project location is 71107, and the manufacturer zip codes are presented in the EPD for each mix design. Table 155 illustrates the project zip code, the manufacturer zip code, and the distance between the project and the manufacturer location (calculated through Google maps). Results in Table 155 indicate that the transportation values are almost the same, since the manufacturer is in the Shreveport area for all alternatives.

Table 155. Total transportation distance (manufacturer to project location)

Alternative number	Project location	Manufacturer location	Total distance (miles)	Total distance (km)
5	71107	71108	13	20.80
6	71107	71111	14	22.40
7	71107	71111	14	22.40

Moreover, the type of truck used to transport concrete must be identified, as well as the total weight to be transported. The transportation will be performed using a heavy duty truck with a weight of 80,000 lb and diesel fuel.

As previously described, the total weight to be transported combines the vehicle weight and the total weight of concrete to be transported. To get the total design weight for concrete, Equation 9 should be used. This can be accomplished through using Equation 9:

$$M = D \times L_v$$

For example, the density for alternative 5 = 4000.819 lb/yd³ and the total design volume = 2151.09 yd³; therefore, the total design weight = 4000.819 lb/yd³ × 2151.09 yd³ = 8606152.733 lb. Then this weight value should be converted to metric ton, which will be accomplished through multiplying the value by 0.00045359. Adjusted weight = 8606152.733 lb × 0.00045359 = 3903.66 ton

The total weight to be transported for each alternative is therefore the sum of the truck weight, as well as of the concrete transported. Final values are illustrated in Table 156. To get the total number of loads required, Equation 10 should be used.

$$\text{Total number of loads} = \text{total weight concrete designed} / \text{truck carrying capacity}$$

For example, for alternative 5, the total number of loads = 8606152.73 lb/54000 lb = 159.37 loads. For example, to calculate the transportation impact from the manufacturing to the project location for GWP, use alternative 5:

$$\text{Adjusted inventory values} = 2 \times 0.324 \text{ kg CO}_2/\text{ton.km} \times 3939.95 \text{ ton} \times 20.8 \text{ km} \times 159.37 = 8463394.48 \text{ kg CO}_2 \text{ eq. All values are illustrated in Table 158.}$$

Table 156. Weight of concrete to transport

Alternative number	Density (lb/yd ³)	Total weight per design volume of concrete (lb)	Total weight per design volume of concrete (ton)	Total number of loads	Total weight (truck+ concrete) (ton)
5	4000.81	8606152.73	3903.66	159.37	3939.95
6	3819.91	8217016.49	3727.15	152.16	3763.44
7	3812.92	8201966.88	3720.33	151.888	3756.61

Table 157. Heavy duty truck emissions

Global Warming Air kg CO ₂ eq	Ozone Depletion Air kg CFC-11 eq	Acidification Air kg SO ₂ eq	Eutrophication Water kg N eq	Smog Air kg O ₃ eq	Fossil Fuel Depletion MJ
3.24E-01	0.00E+00	1.34E-03	5.55E-04	4.62E-02	8.09E-02

Table 158. Transportation impact from the manufacturer to project location

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
5	8463394.48	0.00	35002.92	14497.48	1206817.36	2113236.46	0.00
6	8312446.63	0.00	34378.63	14238.91	1185293.31	2075546.08	0.00
7	8282172.25	0.00	34253.42	14187.05	1180976.41	2067986.83	0.00

Total transportation impact. The total transportation impact is the sum of Part 1 (transportation from raw material extraction to manufacturing) and Part 2 (transportation

from the manufacturer to project location). Values are illustrated in Table 159. These values should be normalized.

Table 159. Total transportation impact per alternative

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
5	8512956.80	0.00	35353.68	14517.08	1216802.40	2792784.81	0.00
6	8374717.94	0.00	34809.72	14263.00	1197534.11	2929385.62	0.00
7	8331608.58	0.00	34603.39	14206.61	1190939.16	2745807.32	0.00

To normalize the total transportation impact values, each value should be divided by the corresponding normalization value. For example, alternative 5 will have the following value after normalization (for GWP) = 8512956.80 kg CO₂ eq/ 24000 kg CO₂ eq = 354.707

The total transportation values are illustrated in Table 160 for the three alternatives.

Table 160. Normalized total transportation impact per alternative

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
5	354.707	0.00	388.502	659.867	869.14	9.67	0.00
6	348.947	0.00	382.524	648.318	855.38	10.15	0.00
7	347.150	0.00	380.257	645.755	850.67	9.51	0.00

5.3.3.6 Total environmental impact

The total environmental impact is the sum of the environmental impact coming from concrete design (EPD), as well as the total transportation impact (from raw material extraction to manufacturing and from manufacturing to project location). This will result from the values given in Table 161. For example, the environmental impact extracted from EPD and adjusted as based on design volume was previously described:

$$\begin{aligned} &\text{Environmental impact from EPD (adjusted per volume) + total transportation impact} \\ &= 507413.99 \text{ kg CO}_2 \text{ eq} + 8512956.80 \text{ kg CO}_2 \text{ eq} = 9020370.80 \text{ kg CO}_2 \text{ eq} \end{aligned}$$

Table 161. Total environmental impact per alternative

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
5	9020370.80	0.007	37435.62	14745.25	1251102.44	6410024.08	409886.74
6	8885249.12	0.007	36915.80	14493.99	1232341.92	6597960.51	414619.55
7	8838816.32	0.007	36684.18	14434.73	1225224.78	6358990.49	409853.61

These total environmental impacts need to be normalized. Values after normalization are illustrated in Table 162.

Table 162. Normalization values for the total environmental impacts

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
5	375.84	0.043	411.38	670.23	893.64	22.21	16.47
6	370.21	0.045	405.66	658.81	880.24	22.86	16.66
7	368.28	0.043	403.12	656.12	875.16	22.03	16.47

5.3.3.7 Weighing the environmental impact

Based on stakeholder preference, weighting can be assigned to the impacts. The weighting procedure will be used here for demonstration. Default weights were used for this case. The weights are illustrated in Table 163.

Table 163. Weights used in the study

GWP	ODP	AP	EP	POCP	NRE	RE	Total
0.200	0.150	0.150	0.150	0.150	0.100	0.100	1

The total environmental impact after the weighting process is illustrated in Table 164. Equation 3 can be used to convert the environmental impacts into weighted environmental impacts:

$$\text{Weighted impact} = \text{assigned weights} \times \text{normalized value}$$

For example, for alternative 5 = $375.84 \times 0.200 = 75.17$

At this point in time, the values are on the same scale due to normalization, which places all the values on the same scale, as well as unitless). The sum of all the environmental values

together is the environmental score per alternative, and then the RE value is deducted =
GWP+ODP+AP+POCP+NRE-RE

The relative score is the environmental impact score compared for each alternative, with respect to the other alternatives. This can be accomplished through Equation 14.

Score for environmental impact for each alternative =

Total environmental score for Alternative i / \sum Environmental impact for all alternatives.

For example, the score for alternative 5 = score for environmental impact for alternative 5/ sum of all scores = $372.03 / (372.03+366.38+364.38) = 0.337$

This equation was repeated for all other alternatives. Values are illustrated in Table 165. The alternative having the lowest score is the one that has the lowest environmental impact, which is alternative 7 in this case. When the stakeholder assigned a weight for the environmental score (which is the case, since the assigned weight is 0.5), then the final environmental score after adjusting the weight may be calculated using Equation 15.

When the stakeholder assigned a weight for the environmental score (which is the case , since the assigned weight is 0.5), then the final environmental score after adjusting the weight may be calculated using Equation 15.

Weighted environmental score per alternative

$EnvW \times \text{Score for environmental impact alternative } i$ for an alternative.

For example, for alternative 5, the weighted score = $0.5 \times 0.337 = 0.169$

Table 164. Total environmental impact after normalizing and weighting

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE	Total
5	75.17	0.007	61.70	100.53	134.04	2.22	1.64	372.03
6	74.04	0.007	60.85	98.82	132.03	2.28	1.66	366.38
7	73.65	0.007	60.46	98.41	131.27	2.20	1.64	364.38

Table 165. Relative score and environmental score

Alternative	Relative score	Assigning environmental score
5	0.337	0.169
6	0.332	0.166
7	0.330	0.165

5.3.3.8 Economic impact

As previously described, the economic analysis will be accomplished through performing a complete lifecycle cost analysis for each alternative. This lifecycle cost analysis consists of an initial present cost, and a maintenance and rehabilitation cost occurring in the future.

The maintenance and rehabilitations schedule is performed based on the Louisiana Department of Transportation and Development schedule, previously described in the literature review. This is indicated in Table 166. The analysis period is 50 years. The initial cost will start at year 0, then there will be a maintenance and rehabilitation cost at years 20 and 30 from the start date of the project.

Table 166. Lifecycle cost analysis based on the State of Louisiana

Project Type	Alternate	Year 0	Year 15	Year 20	Year 30	Year 50
Interstate New Construction	Rigid	New JPC Pavement	No Action	Clean/Seal Joints Patch 1% of Joints	Retexture Patch 3% of Joints	End of life No salvage value.

The initial cost for the selected mix designs is extracted from the database. These values include the profits, overheads, installation fees, etc. Notably, the initial cost exists for all the mix designs. However, there could be a problem associated with the maintenance and rehabilitation, since the mixes have been used for the past five years and therefore, these

mixes would not have maintenance and rehabilitation items associated with them. As for the initial cost items, the values are illustrated in Table 167. The letting date is provided, which can be used to calculate the net present value for this mix design, as well as to compare all mixes at the same point in time, such as the current year, 2017. This can be accomplished by using the net present value equation (Equation 4). For example, for alternative 5, the total price year 2017 = $201.60 (1 + 0.04)^5 = \$245.277$. A discount rate of 4% was used. All the values are illustrated in Table 168. To find the total cost per design volume, the cost should be adjusted per total volume = $\$245.277 \times 2151.097 \text{ yd}^3 = \527615.236 . The adjusted cost per total design volume is illustrated in Table 168.

As for the maintenance and rehabilitation items, the compressive strength value of the mix designs will be matched to the compressive strength value and /or mix design breakdown of older projects which have maintenance and rehabilitation activities, with an assumption that the newer projects will undergo the same maintenance and rehabilitation activities.

The process of selecting activities also will be illustrated. For example, the same item might occur in different districts, and therefore the unit price will vary. The perfect case would be to select the maintenance and rehabilitation activities that occurred in the same district. In the event there are no maintenance and rehabilitation activities that occurred in the same district, the user might select the lowest maintenance and rehabilitation activity from other districts

For alternative 5, the matched projects with associated compressive strength value is illustrated in Table 169. Should the projects have associated mix design breakdowns, these are also illustrated in Table 169, should the user select maintenance and rehabilitation items based on both the compressive strength value and the mix design breakdown. As illustrated in Table 170, the closest mix design breakdown is that of project 195-03-0029 (showing a tolerance up to 10%).

Table 167. Initial cost (bid price for each alternative)

Alternative number	Letting Date	Parish name	Item Description	Bid unit price per (yd ³)	Compressive strength value (psi)
5	11/14/2012	Caddo	Portland Cement Concrete Pavement (10" Thick)	\$201.60	5383
6	5/14/2014	Caddo	Portland Cement Concrete Pavement (9" Thick)	\$280.00	5043
7	6/11/2014	Webster	Portland Cement Concrete Pavement (13" Thick)	\$221.54	4730

Table 168. Initial cost items per alternative

Alternative number	Letting date	Parish name	Item description	Bid unit price at letting date (yd ³)	Bid unit price at current year, 2017 (\$/yd ³)	Bid unit price adjusted per total design volume at current year, 2017 (\$/design)
5	11/14/2012	Caddo	Portland Cement Concrete Pavement (10" Thick)	\$201.60	245.277	527615.236
6	5/14/2014	Caddo	Portland Cement Concrete Pavement (9" Thick)	\$280.00	314.961	677513.812
7	6/11/2014	Webster	Portland Cement Concrete Pavement (13" Thick)	\$221.54	249.200	536058.607

Depending on data availability, the maintenance and rehabilitation items are illustrated in Table 171. However, Projects 451-01-0108, 195-03-0029, and 455-09-0024, did not show any maintenance and rehabilitation activities (all the items shown were related to initial cost items for rigid pavements). Therefore, the user should select maintenance and rehabilitation activities from other projects, with available maintenance and rehabilitation items.

Table 169. Projects associated with the selected compressive strength value alternative 5

Compressive strength value (psi)	Project ID	Mix design available?
5383	H.000792.6	No
5383	H.010351.6	No
5283	H.010487.6	No
5700	195-03-0029	Yes
5500	020-08-0015	Yes
5620.51	455-09-0024	Yes

Table 170. Matching compressive strength value alternative 5

Proposal ID	Compressive strength value (psi)	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Air entertainer (%)
195-03-0029	5700	436	109	1097	404	1293	34.6	4
455-09-0024	5620.51	420	109	1437	1300	415	26	1.5
020-08-0015	5500	508	0	1397	1750	0	29	1.5

As illustrated in Table 171, none of the maintenance and rehabilitation options occurred in the Shreveport district. Therefore, the user has an option to select the maintenance and rehabilitation items from any other district. One option is to select the lowest maintenance and rehabilitation items. For example, there are three costs for the saw cutting which occur in three different districts. Since none of them is in the Shreveport district, the user can select the lowest cost based on net present value at year 2017. In this instance, the maintenance and rehabilitation item occurring in Hammond district, is the lowest in cost and the one selected.

In alternative 6, there are only projects that matched the compressive strength values and none matched the mix design breakdown. Therefore, these will be the items from which to select the maintenance and rehabilitation activities. Associated projects are illustrated in Table 171. As illustrated in Table 171, should there be the same maintenance and rehabilitation activities in various districts, the user can select the lower item. Selected items by the user will have the year of occurrence next to them.

In alternative 7, only projects that matched the compressive strength values are shown; none matched the mix design breakdown. Therefore, these will be the items from which to select the maintenance and rehabilitation activities. Associated projects are illustrated in Table 174.

The maintenance and rehabilitation items associated with Shreveport district are first to be selected. The remainder is selected from other districts, as illustrated in Table 175.

5.3.3.9 Final weight for the economic impact

The economic impact will be performed using initial cost and maintenance and rehabilitation cost. Values for each alternative are illustrated in Tables 176 and 177. There are two scenarios here. The first scenario is to calculate the total cost with respect to the initial cost, pertaining to the material only, and then add the maintenance and rehabilitation cost item. In this case, alternative 7 has the lowest cost. To assign the economic score, this can be accomplished through Equation 16.

Score for economic impact for alternative = net present value for this alternative/net present value for all alternatives or = $\frac{NPV_i}{\sum NPV_a}$

For example, for alternative 5, the resulting score
 $260931.07/(260931.07+263839.20+453914.01) = 0.266$

Table 171. Maintenance and rehabilitation activities for matching projects alternative 5

Proposal number and district	Letting date	Item description	Price at letting date per unit	Unit	Net present value (\$) (2017)	Year of occurrence	Cost at year of occurrence (\$)
H.000792.6 (Alexandria)	6/24/2015	Saw Cutting Portland Cement Concrete Pavement	5	INLF	5.408		
H.010351.6 (Lafayette)	10/8/2014	Saw Cutting Portland Cement Concrete Pavement	1	INLF	1.12		
H.010487.6 (Alexandria)	9/10/2014	Cleaning and Sealing Random cracks	3643.08	Mile	4097.97	2037	8979.16
H.010487.6 (Alexandria)	9/10/2014	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	377.96	Yd ³	425.16	2047	1378.97
H.010487.6 (Alexandria)	9/10/2014	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	377.96	Yd ³	425.16	2037	931.58
020-08-0015 (Hammond)	4/8/2015	Saw Cutting Portland Cement Concrete Pavement	1	INLF	1.08	2037	2.36
020-08-0015 (Hammond)	4/8/2015	Saw Cutting Portland Cement Concrete Pavement	1	INLF	1.08	2047	3.50
Net present value at 2017 for selected items					4950.465		

Table 172. Projects associated with the selected compressive strength value alternative 6

Compressive strength value (psi)	Project ID	Mix design available?
5043	H.010360.6	No
5300	H.012094.6	No
5500	H.009598.6	No

Table 173. Maintenance and rehabilitation items for alternative 6

Proposal number and district	Letting date	Item description	Price at letting date per unit	Unit	Net present value (\$) (2017)	Year of occurrence	Cost at year of occurrence (\$)
H.010360.6 (Alexandria)	2/25/2015	Cleaning and Sealing Random Cracks.	6335.79	Mile	6852.79	2037	15015.32
H.010360.6 (Alexandria)	2/25/2015	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	464.36	Yd ³	502.25	2047	1629.01
H.010360.6 (Alexandria)	2/25/2015	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	464.36	Yd ³	502.25	2037	1190.30
H.010360.6 (Alexandria)	2/25/2015	Saw Cutting Portland Cement Concrete Pavement	0.6	INLF	0.64	2037	1.42
H.010360.6	2/25/2015	Saw Cutting Portland	0.6	INLF	0.64	2047	2.10

Table 173 (cont.)

Proposal number and district	Letting date	Item description	Price at letting date per unit	Unit	Net present value (\$) (2017)	Year of occurrence	Cost at year of occurrence (\$)
(Alexandria)		Cement Concrete Pavement					
H.012094.6 (Hammond)	6/22/2016	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	3522.51	Yd ³	3663.4		
H.009598.6 (Baton Rouge)	5/27/2015	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (9" Thick)	1257.83	Yd ³	1360.47		
H.009598.6 (Baton Rouge)	5/27/2015	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (12" Thick)	486.20	Yd ³	525.87		
Net present value at 2017 for selected items					7858.60		

Table 174. Projects associated with the selected compressive strength value alternative 7

Compressive strength value (psi)	Project ID	Mix design available?
4730	H.001263.6-R1	No
5100	H.009539.6	No
4900	H.009574.6	No
5150	H.003200.6	No

Table 175. Maintenance and rehabilitation activities for alternative 7

Proposal number and district	Letting date	Item description	Price at letting date per unit	Unit	Net present value (\$) (2017)	Year of occurrence	Cost at year of occurrence (\$)
H.001263.6-R1 (Alexandria)	7/24/2013	Cleaning and Sealing Random Cracks	160934.44	Mile	188270.54	2037	412523.94
H.009539.6 (Alexandria)	3/12/2014	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	395.96	Yd ³	445.41		975.94
H.009539.6 (Alexandria)	3/12/2014	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	395.96	Yd ³	445.41		1444.64
H.009574.6 (Shreveport)	5/14/2014	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	467.96	Yd ³	526.39	2037	1153.39

Table 175 (cont.)

Proposal number and district	Letting date	Item description	Price at letting date per unit	Unit	Net present value (\$) (2017)	Year of occurrence	Cost at year of occurrence (\$)
H.009574.6 (Shreveport)	5/14/2014	Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	467.96	Yd ³	526.39	2047	1707.30
H.003200.6 (Lake Charles)	5/13/2015	Saw Cutting Portland Cement Concrete Pavement	2.63	INLF	2.84	2037	6.23
H.003200.6 (Lake Charles)	5/13/2015	Saw Cutting Portland Cement Concrete Pavement	2.63	INLF	2.84	2047	9.22
Net present value at 2017 for selected items					189329.02		

In assigning an economic score for this study case, there is an economic score of 0.5; the final economic score after assigning the economic score can be calculated using Equation 17.

$$\text{EconW} \times \text{Score for Economic impact alternative } i$$

Economic score for alternative 5 = $0.266 \times 0.5 = 0.133$. The best alternative is alternative 5 (lowest score) in both cases (material only or overall bid item material)

Table 176. Cost analysis for alternatives (scenario 1)

Alternative	Initial cost (material)	Maintenance and rehabilitation item	Total (\$/design)	Weighted	Assigning economic score
5	255980.60	4950.465	260931.07	0.266	0.133
6	255980.60	7858.60	263839.20	0.269	0.134
7	264584.99	189329.02	453914.01	0.463	0.231

Table 177. Cost analysis for alternatives (scenario 2)

Alternative	Initial cost (overall)	Maintenance and rehabilitation item	Total (\$/design)	Weighted	Assigning economic score
5	527615.23	4950.465	532565.70	0.274	0.137
6	677513.81	7858.60	685372.41	0.352	0.176
7	536058.60	189329.02	725387.62	0.373	0.186

5.3.3.10 Total sustainability score

The total score can then be calculated using Equation 18:

overall final sustainability score = weighted economic score for alternative + weighted environmental impact for alternative. All the resulting values are illustrated in Table 178. Alternative 5 has the lowest total sustainability score in both scenarios.

Table 178. Total score

Alternative	Economic score		Environmental score	Total score	
	Scenario 1	Scenario 2		Scenario 1	Scenario 2
5	0.133	0.137	0.169	0.302	0.306
6	0.134	0.176	0.166	0.30	0.342
7	0.231	0.186	0.165	0.396	0.351

5.3.3.11 Statistical analysis

To be able to compare statistical significance of the results, another EPD will be used to assess the environmental impact. Note that the economic impact cannot be compared

because cost data does not exist for states other than Louisiana. A compressive strength value of 4400, 5000 and 6000 psi will be used to evaluate the following environmental impact/inventory values: GWP, ODP, AP, EP, POCP, RE and NRE.

The scope will include the following stages: raw material extraction, transportation from raw material extraction to manufacturing, manufacturing, and transportation from manufacturing to project location. The total environmental score will be compared, since the breakdown for EPD is not available for states other than Louisiana. The same procedure will be followed to evaluate the total environmental impact with the same assumptions, only raw data from EPD will change. The raw data used, extracted from EPD, for compressive strength value of 4400 psi are illustrated in Table 179, as a sample. These are the same samples selected for Hammond parish

Table 179. Total environmental impact per alternative

Alternative	GWP kg CO ₂ eq/ yd ³	ODP kg CFC-11 eq/ yd ³	AP kg SO ₂ eq/ yd ³	EP kg N eq/ yd ³	POCP kg O ₃ eq/ yd ³	NRE MJ/ yd ³	RE MJ/ yd ³
5A	305.83	3.51E-06	1.69	0.05	24.31	1673.67	12.54
6B	262.25	3.07E-06	1.48	0.04	21.48	1488.64	10.77
7C	255.37	2.97E-06	1.44	0.04	21.25	1433.59	10.57
Average	274.48	3.18E-06	1.54	0.04	22.35	1531.97	11.29

Final results for the environmental score are illustrated in Table 180. To better understand the data used, descriptive statistics is illustrated in Table 181, including the mean, the standard deviation, and confidence interval. To evaluate results significance, analysis of variance (ANOVA) is performed with a confidence interval of 95%. The resulting P value =1 (> 0.001 indicating insignificance of the results).

Table 180. Environmental impact comparison

Alternative	Environmental score (Louisiana)	Environmental score (4400 psi)	Environmental score (5000 psi)	Environmental score (6000 psi)
5	0.169	0.1696	0.1675	0.1659
6	0.166	0.1656	0.1683	0.1668
7	0.165	0.1648	0.1642	0.1674
Mean	0.166667	0.166667	0.166667	0.1667
Standard deviation	0.002082	0.002572	0.002173	0.000755

Table 181. Descriptive statistics for the environmental impact values

Criteria	Louisiana data	4400 psi	5000 psi	6000 psi
Mean	0.166667	0.166667	0.166667	0.1667
Standard error	0.001202	0.001485	0.001255	0.000436
Median	0.166	0.1656	0.1675	0.1668
Standard deviation	0.002082	0.002572	0.002173	0.000755
Sample variance	4.33E-06	6.61E-06	4.72E-06	5.7E-07
Skewness	1.293343	1.545393	-1.47178	-0.58558
Range	0.004	0.0048	0.0041	0.0015
Minimum	0.165	0.1648	0.1642	0.1659
Maximum	0.169	0.1696	0.1683	0.1674
Sum	0.5	0.5	0.5	0.5001
Count	3	3	3	3
Confidence level (95.0%)	0.005171	0.006388	0.005399	0.001875

Table 182. Analysis of variance results

Source of Variation	SS	df	MS	F	P-value	F critical
Between Groups	2.5E-09	3	8.33E-10	0.000205	1	4.066181
Within Groups	3.25E-05	8	4.06E-06			
Total	3.25E-05	11				

5.3.3.12 Sensitivity analysis

Sensitivity analysis is an important criteria in decision making. Sensitivity analysis should determine the sensitivity of an output to a change in input, while keeping all the other alternatives constant. In this section, sensitivity analysis will be performed to evaluate how

the change in the following criteria affects the total environmental impact for each alternative.

- 1) Environmental impact of raw material extraction and manufacturing (reported from EPD)
- 2) Environmental impact of transportation
 - a) From raw material extraction to manufacturing (from EPD)
 - b) From manufacturing to project location
 - c) Total environmental impact of transportation from raw material extraction to manufacturing and from manufacturing to project location
- 3) Impact of total distance traveled from raw material extraction to project location.

The sensitivity levels that will be evaluated by an increase of 10% in the previous factors.

Final results are illustrated in Table 183

Table 183. Sensitivity analysis and final environmental impact

Criteria	Change on total environmental impact (%)
Environmental impact of raw material extraction and manufacturing (reported from EPD)	0.341
Environmental impact of transportation (from raw material extraction to manufacturing)	0.071
Environmental impact of transportation (from manufacturing to project location), by changing the inventory values/environmental impact of heavy duty truck	9.587
Total distance traveled from manufacturing to project location	9.587
Environmental impact of total transportation module (transportation from raw material extraction to manufacturing and from manufacturing to project location)	9.658

By further interpretation for the results illustrated in Table 183, it is clear that the final environmental impacts are highly altered by changing criteria in the transportation module: either in changing the environmental impact of the transportation stage from manufacturing to project location, by changing the total distance traveled from manufacturing to project location, or by changing the total environmental impact of transportation (transportation from raw material extraction to manufacturing and from manufacturing to project location).

As for changing raw material extraction and manufacturing stages of concrete, changing these criteria did not change the total environmental impact compared to the transportation stages. This example illustrates the importance of the transportation module and proves that it represents a sensitive criteria towards the total environmental impact.

5.3.4 CASE STUDY 4: BENCHMARKING MODULE

The same case study will be performed using the benchmarking module for illustration. A step by step procedure will be displayed. The same procedure and format will be followed in this module.

5.3.4.1 Environmental impact

1. Select the state you want to use the mix design: The state is Louisiana.
2. The purpose of the design is benchmarking. The stakeholder is interested in benchmarking the product, and wants to know whether the product is below or above the average.
3. Select the number of products to benchmark: The stakeholder might choose to benchmark the product with respect to various criteria, including a certain region for example, either with respect to the Shreveport district or with respect to a specific parish. Also, the user might want to measure the cost of the product to know whether the product is above or below the market average.

4. Assign weights for the environmental and economic impacts. Both impacts will be assigned a weight of 0.5.

5. Convert the modulus of rupture to compressive strength value, using Equation 8, where:

$$\text{MOR (psi)} = 2.3 (f_c)^{2/3} \text{ or } f_c = (\text{MOR}/2.3)^{3/2}.$$

This results in a compressive strength value of $(600/2.3)^{3/2} = 4213$ psi

6. Select alternative mixes from the EPD data, to evaluate the environmental impact. The user enters a specific mix design (required by the design) to look for its environmental impact in the database. The stakeholder is interested in getting cement content around the 500 lb value. The mixes are illustrated in Table 184. The same procedure used in alternative design comparison will be applied here.

Table 184. Required mix design

Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Air entertainer (%)
500	100	1501	1520	750	29	3

This exact mix design is not in the database; therefore, the stakeholder can select from among the existing mixes. The nearest mixes, based on the cement amount, are illustrated in Table 185. In Table 185, there are various mix designs that appear. There should be some filtering criteria for the stakeholder. For example, one of the filtering criteria can show the proximity to project location. The user will select the benchmark for the product with respect to all the mixes produced in the Shreveport district.

This narrows down the mixes to options 5, 6, and 7 (based on user selection). The new selections are illustrated in Table 186. Now the design will proceed with the average results and not with the individual mix designs. The average value was calculated, using Equation 19.

$$\text{Benchmarking} = \sum \text{environmental impact} / \text{total number of mixes}$$

In case the user wants to benchmark his product with respect to the Shreveport district, the average cement content in the mix designs is around 508 lb, and the fly ash is around 0 lb. The average price for the mixes in this area is \$120.33. All values are illustrated in Table 186.

The environmental impact of the mixes 5, 6, and 7 are illustrated in Table 187. These are the values extracted from EPD, with no modifications. Values showing the environmental impact values will be averaged, and the design will proceed with the average value. This is one of the differences between the alternative design module and the benchmarking module. As illustrated, the values are given per 1 yd³. These are the impacts for A1: raw material extraction and A3: manufacturing.

These values are given per 1 yd³; some adjustments must be performed to adjust the environmental impacts per the total design volume.

The total design volume calculation is illustrated in Table 188 for the 11 inch thickness. The calculation was performed using Equation 6: $L_v = L_T \times L_W \times L_L$. This step remains the same, since the design will not change.

The total environmental impact for the design then should be adjusted according to the overall design volume, using Equation 7.

Environmental impact reported from EPD \times L_v

For example, the total adjusted GWP for the average value is:

Which means the volume $2151.09 \text{ yd}^3 \times 236.34 \text{ kg CO}_2 \text{ eq/yd}^3 = 508384.304 \text{ kg CO}_2 \text{ eq}$

The environmental impact will be adjusted accordingly for each alternative. Final results are indicated in Table 189.

As illustrated, the values have different units. Therefore, these should be normalized to have consistent, unitless units that can be summed up altogether in the end.

Table 185. Corresponding mix design

Alternative	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Water reducer (oz)	District	Initial cost (\$/yd ³)
1	517	0	1235.00	1332.00	450	30.9	23.23	Hammond	112
2	510	0	1052.00	1638.00	402	28.1	30.8	Lafayette	116
3	517	0	1006.00	1488.00	555	29.4	2.5	Lafayette	116
4	545	0	1445.00	390	1446.00	28.8	21.8	New Orleans	155
5	508	0	737	1698.00	752	29.5	30.5	Shreveport	119
6	508	0	1737.00	1698.00	752	29.2	20.3	Shreveport	119
7	508	0	730	1698.00	752	29.2	20.3	Shreveport	123

Table 186. Filtering criteria based on manufacturer location

Alternative	Cement (lb)	Fly ash (lb)	Fine aggregate (lb)	Coarse aggregate 1 (lb)	Coarse aggregate 2 (lb)	Mixing water (gallons)	Water reducer (oz)	District	Initial cost (\$/yd ³)
5	508	0	737.00	1698.00	752	29.5	30.5	Shreveport	119
6	508	0	1737.00	1698.00	752	29.2	20.3	Shreveport	119
7	508	0	730.00	1698.00	752	29.2	20.3	Shreveport	123
Average	508	0	1698.00	1698.00	752	29.300	23.700	Shreveport	120.33

Table 187. Environmental impact extracted from EPD (A1 and A3)

Alternative	GWP kg CO ₂ eq/yd ³	ODP kg CFC-11 eq/yd ³	AP kg SO ₂ eq/yd ³	EP kg N eq/yd ³	POCP kg O ₃ eq/yd ³	NRE MJ/yd ³	RE MJ/yd ³
5	235.88	3.23E-06	0.96	0.10	15.94	1681.57	190.54
6	237.33	3.34E-06	0.97	0.10	16.18	1705.44	192.74
7	235.79	3.23E-06	0.96	0.10	15.93	1679.69	190.53
Average	236.34	3.27E-06	0.97	0.11	16.02	1688.90	191.28

Table 188. Final layer volume

Dimension	Value	Unit	Unit conversion	Final unit
Layer Thickness	11	Inch	1/36	Yd
Length	1	Mile	1760	Yd
Width	12	Feet	0.33	Yd
Total volume			2151.09	Yd ³

Table 189. Adjusted environmental impact per volume

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
Average	508384.30	0.007	2089.60	229.09	34464.49	3632999.10	411453.30

The normalization values used are illustrated in Table 190. This step is the same as previously noted.

Table 190. Normalization values used

GWP (kg CO ₂ eq/ yd ³)	24000
ODP (kg CFC-11 eq/ yd ³)	0.160
AP (kg SO ₂ eq/ yd ³)	91
EP (kg N eq/ yd ³)	22
POCP (kg O ₃ eq/ yd ³)	1400
NRE (MJ/ yd ³)	288572.509
RE (MJ/ yd ³)	24874.54785

The normalization can be performed by dividing the environmental impact per the normalization value. This can be accomplished by following Equation 2.

$$\text{Normalized value} = \text{Impact}_A / \text{Normalization value for impact}_A$$

For example, the normalization value for the GWP for the average value is:

508384.304kg CO₂ eq/24000 kg CO₂ eq = 21.183. Final normalization values are indicated in Table 191.

Table 191. Normalized value for adjusted environmental impact per total volume

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
Average	21.183	0.044	22.963	10.414	24.617	12.590	16.541

5.3.4.2 Transportation impact

Transportation from the raw material extraction to the manufacturing phase. These are given per Athena Institute for each mix design. The values are given per 1 yd³. The values are illustrated in Table 192. These values should be adjusted to total design volume. Since this is the benchmarking module, the average value is computed to work as necessary.

Table 192. Transportation from raw material extraction to manufacturing (A2)

Alternative	GWP kg CO ₂ eq/ yd ³	ODP kg CFC-11 eq/yd ³	AP kg SO ₂ eq/yd ³	EP kg N eq/yd ³	POCP kg O ₃ eq/yd ³	NRE MJ/ yd ³	RE MJ/ yd ³
5	23.040	8.76E-10	0.163	0.0091	4.64	315.90	0.00
6	28.948	1.10E-09	0.200	0.0111	5.69	396.93	0.00
7	22.981	8.74E-10	0.162	0.0090	4.63	315.10	0.00
Average	24.99	9.50E-10	0.18	0.01	4.99	342.65	0.00

The adjustment process is illustrated in Table 193, which is performed by multiplying the values in Table 192 by the total design volume. For example, the adjusted GWP for the average alternative = 24.99 kg CO₂ eq/ yd³ × 2151.09 yd³ = 53756.655kg CO₂ eq. The final values are illustrated in Table 193.

Table 193. Adjusted transportation impact per design volume

GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
53756.65	0.00	377.27	21.08	9985.03	737069.46	0.00

Part 2 Transportation impact from the raw material extraction to project location

To calculate the transportation impact from the raw material extraction to project location, the distance between the manufacturers to project location should be determined. This can be accomplished through calculating the distance between the two zip codes: the zip code of the

project location, as well as the manufacturer zip code. The zip code of the project location is 71107, and the manufacturer zip codes are user input, as indicated in Table 194. The distance can be calculated using Google maps. Results in Table 194 indicate that the transportation values are similar, since the manufacturer is in the Shreveport area for all alternatives. The average transportation distance is 31.66 miles or 21.86 kms. The average distance will be used.

Table 194. Total transportation distance (manufacturer to project location)

Alternative number	Project location	Manufacturer location	Total distance (miles)	Total distance (km)
5	71107	71108	13	20.80
6	71107	71111	14	22.40
7	71107	71111	14	22.40
Average			13.66	21.86

Also, the total weight to be transported should be identified. The transportation will be performed using a heavy duty truck with a weight of 80,000 lb and diesel fuel. The average weight of concrete to be transported is illustrated in Table 195. These values exist in the database (originally gathered from the manufacturer). As previously described, the total weight to be transported is the vehicle weight and the total weight of concrete to be transported.

This can be accomplished through using Equation 9: $M = D \times L_v$

For example, the density for the average alternative = 3877.89 lb/yd³ and the total design volume = 2151.09 yd³; therefore, the total average design weight = 3877.89 lb/yd³ × 2151.09 yd³ = 8341712.04 lb. Then this weight value should be converted to metric ton, which will be accomplished by multiplying the value by a factor of 0.00045359

The average concrete weight to be transported = 8341712.04 lb × 0.00045359 = 3783.72 ton.

The total weight to be transported for the average alternative is therefore the sum of the truck weight, as well as the average concrete transported. To obtain the total number of loads required to transport the total concrete, Equation 10 should be used

Total number of loads = total weight concrete designed/ truck carrying capacity

=8341712.04 lb/54000 lb = 154.5 loads

Table 195. Weight of concrete to transport

Alternative number	Density (lb/yd ³)	Total weight per design volume of concrete (lb)	Weight of concrete (ton)	Truck weight (ton)	Total number of loads	Total weight (truck+ concrete) (ton)
Average	3877.89	8341712.04	3783.72	36.28	154.5	3820

To adjust the inventory values coming from the transportation module, Equation 11 should be used:

$2 \times \text{Emissions of each truck} \left(\frac{\text{kg}}{\text{ton.km}} \right) \times \text{total weight transported (truck weight (ton) + weight of concrete transported (ton))} \times \text{total distance (km)} \times \text{total number of trucks}$

The emissions/ inventory for the heavy duty truck is illustrated in Table 196.

Table 196. Heavy duty truck emissions

Global Warming Air kg CO ₂ eq	Ozone Depletion Air kg CFC-11 eq	Acidification Air kg SO ₂ eq	Eutrophication Water kg N eq	Smog Air kg O ₃ eq	Fossil Fuel depletion MJ
3.24E-01	0.00E+00	1.34E-03	5.55E-04	4.62E-02	8.09E-02

For example, to calculate the transportation impact from the manufacturing to the project location for GWP, Adjusted inventory values = $2 \times 0.324 \text{ kg CO}_2/\text{ton.km} \times 3820 \text{ ton} \times 21.86 \text{ km} \times 154.5 = 8361475.1 \text{ kg CO}_2 \text{ eq}$. Values are illustrated in Table 197.

Total transportation impact. The total transportation impact is the sum of Part 1 (transportation from raw material extraction to manufacturing) and Part 2 (transportation from the manufacturer to project location). Values are illustrated in Table 198. These values should be added and then normalized.

To normalize the total transportation impact values, each environmental impact should be divided by the corresponding normalization value. For example, the average mix

design will have the following value after normalization (for GWP) = 8415231.83 kg CO₂ eq/ 24000 kg CO₂ eq =350.63 .The total transportation values are illustrated in Table 199 for the three alternatives.

5.3.4.3 Total environmental impact

The total environmental impact is the total of the environmental impact coming from concrete design (EPD), as well as the total transportation impact (from raw material extraction to manufacturing and from manufacturing to project location). This will result from the values given in Table 200. For example, the environmental impact extracted from EPD and adjusted based on design volume was previously described:

Environmental impact from EPD (adjusted per volume) + total transportation impact
= 508384.30kg CO₂ eq + 8415231.83CO₂ eq =8923616.13kg CO₂. These total environmental impacts must be normalized. Values after normalization are illustrated in Table 201.

5.3.4.4 Weighing the environmental impact

Based on stakeholder preference, weighting can be assigned to the average environmental impacts. The weighting procedure will be used here for demonstration. The weights used are illustrated in Table 197.

Table 197. Transportation impact from the manufacturer to project location

Alternative	GWP kg CO ₂ eq	ODP kg CFC- 11 eq	AP kg SO ₂ - eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
Average	8361475.17	0.00	34581.40	14322.89	1192284.42	2087788.09	0.00

Table 198. Total transportation impact per alternative

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
Average	8415231.83	0.00	34958.68	14343.97	1202269.46	2824857.55	0.00

Table 199. Total normalized transportation impact per alternative

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
Average	350.63	0.00	384.16	651.99	858.76	9.78	0.00

Table 200. Total environmental impact per alternative

Alternative	GWP kg CO ₂ eq	ODP kg CFC-11 eq	AP kg SO ₂ eq	EP kg N eq	POCP kg O ₃ eq	NRE MJ	RE MJ
Average	8923616.13	0.007	37048.28	14573.07	1236733.95	6457856.66	411453.30

Table 201. Normalization values for the total environmental impacts

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE
Average	371.817	0.044	407.124	662.413	883.381	22.379	16.541

Table 202. Weights used in the study

GWP	ODP	AP	EP	POCP	NRE	RE	Total
0.200	0.150	0.150	0.150	0.150	0.100	0.100	1

The sum of all the environmental values together is the total environmental score for the average impact, minus the RE value. $GWP+ODP+AP+POCP+NRE-RE = 367.8$

Here the relative score does not exist, since the average value is taken. Values are illustrated in Table 203. In the event the stakeholder assigned a weight for the environmental score (since the assigned weight is 0.5), then the final environmental score after adjusting per the weight may be calculated using Equation 15. The weighted environmental score per alternative =

EnvW × Score for environmental impact alternative i

For example, for the average alternative, the weighted score = $0.5 \times 367.892 = 183.946$

Calculations are illustrated in Table 203.

Table 203. Total environmental impact after normalizing and weighting

Alternative	GWP	ODP	AP	EP	POCP	NRE	RE	Total
Average	74.363	0.007	61.069	99.362	132.507	2.238	1.654	367.89

5.3.4.5 Economic impact

As previously described, the economic analysis will be accomplished by performing a complete lifecycle cost analysis for each alternative. This was calculated earlier in the alternative design module. However, while values will not be treated individually, the average will be taken for the benchmarking module. As illustrated in Tables 204 and 205, the

average material cost adjusted to total design volume is \$258,848.73, and the total initial cost (as a bid item) is \$58,0395.88. The average cost for each maintenance and rehabilitation activities is illustrated per activity in Table 204, 205, and 206. The stakeholder can benchmark with respect to these values.

Table 204. Cost analysis for alternatives (scenario 1)

Alternative	Initial cost (material)
5	255980.60
6	255980.60
7	264584.99
Average	258848.73

Table 205. Cost analysis for alternatives (scenario 2)

Alternative	Initial cost (overall)
5	527615.23
6	677513.81
7	536058.60
Average	580395.88

Table 206. Average maintenance and rehabilitation activities

Item	Design 5 (\$)	Design 6 (\$)	Design 7 (\$)	Average (\$)
Full Depth Patching of Jointed Concrete Pavement (16.1 square yards to 48.0 square yards) (10" Thick)	425.16	502.25	526.39	484.6/ Yd ³
Cleaning and Sealing Random Cracks	4097.97	6852.79	188270.54	66407.1/ Mile
Saw Cutting Portland Cement Concrete Pavement	1.08	0.64	2.84	1.52/ INLF

5.4 SUMMARY

- This chapter presented various case studies in various states/climatic regions to test the newly developed framework. The software was used for both alternative designs comparison and benchmarking.
- For alternative designs comparison, the data associated with each state was used (For example, for Texas, the EPD data associated with the State of Texas was used and the

Pavement ME software was calibrated for the State of Texas, with the same approach followed same for the State of Louisiana, etc...).

- For benchmarking; the user can select any region and benchmark his product with respect to it. He can also filter the database with respect to many criteria. such as the compressive strength value and the mix design breakdown.

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CHAPTER 6. FINDINGS, CONCLUSION, DISCUSSION, AND FUTURE WORK

The objective for this study was to develop a decision making tool to evaluate rigid pavement design sustainability (applying two pillars of environmental and economic criteria) for the State of Louisiana. The scope is inclusive of cradle to gate, as well as the transportation stage from the manufacturer to project location.

To achieve this objective, the first question was how to integrate the sustainability criteria, since the existing framework contains no sustainability criteria. This involved a change to the original rigid pavement design framework in order to enable the inclusion of a new factor.

To evaluate the environmental aspect of sustainability, an extensive literature review was performed. The most widely used tool to evaluate the environmental impact of a product is LCA. However, LCA has various drawbacks. When applied by various researchers in an inconsistent way, a lack of comparability arises, due to reasons such as the use of a different system boundary, different geographic locations, or different data sources. These unforeseen inconsistencies can lead to an incomparability across studies.

To solve this issue, this study used data from EPD. EPD is defined as quantified environmental data for a product, based on a pre-set category of parameters, which in turn were established to homogenize assumptions while performing an LCA. In fact, EPDs follow the same LCA procedure for quantifying the environmental impact. However, the method used to issue an EPD guarantees consistency in the data collection process, thus enabling a comparison between products fulfilling the same function.

To evaluate the economic impact, cost data was collected for the State of Louisiana in order to perform a full lifecycle cost analysis. This involved collecting costs occurring at the present (mostly material costs), as well as maintenance and rehabilitation cost items occurring in the future. The initial cost was collected from manufacturers, and the

maintenance and rehabilitation items were collected from LaDOTD. To evaluate the Transportation impact from the manufacturer to project location, a Lifecycle inventory for various types of trucks and fuel was used, and an LCA was performed to evaluate the environmental impact. Additionally, to facilitate the use and querying of all data, these data were stored in a database format. A new software/tool was developed with a simple user interface to facilitate data manipulation.

The developed software follows the methodology of the framework, as previously illustrated. The software can accommodate work on two modules; the first module is the product comparison module, while the second module is the benchmarking module. The product comparison module enables the comparison of various products based on economic and environmental scores. The stakeholder can then select the product based on a weighted average between the environmental and economic criteria. Moreover, the benchmarking module enables the user to benchmark the product with respect to various criteria, such as mix design breakdown, compressive strength value, or a certain geographic location.

The developed framework/tool also has other applications, which form a bigger picture, such as accounting, decision making, and process improvement. The accounting method is the process of measurement for the sake of reporting. This is mostly used to respond to laws and mandates requiring quantifications of emissions, such as the cap and trade legislation. Both modules (product comparison and benchmarking) can aid the accounting method. For example, the product comparison module may help to quantify the total emissions released during concrete production which at times are required by law, such as the California mandate.

Moreover, the benchmarking module can help the user to measure the impact of the product with respect to the market average. By benchmarking, the user can then lower the

emissions, in case such emissions exceed the average limit. Also, the benchmarking module will allow the stakeholder to benchmark the product for certification for the LEED credit.

Also, the developed framework works for process improvement. The benchmarking module allows the stakeholder to benchmark the product with respect to similar products (such as similar compressive strength value, mix design breakdown, or geographic location), in order to find whether the environmental impact of the product is below or above the average. In the event the product is above average, more process improvement should be performed to achieve a lower environmental impact. An improvement might involve the use of more advanced technology, or more research and development

The study performed various case studies in different locations to validate the framework. Case studies included the State of Texas and the State of Louisiana. The framework was used in both the benchmarking module and the product comparison module. For the product comparison module, the framework was used to evaluate the sustainability score for various mix designs based on a single sustainability score. By examining the total score, one could estimate which product has higher or lower environmental and/or economic impact. However, by evaluating results significance at a confidence interval of 95%, the final sustainability scores proved to be insignificant. This was based on a sample size of three. However, these values might change by changing the sample size or the database used. For this reason, descriptive statistics were also provided including a confidence interval, to allow the user to make a decision.

Also, to answer the research questions of this study, the framework was used to test how sensitive the total environmental impact of a product (from cradle to gate and the transportation stage from manufacturing to project location) would be, in regard to the transportation stage vs. changing the environmental impact coming from raw material extraction and manufacturing stages. This was performed by performing a sensitivity analysis

for the following criteria and observing the final results for the a) environmental impact of raw material extraction and manufacturing (reported from EPD), b) the environmental impact of transportation (from raw material extraction to manufacturing), c) the environmental impact of transportation (from manufacturing to project location), d) by changing the inventory values/environmental impact of heavy duty truck, e) the total distance traveled from manufacturing to project location, and f) the environmental impact of total transportation module (transportation from raw material extraction to manufacturing and from manufacturing to project location).

Results proved that the total environmental impact is more sensitive to changing the following criteria: environmental impact of transportation(from manufacturing to project location), by changing the inventory values/environmental impact of heavy duty truck, total distance traveled from manufacturing to project location, and environmental impact of total transportation module (transportation from raw material extraction to manufacturing and from manufacturing to project location), more than changing values of raw material extraction and manufacturing stages. For example, by varying each of the previous values by 10%, the final environmental impacts increased by around 0.10% when varying the environmental impacts from raw material extraction and manufacturing stages. However, the final environmental impact changes by approximately 0.0259% when varying the environmental impact of transportation from raw material extraction to manufacturing. When varying the remaining criteria, the final environmental impact increased by 9.86%. This finding also explains, the insignificance of the final results, when changing the EPD used. This is due to the fact that the transportation module from the manufacturing to project location, the total distance traveled, proved to contribute more to final environmental impacts, more than raw material extraction, manufacturing, and the transportation stage from raw material extraction to manufacturing.

6.1 DISCUSSION

Case studies included various states in order to validate the framework in different climatic regions in the South. The designs performed included internally cured concrete in Texas, as well as the evaluation of existing pavement design sustainability in Louisiana.

Results and analysis of case studies established the following: The case study for Texas showed that internally cured concrete proved to be a better option than conventional concrete on the economic level, as well as on the environmental level. This outcome emanates from the fact that the use of internally cured concrete enables the use of smaller design thicknesses, thus leading to lower environmental impacts, as well as economic impacts. This reinforces the finding that this framework can be validated anywhere, as far as data are available (both environmental and economic). Notably, the economic data for the case study performed in Texas does not exist in the study database/software, and thus the data were collected from the project.

The case study for Louisiana: The situation in Louisiana was different from other states, which had previously issued EPDs. A survey was performed in Louisiana to assess companies that issued individual EPDs earlier, or participated in industry wide averaging of EPDs. The results revealed that there are five companies and a total of sixteen plants that have already participated in an industry wide average EPD study with the National Ready Mix Concrete Association. Contact with the consultant (Athena Institute) revealed that there exists no environmental impact/inventory matrix solely for the State of Louisiana. Data for the southern region (including states other than Louisiana) were compiled to produce an environmental impact and inventory matrix for the southern region.

To produce an EPD for Louisiana based on the survey performed, the aggregated data of the five companies and the sixteen plants were averaged to produce an environmental impact/inventory matrix for the State of Louisiana.

Case studies performed in Louisiana were very specific for each mix design. Each mix design was tracked for both environmental and economic impacts. Therefore, when performing an analysis between various products, results will be as accurate as the available data.

Results of the sensitivity analysis performed highlight the importance of the transportation stage in a product lifecycle, contributing to higher environmental impacts vs. raw material extraction and manufacturing. This finding should push stakeholders to limit the total distance traveled by a truck. This can be accomplished by ordering concrete from the nearest available manufacturer, if possible. Also, this finding might encourage stakeholders to find more sustainable technologies to reduce emissions resulting from transportation.

By examining concrete and cement production processes, it is revealed that cement has an intensive production process requiring energy. Despite this, there remain problems associated with the data/inventory values that are available for the energy used during the production process. Also, data associated with the clinker are not accurately used, in an event where the clinker is imported and yet treated as a local material. This lack of data has various drawbacks. First, researchers do not have data to accurately model local data. Second, companies might not be able to benchmark their products with respect to available data. This might prevent the process improvement, or hinder the use of a better technology, since there is no accurate data for companies to benchmark their performance with respect to the local market.

Moreover, as concrete is a mixture of various products, the process of allocation should be well understood. However, this is not the current case. The lack of knowledge regarding the allocation process also leads to inaccurate results, which would mislead researchers and decision makers about the actual environmental impact of issues associated with concrete.

Another point to highlight is the importance of inclusion of all the environmental impacts that result during the production of concrete. This is really critical, should the concrete contain chemical items. However, this concern is not currently taken into consideration, which will have environmental as well as health impacts.

6.2 STUDY LIMITATIONS

The limitation of this study is mostly associated with the data limitation. First, there were many problems associated with the data collection process for both EPD and cost analysis data. For the EPD data collection process, many issues associated with the data proprietary issues, especially for the State of Louisiana, culminated with issuing an industry wide average EPD, rather than individual EPDs for companies. Companies were reluctant to give relevant information, due to concerns regarding any loss of competitiveness in the market. As for the scope, the environmental impact was limited to cradle to gate analysis only, which should be expanded in the future.

Concerning the economic aspect and cost data for Louisiana, many issues were involved in this data collection process as well. In order to compile the history for pavement maintenance and rehabilitation items, the history necessary for data was tracked back for 20 to 30 years, which provided not only relatively old data, but the absence of some information, which could not be located. In addition, the older cost data was no longer available. To solve this problem, the compressive strength values of the selected mix designs were matched to the compressive strength values for old mix designs/projects. As a result, the maintenance and rehabilitation items were matched accordingly.

The study only included two pillars of sustainability, the economic and the environmental aspects, and did not include the social pillar of sustainability. This is due to the fact that the social lifecycle assessment models are not yet fully developed. The scope of the study was only limited to cradle to gate analysis (since this is the scope of EPD) and did not

cover all pavement lifecycle phases from cradle to grave. Also, the study did not include an economic analysis (or lifecycle cost analysis) for states other than Louisiana, which makes it difficult to perform a lifecycle cost analysis for states other than Louisiana.

6.3 FUTURE WORK

- This study presented existing problems in pavement LCA per lifecycle phase. General shortcomings about performing LCA in general include: the use of different system boundaries, the use of different functional units, and the use of different data sources; these obstacles made the overall comparison between studies almost impossible.
- More work should be performed in the material extraction phase, such as issues related to feedstock energy. For the use phase, more research should be performed that relate all factors involved in the use phase together, such as noise, lighting, leachate, etc.; the impact of all these items interacting has not yet been studied.
- The construction phase should be considered in performance of more work-related activities, such as equipment mobilization and demobilization, equipment use at the site, and transport of materials from the site to the final disposal option, as well as traffic congestion related to construction activities.
- The maintenance and rehabilitation phase should be project-specific for future study; the timings of the activities should be calculated for each project, since such data cannot be generalized for all projects.
- For the end of life option, not only should more work be performed in allocation methods, but also more research should be extended to determine the exact amount of concrete going to recycling/or landfill.
- As for the lifecycle assessment of concrete vs. cement, there remain various unexplored areas, such as raw material preparation, grinding, milling, and transportation stages for Portland cement. As for Portland cement concrete, more work should be performed with a

focus on studying the inclusion of admixtures and allocation criteria. Also, since not all of the environmental impacts were studied, future research should examine environmental impacts, such as Volatile Organic Compounds.

- Also, accurate information should be used when using imported clinker, mostly to identify the country of origin and the data source, rather than local data.
- For future work, this study recommends an expansion of software to evaluate the sustainability of other materials (such as aggregates and steel), whenever the EPDs become available.
- As for future work related to the developed framework and its scope; future work might also focus on expanding the scope of the work to evaluate the environmental impact from cradle to grave, rather than from cradle to gate, as in this study.
- Also, future studies might include cost data for other states, since EPDs were collected for other states as well. In this manner, a full lifecycle cost analysis can be performed for states other than Louisiana.
- In the future, individual EPDs for the State of Louisiana should be issued. This will provide a more accurate comparison between products vs. the industry average EPD.
- Future research should also focus on integrating the social aspect, together with the environmental and the economic criteria into the pavement design framework, whenever the social models become more developed.
- Future work should focus on evaluating transportation cost; this study solely focused on the environmental impact of transportation stage.

APPENDICES

APPENDIX A. INDIVIDUAL EPD COMPILATION

The units used for All EPDs are as follows:

Environmental impact/inventory	Unit
GWP	kg CO ₂ -eq/yd ³
ODP	kg CFC-11-eq/yd ³
AP	kg SO ₂ -eq/yd ³
EP	kg N-eq/yd ³
POCP	kg O ₃ -eq/yd ³
PEC	MJ/yd ³
NRE	MJ/yd ³
RE	MJ/yd ³
NRM	kg/yd ³
RM	kg/yd ³
CBW	m ³ /yd ³
CWW	m ³ /yd ³
TW	m ³ /yd ³
CHW	kg/yd ³
CNHW	kg/yd ³

Mix design properties	Unit
Cement	lb
Slag	lb
Fly Ash	lb
Fine Aggregate	lb
Coarse Aggregate1	lb
Coarse Aggregate1	lb
Mixing_ Water (Louisiana)	gallons
Mixing_ Water (all other states)	lb

Mix design properties	Unit
Water_Reducer	oz
Set_Accelerator	oz
Super_Placticizer	oz
Special_Additive_A	oz
Special_Additive_B	oz
Special_Additive_C	oz
Retarder	oz
Total weight	lb
Density	lb/ft3
Mix design cost	\$/y3
Values are given per 1 yd3	

Product ID	UNITS_OF_VOLUME	COMPANY_NAME	ZIP_CODE	COMPRESSIVE_STRENGTH (PSI)	GWP	ODP
1597	yd3	Argos-Mesquite	75149	3000	264.55	3.05E-06
1734	yd3	Argos-Mesquite	75149	4500	288.25	3.31E-06
1735	yd3	Argos-Mesquite	75149	4000	312.72	3.56E-06
1738	yd3	Argos-Mesquite	75149	4400	305.83	3.51E-06
1811	yd3	Argos-Mesquite	75149	4500	259.96	2.99E-06
1841	yd3	Argos-Mesquite	75149	4500	336.42	3.82E-06
1899	yd3	Argos-Mesquite	75149	5000	360.88	4.08E-06
2554	yd3	Argos-Mesquite	75149	3000	265.31	3.07E-06
4070	yd3	Argos-Mesquite	75149	4500	201.85	2.38E-06
4072	yd3	Argos-Mesquite	75149	6000	231.67	2.69E-06
4176	yd3	Argos-Mesquite	75149	9000	430.46	4.92E-06
8482	yd3	Argos-Mesquite	75149	5000	318.83	3.66E-06
9279	yd3	Argos-Mesquite	75149	6000	385.35	4.47E-06
9630	yd3	Argos-Mesquite	75149	5000	360.88	4.10E-06
9908	yd3	Argos-Mesquite	75149	8000	409.82	4.71E-06
9920	yd3	Argos-Mesquite	75149	8000	383.06	4.43E-06
9930	yd3	Argos-Mesquite	75149	9000	404.47	4.62E-06
9932	yd3	Argos-Mesquite	75149	9000	405.23	4.67E-06
1597	yd3	Argos-Downtown Dallas	75212	4000	267.60	3.13E-06
1734	yd3	Argos-Downtown Dallas	75212	3000	290.54	3.39E-06
1735	yd3	Argos-Downtown Dallas	75212	4500	315.01	3.65E-06
1738	yd3	Argos-Downtown Dallas	75212	4000	308.89	3.59E-06

Product ID	UNITS_OF_VOLUME	COMPANY_NAME	ZIP_CODE	COMPRESSIVE_STRENGTH (PSI)	GWP	ODP
1811	yd3	Argos-Downtown Dallas	75212	4400	262.25	3.07E-06
1841	yd3	Argos-Downtown Dallas	75212	4500	339.48	3.90E-06
1899	yd3	Argos-Downtown Dallas	75212	4500	363.18	4.16E-06
2554	yd3	Argos-Downtown Dallas	75212	5000	267.60	3.15E-06
4070	yd3	Argos-Downtown Dallas	75212	3000	204.14	2.46E-06

Product ID	AP	EP	POCP	TOTAL_PRIMARY_ENERGY_CONSUMPTION	NON_RENEWABLE_ENERGY_CONSUMPTION	RENEWABLE_PRIMARY_ENERGY_CONSUMPTION
1597	1.49	0.05	21.56	1488.65	1477.94	11.14
1734	1.61	0.05	23.24	1602.57	1590.34	11.92
1735	1.73	0.05	24.70	1713.43	1701.20	12.52
1738	1.70	0.05	24.31	1685.91	1673.68	12.55
1811	1.47	0.05	21.64	1468.77	1458.06	10.76
1841	1.86	0.06	26.38	1827.36	1813.59	13.18
1899	1.98	0.06	27.91	1938.99	1925.22	13.92
2554	1.49	0.05	21.56	1494.00	1482.53	11.33
4070	1.18	0.04	18.20	1208.81	1200.40	9.14
4072	1.34	0.04	20.26	1349.49	1339.55	9.90
4176	2.34	0.07	32.42	2286.87	2270.82	16.37
8482	1.77	0.05	25.31	1749.37	1736.37	12.78
9279	2.11	0.06	29.44	2075.85	2060.56	15.07
9630	1.98	0.06	27.75	1941.28	1926.75	14.20
9908	2.23	0.06	31.04	2187.48	2172.18	15.75

9920	2.11	0.06	29.59	2067.44	2052.14	14.79
9930	2.22	0.06	31.04	2167.60	2152.31	15.35
9932	2.22	0.06	30.97	2171.42	2155.36	15.44
1597	1.50	0.05	21.41	1520.76	1510.05	11.16
1734	1.62	0.05	23.17	1635.45	1623.21	11.94
1735	1.75	0.05	24.62	1744.78	1731.78	12.55
1738	1.71	0.05	24.24	1719.55	1706.55	12.57
1811	1.48	0.05	21.48	1499.35	1488.65	10.77
1841	1.87	0.05	26.23	1857.18	1844.18	13.21
1899	1.99	0.06	27.75	1968.80	1955.04	13.95
2554	1.50	0.05	21.48	1526.88	1516.17	11.35
4070	1.19	0.04	18.04	1240.16	1230.98	9.14

Product ID	NON_RENEWABLE_MATERIAL_RESOURCES_CONSUMPTION	RENEWABLE_MATERIAL_RESOURCES_CONSUMPTION	CONCRETE_BATCHING_WATER_CONSUMPTION	CONCRETE_WASHING_WATER_CONSUMPTION
1597	1477.94	0.48	0.11	0.05
1734	1590.34	0.52	0.12	0.05
1735	1701.20	0.56	0.12	0.05
1738	1673.68	0.55	0.12	0.05
1811	1458.06	0.47	0.12	0.05
1841	1813.59	0.59	0.12	0.05
1899	1925.22	0.63	0.12	0.05
2554	1482.53	0.49	0.12	0.05
4070	1200.40	0.39	0.10	0.05
4072	1339.55	0.43	0.11	0.05

Product ID	NON_RENEWABLE_MATERIAL_RESOURCES_CONSUMPTION	RENEWABLE_MATERIAL_RESOURCES_CONSUMPTION	CONCRETE_BATCHING_WATER_CONSUMPTION	CONCRETE_WASHING_WATER_CONSUMPTION
4176	2270.82	0.73	0.12	0.05
8482	1736.37	0.56	0.13	0.05
9279	2060.56	0.66	0.11	0.05
9630	1926.75	0.63	0.13	0.05
9908	2172.18	0.70	0.12	0.05
9920	2052.14	0.66	0.12	0.05
9930	2152.31	0.69	0.12	0.05
9932	2155.36	0.69	0.13	0.05
1597	1834.24	0.47	0.11	0.05
1734	1888.52	0.51	0.12	0.05
1735	1844.94	0.54	0.12	0.05
1738	1899.23	0.53	0.12	0.05
1811	1818.95	0.46	0.12	0.05
1841	1849.53	0.58	0.12	0.05
1899	1857.94	0.61	0.12	0.05
2554	1886.23	0.47	0.12	0.05
4070	1885.47	0.38	0.10	0.05

Product_ID	TOTAL_WATER_CONSUMPTION	CONCRETE_HAZARDOUS_WASTE	CONCRETE_NON_HAZARDOUS_WASTE	Cement Weight (lb)
1597	0.16	0.00	0.96	492.00

Product_ ID	TOTAL_WATER_ CONSUMPTION	CONCRETE_HAZARDOUS_WASTE	CONCRETE_NON_HAZARDOUS_WASTE	Cement Weight (lb)
1734	0.17	0.00	0.96	411.00
1735	0.17	0.00	0.96	451.00
1738	0.17	0.00	0.96	441.00
1811	0.17	0.00	0.96	367.00
1841	0.17	0.00	0.96	489.00
1899	0.17	0.00	0.96	526.00
2554	0.16	0.00	0.96	376.00
4070	0.15	0.00	0.96	276.00
4072	0.16	0.00	0.96	322.00
4176	0.17	0.03	0.96	635.00
8482	0.18	0.00	0.96	461.00
9279	0.16	0.02	0.96	564.00
9630	0.18	0.00	0.96	526.00
9908	0.16	0.02	0.96	602.00
9920	0.17	0.03	0.96	559.00
9930	0.17	0.03	0.96	592.00
9932	0.17	0.03	0.96	595.00
1597	0.16	0.00	0.96	376.00
1734	0.17	0.00	0.96	411.00
1735	0.17	0.00	0.96	451.00
1738	0.17	0.00	0.96	441.00
1811	0.17	0.00	0.96	367.00

Product_ID	TOTAL_WATER_CONSUMPTION	CONCRETE_HAZARDOUS_WASTE	CONCRETE_NON_HAZARDOUS_WASTE	Cement Weight (lb)
1841	0.17	0.00	0.96	489.00
1899	0.17	0.00	0.96	526.00
2554	0.16	0.00	0.96	376.00
4070	0.15	0.00	0.96	276.00

Product ID	Water Cement Ratio	Mixing Water (lb)	Fly Ash (lb)	Slag (lb)	Fine Aggregate (lb)	Coarse Aggregate (lb)	Total Weight (lb)
1597	0.50	246.00	118.00	0.00	1309.00	1875.00	3924.00
1734	0.45	262.00	176.00	0.00	1346.00	1840.00	4035.00
1735	0.43	257.00	141.00	0.00	1193.00	1875.00	3917.00
1738	0.44	261.00	147.00	0.00	1353.00	1840.00	4042.00
1811	0.42	254.00	244.00	0.00	1202.00	1840.00	3906.00
1841	0.41	263.00	153.00	0.00	1108.00	1900.00	3913.00
1899	0.39	267.00	165.00	0.00	1079.00	1875.00	3912.00
2554	0.53	249.00	94.00	0.00	1433.00	1900.00	4052.00
4070	0.43	242.00	288.00	0.00	1340.00	1900.00	4045.00
4072	0.36	240.00	336.00	0.00	1256.00	1900.00	4045.00
4176	0.31	260.00	212.00	0.00	1256.00	1750.00	4073.00
8482	0.42	275.00	197.00	0.00	1248.00	1840.00	4021.00
9279	0.35	250.00	141.00	0.00	1285.00	1840.00	4080.00
9630	0.42	275.00	132.00	0.00	1200.00	1900.00	4033.00

9908	0.33	251.00	150.00	0.00	1241.00	1840.00	4084.00
9920	0.32	259.00	240.00	0.00	1204.00	1800.00	4062.00
9930	0.31	262.00	254.00	0.00	1840.00	1840.00	4062.00
9932	0.32	273.00	255.00	0.00	1172.00	1750.00	4044.00
1597	0.50	246.00	118.00	0.00	1309.00	1875.00	3924.00
1734	0.45	262.00	176.00	0.00	1346.00	1840.00	4035.00
1735	0.43	257.00	141.00	0.00	1193.00	1875.00	3917.00
1738	0.44	261.00	147.00	0.00	1353.00	1840.00	4042.00
1811	0.42	254.00	244.00	0.00	1202.00	1840.00	3906.00
1841	0.41	263.00	153.00	0.00	1108.00	1900.00	3913.00
1899	0.39	267.00	165.00	0.00	1079.00	1875.00	3912.00
2554	0.53	249.00	94.00	0.00	1433.00	1900.00	4052.00
4070	0.43	242.00	288.00	0.00	1340.00	1900.00	4045.00

Product_ ID	Price_ \$/Y3	REGION	STATE	Validity	Slump (Inch)	Air Percent
1597	201.25	South	Texas	August 26th, 2019	4.00 +/- 1.00	4.50 +/- 1.50
1734	206.25	South	Texas	August 26th, 2019	4.00 +/- 1.00	1.50 +/- 1.50
1735	206.30	South	Texas	August 26th, 2019	4.00 +/- 1.00	4.50 +/- 1.50
1738	206.25	South	Texas	August 26th, 2019	4.00 +/- 1.00	1.50 +/- 1.50
1811	207.50	South	Texas	August 26th, 2019	4.00 +/- 1.00	4.50 +/- 1.50
1841	208.80	South	Texas	August 26th, 2019	4.00 +/- 1.00	4.50 +/- 1.50
1899	211.35	South	Texas	August 26th, 2019	4.00 +/- 1.00	4.50 +/- 1.50
2554	198.75	South	Texas	August 26th, 2019	4.00 +/- 1.00	1.50 +/- 1.50
4070	208.00	South	Texas	August 26th, 2019	6.00 +/- 1.00	1.50 +/- 1.50
4072	212.00	South	Texas	August 26th, 2019	6.00 +/- 1.00	1.50 +/- 1.50

Product_ ID	Price_ \$/Y3	REGION	STATE	Validity	Slump (Inch)	Air Percent
4176	229.00	South	Texas	August 26th, 2019	7.50 +/- 1.00	1.50 +/- 1.50
8482	213.00	South	Texas	August 26th, 2019	6.00 +/- 1.00	1.50 +/- 1.50
9279	222.50	South	Texas	August 26th, 2019	7.50 +/- 1.00	1.50 +/- 1.50
9630	213.00	South	Texas	August 26th, 2019	6.00 +/- 1.00	1.50 +/- 1.50
9908	227.50	South	Texas	August 26th, 2019	7.50 +/- 1.00	1.50 +/- 1.50
9920	224.00	South	Texas	August 26th, 2019	7.50 +/- 1.00	1.50 +/- 1.50
9930	229.00	South	Texas	August 26th, 2019	7.50 +/- 1.00	1.50 +/- 1.50
9932	229.25	South	Texas	August 26th, 2019	7.50 +/- 1.00	1.50 +/- 1.50
1597	201.25	South	Texas	August 26th, 2019	4.00 +/- 1.00	4.50 +/- 1.50
1734	206.25	South	Texas	August 26th, 2019	4.00 +/- 1.00	1.50 +/- 1.50
1735	206.30	South	Texas	August 26th, 2019	4.00 +/- 1.00	4.50 +/- 1.50
1738	206.25	South	Texas	August 26th, 2019	4.00 +/- 1.00	1.50 +/- 1.50
1811	207.50	South	Texas	August 26th, 2019	4.00 +/- 1.00	4.50 +/- 1.50
1841	208.80	South	Texas	August 26th, 2019	4.00 +/- 1.00	4.50 +/- 1.50
1899	211.35	South	Texas	August 26th, 2019	4.00 +/- 1.00	4.50 +/- 1.50
2554	198.75	South	Texas	August 26th, 2019	4.00 +/- 1.00	1.50 +/- 1.50
4070	208.00	South	Texas	August 26th, 2019	6.00 +/- 1.00	1.50 +/- 1.50

APPENDIX B. INDUSTRY WIDE AVERAGE EPD COMPILATION

Table E1-NRMCA U.S. National LCA Results															
Indicator/LCI		GWP	ODP	AP	EP	POCP	PEC	NRE	RE	NRM	RM	CBW	CWW	TW	CNHW
Metric Unit		kg CO2	kg CFC-11	kg SO2	kg N	kg O3	MJ	MJ	MJ	kg	kg	m3	m3	m3	kg
2500 psi	per yd3	220.14	5.61E-06	0.77	0.27	16.07	1,503.6	1,475.9	27.7	1,703.2	1.62	0.14	0.13	0.30	0.33
3000 psi	per yd3	245.28	6.25E-06	0.84	0.30	17.38	1,642.6	1,611.9	30.8	1,709.1	1.80	0.14	0.13	0.29	0.33
4000 psi	per yd3	300.30	7.63E-06	0.98	0.36	20.25	1,950.7	1,913.2	37.5	1,726.7	2.20	0.14	0.13	0.29	0.33
5000 psi	per yd3	371.14	9.41E-06	1.17	0.44	23.91	2,347.6	2,301.5	46.1	1,723.4	2.71	0.14	0.13	0.30	0.34
6000 psi	per yd3	391.09	9.91E-06	1.23	0.47	25.06	2,466.6	2,418.1	48.6	1,791.8	2.86	0.15	0.14	0.32	0.34
8000 psi	per yd3	476.85	1.21E-05	1.46	0.57	29.51	2,950.1	2,891.1	59.0	1,808.2	3.48	0.15	0.14	0.32	0.34
3000 psi	per yd3	379.36	1.60E-05	1.69	0.50	24.94	3,223.2	3,183.8	39.4	1,407.6	8.50	0.14	0.13	0.52	0.33
4000 psi	per yd3	437.97	1.76E-05	1.85	0.57	28.01	3,572.7	3,526.4	46.4	1,415.9	9.05	0.14	0.13	0.53	0.33
5000 psi	per yd3	501.36	1.94E-05	2.03	0.64	31.33	3,951.3	3,897.3	53.9	1,425.3	9.63	0.14	0.13	0.53	0.34

Table E2-Eastern LCA Results															
Indicator/LCI		GWP	ODP	AP	EP	POCP	PEC	NRE	RE	NRM	RM	CBW	CWW	TW	CNHW
Metric Unit		kg CO2	kg CFC-11	kg SO2	kg N	kg O3	MJ	MJ	MJ	kg	kg	m3	m3	m3	kg
2500 psi	per yd3	228.62	6.15E-06	0.82	0.28	16.53	1,593.3	1,563.4	29.9	1,731.1	1.73	0.14	0.12	0.30	0.02
3000 psi	per yd3	254.96	6.85E-06	0.90	0.31	17.93	1,744.1	1,710.8	33.3	1,751.9	1.93	0.14	0.12	0.30	0.02
4000 psi	per yd3	312.54	8.39E-06	1.06	0.38	21.00	2,077.2	2,036.5	40.7	1,799.8	2.35	0.14	0.12	0.30	0.03
5000 psi	per yd3	385.60	1.03E-05	1.26	0.46	24.69	2,489.9	2,439.9	50.1	1,740.6	2.89	0.15	0.13	0.31	0.03
6000 psi	per yd3	406.40	1.09E-05	1.32	0.49	25.89	2,616.8	2,564.1	52.7	1,810.5	3.05	0.16	0.14	0.33	0.04
8000 psi	per yd3	495.57	1.32E-05	1.56	0.59	30.54	3,131.1	3,067.0	64.1	1,828.9	3.71	0.16	0.14	0.33	0.05
3000 psi	per yd3	391.71	1.69E-05	1.76	0.52	25.50	3,354.2	3,312.3	41.9	1,398.8	8.82	0.15	0.13	0.54	0.02
4000 psi	per yd3	452.40	1.87E-05	1.94	0.59	28.69	3,723.0	3,673.5	49.5	1,405.0	9.39	0.15	0.13	0.54	0.03
5000 psi	per yd3	517.98	2.05E-05	2.13	0.67	32.14	4,122.1	4,064.4	57.7	1,412.3	10.00	0.15	0.13	0.55	0.03

Table E3-Great Lakes Midwest LCA Results																
Indicator/LCI		GWP	ODP	AP	EP	POCP	PEC	NRE	RE	NRM	RM	CBW	CWW	TW	CHW	CNHW
Metric Unit		kg CO2	kg CFC-11	kg SO2	kg N	kg O3	MJ	MJ	MJ	kg	kg	m3	m3	m3	kg	kg
2500 psi	per yd3	200.57	5.04E-06	0.72	0.24	15.17	1,392.9	1,369.0	23.9	1,727.2	1.44	0.12	0.07	0.22	0.01	1.50
3000 psi	per yd3	223.08	5.61E-06	0.78	0.27	16.33	1,517.7	1,491.0	26.7	1,743.2	1.61	0.12	0.07	0.22	0.01	1.69
4000 psi	per yd3	272.28	6.85E-06	0.91	0.33	18.86	1,794.0	1,761.3	32.7	1,780.4	1.96	0.12	0.07	0.22	0.02	2.11
5000 psi	per yd3	335.14	8.42E-06	1.07	0.40	22.00	2,143.6	2,103.2	40.3	1,764.1	2.42	0.12	0.07	0.22	0.02	2.65
6000 psi	per yd3	353.06	8.87E-06	1.12	0.42	23.01	2,250.5	2,208.0	42.5	1,831.0	2.55	0.14	0.08	0.24	0.02	2.80
8000 psi	per yd3	429.13	1.08E-05	1.32	0.51	26.86	2,678.0	2,626.2	51.8	1,846.5	3.10	0.14	0.08	0.24	0.03	3.45
3000 psi	per yd3	366.92	1.61E-05	1.69	0.49	24.47	3,209.8	3,173.8	36.0	1,429.9	8.75	0.12	0.07	0.47	0.01	1.72
4000 psi	per yd3	420.04	1.75E-05	1.84	0.55	27.18	3,527.4	3,485.0	42.4	1,439.1	9.25	0.12	0.07	0.47	0.02	2.15
5000 psi	per yd3	477.49	1.91E-05	2.00	0.62	30.11	3,871.5	3,822.3	49.2	1,449.6	9.79	0.12	0.07	0.47	0.02	2.61

Table E4-North Central LCA Results																
Indicator/LCI Metric Unit (equivalent)		GWP	ODP	AP	EP	POCP	PEC	NRE	RE	NRM	RM	CBW	CWW	TW	CHW	CNHW
		kg CO2	kg CFC-11	kg SO2	kg N	kg O3	MJ	MJ	MJ	kg	kg	m3	m3	m3	kg	kg
2500 psi	per yd3	194.09	3.20E-06	0.86	0.16	11.83	1,591.9	1,580.5	11.4	1,723.5	0.37	0.11	0.18	0.29	0.00	1.94
	per m3	253.86	4.19E-06	1.12	0.21	15.48	2,082.2	2,067.3	14.9	2,254.2	0.48	0.15	0.23	0.38	0.00	2.54
3000 psi	per yd3	215.95	3.54E-06	0.94	0.17	12.79	1,745.0	1,732.5	12.5	1,725.0	0.39	0.11	0.18	0.29	0.00	1.94
	per m3	282.45	4.63E-06	1.23	0.23	16.72	2,282.4	2,266.1	16.3	2,256.2	0.51	0.15	0.23	0.38	0.00	2.54
4000 psi	per yd3	264.14	4.28E-06	1.13	0.21	14.92	2,087.2	2,072.4	14.8	1,747.7	0.45	0.11	0.18	0.29	0.00	1.94
	per m3	345.49	5.59E-06	1.48	0.27	19.51	2,730.0	2,710.6	19.3	2,285.9	0.58	0.15	0.23	0.38	0.00	2.54
5000 psi	per yd3	326.42	5.23E-06	1.94	0.29	23.76	2,530.6	2,512.8	17.8	1,761.1	0.51	0.12	0.18	0.30	0.00	1.94
	per m3	426.94	6.84E-06	2.53	0.38	31.08	3,309.8	3,286.6	23.3	2,303.4	0.67	0.15	0.24	0.39	0.00	2.54
6000 psi	per yd3	343.86	5.50E-06	2.01	0.30	24.62	2,660.5	2,641.8	18.7	1,826.5	0.54	0.13	0.20	0.32	0.00	1.94
	per m3	449.76	7.19E-06	2.63	0.39	32.20	3,479.8	3,455.4	24.4	2,388.9	0.70	0.16	0.26	0.42	0.00	2.54
8000 psi	per yd3	419.68	6.66E-06	2.31	0.35	27.97	3,202.4	3,180.0	22.3	1,857.8	0.62	0.13	0.20	0.32	0.00	1.94
	per m3	548.92	8.71E-06	3.02	0.46	36.58	4,188.5	4,159.3	29.2	2,429.9	0.81	0.16	0.26	0.42	0.00	2.54
3000 psi Lightweight	per yd3	346.55	1.53E-05	1.59	0.46	22.52	3,040.7	3,006.1	34.6	1,437.6	8.44	0.11	0.18	0.56	0.01	3.53
	per m3	453.27	2.01E-05	2.08	0.61	29.45	3,977.1	3,931.9	45.3	1,880.3	11.04	0.15	0.23	0.73	0.01	4.61
4000 psi Lightweight	per yd3	397.04	1.67E-05	1.73	0.52	25.22	3,345.3	3,304.7	40.5	1,447.9	8.92	0.11	0.18	0.56	0.01	3.93
	per m3	519.30	2.19E-05	2.27	0.69	32.99	4,375.4	4,322.4	53.0	1,893.8	11.67	0.15	0.23	0.74	0.02	5.14

Table E5-Pacific Northwest LCA Results																
Indicator/LCI		GWP	ODP	AP	EP	POCP	PEC	NRE	RE	NRM	RM	CBW	CWW	TW	CHW	CNHW
Metric Unit		kg CO2	kg CFC-11	kg SO2	kg N	kg O3	MJ	MJ	MJ	kg	kg	m3	m3	m3	kg	kg
2500 psi	per yd3	204.00	5.12E-06	0.75	0.24	16.01	1,392.6	1,364.4	28.2	1,767.9	1.47	0.13	0.05	0.20	0.01	5.47
3000 psi	per yd3	227.91	5.73E-06	0.82	0.27	17.46	1,527.6	1,496.4	31.2	1,771.2	1.65	0.13	0.05	0.20	0.02	5.67
4000 psi	per yd3	280.38	7.06E-06	0.97	0.33	20.65	1,827.5	1,789.9	37.6	1,783.4	2.03	0.13	0.05	0.20	0.02	6.11
5000 psi	per yd3	348.27	8.78E-06	1.17	0.41	24.77	2,217.5	2,171.5	46.0	1,787.3	2.52	0.13	0.05	0.20	0.02	6.68
6000 psi	per yd3	367.01	9.26E-06	1.23	0.44	26.00	2,330.4	2,282.1	48.3	1,854.6	2.65	0.14	0.06	0.22	0.03	6.84
8000 psi	per yd3	449.58	1.13E-05	1.48	0.53	31.02	2,807.1	2,748.7	58.4	1,877.7	3.25	0.14	0.06	0.22	0.03	7.53
3000 psi	per yd3	386.66	1.68E-05	1.80	0.51	26.77	3,356.9	3,313.9	43.0	1,436.5	9.05	0.13	0.05	0.46	0.02	5.77
4000 psi	per yd3	444.90	1.84E-05	1.98	0.58	30.29	3,711.5	3,661.5	50.1	1,449.1	9.59	0.13	0.05	0.46	0.02	6.24
5000 psi	per yd3	509.38	2.03E-05	2.19	0.66	34.19	4,113.1	4,055.3	57.8	1,460.3	10.24	0.13	0.05	0.47	0.03	6.74

Table E6-Pacific Southwest LCA Results																
Indicator/LCI Metric		GWP	ODP	AP	EP	POCP	PEC	NRE	RE	NRM	RM	CBW	CWW	TW	CHW	CNHW
Unit (equivalent)		kg CO2	kg CFC-11	kg SO2	kg N	kg O3	MJ	MJ	MJ	kg	kg	m3	m3	m3	kg	kg
2500 psi	per yd3	250.52	6.15E-06	0.81	0.30	17.07	1,638.0	1,605.3	32.7	1,691.2	1.82	0.15	0.16	0.34	0.01	26.18
3000 psi	per yd3	280.10	6.88E-06	0.89	0.33	18.57	1,800.5	1,764.2	36.3	1,703.8	2.03	0.15	0.16	0.34	0.02	26.43
4000 psi	per yd3	344.60	8.47E-06	1.05	0.41	21.81	2,157.2	2,113.2	44.0	1,722.2	2.50	0.15	0.16	0.34	0.02	26.99
5000 psi	per yd3	427.70	1.05E-05	1.26	0.50	25.95	2,617.5	2,563.6	53.9	1,724.4	3.09	0.16	0.17	0.35	0.02	27.70
6000 psi	per yd3	451.02	1.11E-05	1.33	0.53	27.23	2,753.8	2,697.0	56.7	1,796.6	3.26	0.17	0.18	0.38	0.03	27.90
8000 psi	per yd3	551.48	1.36E-05	1.58	0.65	32.27	3,313.5	3,244.7	68.7	1,821.9	3.98	0.17	0.18	0.38	0.03	28.76
3000 psi	per yd3	406.29	1.61E-05	1.69	0.52	25.72	3,288.5	3,243.9	44.5	1,407.6	8.32	0.16	0.16	0.56	0.02	26.45
4000 psi	per yd3	474.36	1.79E-05	1.87	0.60	29.16	3,686.6	3,634.0	52.5	1,421.2	8.93	0.16	0.16	0.56	0.02	27.01
5000 psi	per yd3	547.93	1.98E-05	2.07	0.69	32.88	4,117.4	4,056.2	61.2	1,436.4	9.58	0.16	0.16	0.57	0.02	27.62

Table E7-Rocky Mountains LCA Results																
Indicator/LCI		GWP	ODP	AP	EP	POCP	PEC	NRE	RE	NRM	RM	CBW	CWW	TW	CHW	CNHW
Metric Unit		kg CO2	kg CFC-11	kg SO2	kg N	kg O3	MJ	MJ	MJ	kg	kg	m3	m3	m3	kg	kg
2500 psi	per yd3	216.92	3.39E-06	0.96	0.09	13.04	1,776.3	1,745.8	30.4	1,725.7	0.38	0.13	0.07	0.21	0.00	0.52
3000 psi	per yd3	240.85	3.72E-06	1.05	0.10	13.95	1,939.3	1,905.7	33.6	1,732.1	0.40	0.13	0.07	0.21	0.00	0.52
4000 psi	per yd3	293.19	4.45E-06	1.25	0.12	15.95	2,299.5	2,258.9	40.6	1,751.1	0.46	0.13	0.07	0.21	0.00	0.52
5000 psi	per yd3	360.51	5.39E-06	2.07	0.17	24.61	2,762.8	2,713.3	49.5	1,749.3	0.52	0.14	0.08	0.21	0.00	0.52
6000 psi	per yd3	379.73	5.67E-06	2.14	0.18	25.45	2,902.0	2,850.0	52.0	1,818.9	0.55	0.15	0.08	0.23	0.00	0.52
8000 psi	per yd3	461.40	6.81E-06	2.45	0.20	28.58	3,468.3	3,405.5	62.8	1,851.4	0.63	0.15	0.08	0.23	0.00	0.52
3000 psi	per yd3	379.60	1.60E-05	1.69	0.49	24.74	3,253.8	3,213.0	40.7	1,417.4	8.52	0.13	0.07	0.47	0.01	2.38
4000 psi	per yd3	437.56	1.76E-05	1.85	0.56	27.67	3,596.6	3,549.1	47.5	1,426.9	9.06	0.13	0.07	0.47	0.02	2.85
5000 psi	per yd3	500.27	1.93E-05	2.02	0.64	30.86	3,968.1	3,913.2	54.9	1,437.7	9.63	0.13	0.07	0.48	0.02	3.36

Table E8-South Central LCA Results																
Indicator/LCI		GWP	ODP	AP	EP	POCP	PEC	NRE	RE	NRM	RM	CBW	CWW	TW	CHW	CNHW
Metric Unit		kg CO2	kg CFC-11	kg SO2	kg N	kg O3	MJ	MJ	MJ	kg	kg	m3	m3	m3	kg	kg
2500 psi	per yd3	195.56	4.88E-06	0.70	0.24	14.81	1,346.9	1,323.5	23.4	1,691.3	1.42	0.12	0.20	0.35	0.01	11.01
3000 psi	per yd3	217.71	5.43E-06	0.76	0.26	15.99	1,468.4	1,442.4	26.1	1,707.2	1.58	0.12	0.20	0.35	0.01	11.20
4000 psi	per yd3	265.88	6.62E-06	0.88	0.32	18.52	1,733.2	1,701.4	31.9	1,715.4	1.93	0.12	0.20	0.35	0.01	11.61
5000 psi	per yd3	328.17	8.16E-06	1.05	0.39	21.80	2,078.8	2,039.4	39.4	1,728.3	2.37	0.12	0.21	0.36	0.02	12.15
6000 psi	per yd3	345.78	8.60E-06	1.10	0.41	22.84	2,183.3	2,141.8	41.5	1,794.2	2.50	0.13	0.22	0.39	0.02	12.29
8000 psi	per yd3	421.14	1.05E-05	1.30	0.50	26.83	2,603.8	2,553.3	50.5	1,824.4	3.04	0.13	0.22	0.38	0.02	12.94
3000 psi	per yd3	352.20	1.52E-05	1.61	0.46	23.58	3,047.1	3,012.5	34.6	1,434.5	8.28	0.12	0.20	0.58	0.01	11.22
4000 psi	per yd3	405.97	1.68E-05	1.77	0.53	26.43	3,375.2	3,334.3	40.8	1,444.0	8.85	0.12	0.20	0.58	0.01	11.65
5000 psi	per yd3	464.05	1.84E-05	1.94	0.60	29.52	3,729.4	3,681.8	47.6	1,454.9	9.45	0.12	0.20	0.59	0.02	12.11

APPENDIX C. SURVEY PERFORMED IN LOUISIANA AND ASSOCIATED RESULTS

A survey was performed in Louisiana to evaluate whether any companies have measured any lifecycle impact assessment for their products. Results revealed that only companies participated in the industry wide average survey, since this process is very expensive to perform. However, very few companies (five companies) participated in this industry wide average EPD, showing a total of 18 plants. The sample was not statistically representative, and the data had to be aggregated, together with other values in the south central region.

The survey was prepared under the supervision of the Institutional Review Board (IRB) at Louisiana State University, and is composed of the following sections:

- Project description: The first page described the project. Also, the link to the project website was provided for details.
- A guide to consent form: This page gives contact information about the preparers, the purpose of the research and data sensitivity, the study procedures, the risk involved in participation, and the right to refuse to participate.
- Finally, the actual survey is provided.

A brief project description

The aim of this research is to provide the Louisiana Department of Transportation and Development (DOTD) with a user-friendly decision making tool for quantifying the sustainability of pavement designs.

To achieve this objective, this survey aims to collect data related to lifecycle environmental impact and inventory data for concrete products produced in Louisiana. The collected data will be integrated into the pavement Mechanistic-Empirical design framework, as a sustainability input and the overall design will be evaluated based on performance, environmental and economic criteria.

More information about the project can be found in this

website: http://www.ltrc.lsu.edu/pdf/2016/capsule_17-3P.pdf

Guide to Consent

1. Name and contact information of the investigator(s).

The researchers conducting this survey are:

Neveen Soliman. Please direct any questions you have to ntalaa1@lsu.edu

Co-investigator: Prof. Marwa Hassan

Contact information: marwa@lsu.edu

2. Purpose of the research and data sensitivity

The purpose of this research is to measure/assess lifecycle category indicators and inventory metrics in Louisiana Plants producing concrete.

The answers to this survey might be sensitive. However, the data will be kept confidential.

3. Study procedures.

To participate in this study: 1) your plant should be located in Louisiana, and 2) you should be producing concrete.

You will be asked to fill in a survey about your concrete plant located in Louisiana.

The purpose is to collect data about lifecycle category indicators and inventory metrics. If you performed these measurements, please provide them. If you did not perform any of these measurements, please state the reason.

4. Risk involved in participation

There is no risk involved in this study except for data sensitivity. However, the data will be kept confidential.

5. Inform the participants of their right to refuse.

“Subjects may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which they might otherwise be entitled.”

Subjects may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which they might otherwise be entitled.

The extent to which your privacy will be protected by the following procedures:

All your answers will be confidential. The answers for this study will be kept private.

If answers were made public, we will not reveal any information that will make it possible to identify you.

“By continuing this survey, you are giving consent to participate in this study.”

Note: The Institutional Review Board (IRB) looked at the project and determined there was no need for a formal review.

Section 1: General information

1. Please provide information about your company.

Company name

Company address

Street

City

State

Zip code

2. Please provide information about your plant, located in Louisiana.

Plant name

Plant address

City

State

Zip code

3. Please provide information about the preparer.

Name of the preparer

Position

Contact information

Section 2: Measurement

4. Please indicate if you measured the following lifecycle environmental impact data/inventory metrics in your plant for the produced concrete mix designs.

- ☐ Global Warming Potential
- ☐ Acidification Potential
- ☐ Eutrophication Potential
- ☐ Ozone Depletion Potential
- ☐ Photochemical Ozone Creation Potential
- ☐ Total primary energy consumption
- ☐ Depletion of non-renewable energy resources
- ☐ Use of renewable primary energy
- ☐ Depletion of non-renewable material resources
- ☐ Use of renewable material resources
- ☐ Concrete batching water consumption
- ☐ Concrete washing water consumption
- ☐ Total water consumption
- ☐ Concrete hazardous waste
- ☐ Concrete non-hazardous waste
- ☐ None of the above

5. If the answer to the above is “none of the above.” Please indicate the reason.

- ☐ The plant is small

☐ Not required per regulation

☐ All of the above

☐ Other: Please indicate

If you answered any of the options in Question 4, please proceed to sections 3 and 4.

Section 3: Mix design properties

Please provide information about the mix designs produced in your plant and for which you measured any of the options in Question 4.

Section 4: Lifecycle environmental impact data/inventory metrics

Please provide information about lifecycle environmental impact data/inventory metrics measured for the mix designs in section 3.

Section 5: Other information (optional). Please provide any information you find useful or anything you want to add

APPENDIX D. RESULTS OF LOUISIANA SURVEY AND DEVELOPED EPD FOR LOUISIANA

Based on the accomplished survey, the following are the companies/plants that participated in the industry wide EPD. As illustrated, there are five companies with a total of sixteen plants.

Count	Company	Plant Name
1	Angelle Concrete Group, LLC	Denham Springs
2	Angelle Concrete Group, LLC	Westport
3	Angelle Concrete Group, LLC	Zachary
4	Builders Supply Co., Inc.	Forth Street Plant
5	Builders Supply Co., Inc.	Minden Plant
6	Builders Supply Co., Inc.	Natchitoches Plant
7	Builders Supply Co., Inc.	St. Vincent Plant
8	Builders Supply Co., Inc.	Viking Dr. Plant
9	Dolese Bros. Co.	South Choctaw Batch Baton Rouge Louisiana Plant
10	Lafarge North America	Plant 30408-Airport
11	Lafarge North America	Plant 30442-Gramercy
12	Lafarge North America	Plant 30453-Houma
13	Martin Marietta	Cheniere
14	Martin Marietta	Jonesville
15	Martin Marietta	Monroe B
16	Martin Marietta	West Monroe

The mix designs had the following format/headings: cement, fly ash, slag, coarse aggregate 1, coarse aggregate 2, water, water reducer, air, air entertainer, set accelerator, super plasticizer, special additives (A), special additive (B) and special additive (C). The sources/ types of each material is illustrated.

Material	Type
Cement	Type 1 or Type 2
Fly ash	Class C
Slag	None of the selected mixes contain slag
Fine aggregate	Fine Aggregate (concrete sand)
Coarse aggregate1	Grade A coarse aggregate (Stone) for concrete and Grade A coarse aggregate (gravel) for concrete
Coarse aggregate 2	Grade F and Grade A coarse aggregate (stone aggregate)

Sample of the EPD created for Louisiana, company names were omitted.

No	Class Type	Construction Type	Compressive strength	Cement Weight	Fly Ash	Slag	Fine	Coarse Aggregate l
1	B	PCC Pavement	6580	414	103	0	1180	1481
2	E	PCC Pavement	5240	752	0	0	1259	1790
3	B	PCC Pavement	4800	455	80	0	1439	1409
4	B	PCC Pavement	4800	455	80	0	1439	1409
5	B	PCC Pavement	4800	479	85	0	1378	1351
6	E	PCC Pavement	5240	705	0	0	1297	1273
7	B	PCC Pavement	4730	380	95	0	1430	1515
8	B	PCC Pavement	4730	475	0	0	1441	1527
9	B	PCC Pavement	4800	455	80	0	1439	1409
10	B	PCC Pavement	6580	414	103	0	1291	1559
11	B	PCC Pavement	4970	475	0	0	993	2006
12	E	PCC Pavement	5240	880	0	0	1074	1975
13	B	PCC Pavement	6580	414	103	0	1092	1353
14	B	PCC Pavement	4800	475	0	0	1570	1570
15	B	PCC Pavement	5120	468	83	0	1510	1325
16	B	PCC Pavement	6470	420	105	0	1267	1272
17	B	PCC Pavement	6470	420	105	0	1236	1538
18	E	PCC Pavement	4400	658	0	0	1345	1810
19	E	PCC Pavement	4400	510	100	0	1354	1866
20	E	PCC Pavement	4400	550	61	0	1365	1857
21	B	PCC Pavement	5100	414	103	0	1285	1379
22	B	PCC Pavement	5100	420	105	0	1256	1230
23	B	PCC Pavement	5100	414	103	0	1281	1376

No	Class Type	Construction Type	Compressive strength	Cement Weight	Fly Ash	Slag	Fine	Coarse Aggregate l
24	B	PCC Pavement	6470	400	70	0	1389	1945
25	B	PCC Pavement	6490	420	105	0	1256	1230
26	E	PCC Pavement	5240	455	80	0	1439	1409
27	B	PCC Pavement	5540	413	104	0	1483	1421
28	E	PCC Pavement	5300	600	0	0	1411	1850
29	B	PCC Pavement	4800	414	103	0	1399	1652
30	B	PCC Pavement	5455	455	80	0	1439	1409
31	B	PCC Pavement	4720	488	122	0	1498	1230
32	B	PCC Pavement	4720	408	102	0	1466	1628

No	Coarse Aggregate 2	Mixing Water	Water cement ratio	Water Reducer	Air Percent	Air Entertainer	Set Accelerator	Super Plasticizer	Special Additive A
1	413	29.6	0.6	20.7	5±2	2.1	0	0	0
2	0	31.6	0.35	30.1	5±2	0	0	0	0
3	213	28	0.51	20	5±2	4.5	0	0	0
4	213	28	0.51	20	5±2	0	0	0	0
5	479	30	0.52	17.4	5±2	0	0	0	0
6	451	33.8	0.4	21.8	5±2	0	0	0	0
7	152	27.3	0.6	23.8	5±2	2.4	0	0	0
8	153	27.3	0.48	33.3	5±2	2.3	0	0	0
9	213	28	0.51	21	5±2	4.5	0	0	0
10	413	31	0.62	20.7	5±2	0	0	0	0
11	0	27.3	0.48	0	5±2	5	0	0	0
12	0	25	0.24	0	5±2	0	640	80	0
13	846	30.3	0.61	15.51	5±2	0	0	0	0
14	0	26.9	0.47	16	5±2	3.6	0	0	0

No	Coarse Aggregate 2	Mixing Water	Water cement ratio	Water Reducer	Air Percent	Air Entertainer	Set Accelerator	Super Plasticizer	Special Additive A
15	210	29.5	0.53	20.8	5±2	2	0	0	0
16	430	30.1	0.6	15.75	5±2	5	0	0	0
17	240	15.75	0.31	0	5±2	5	0	0	0
18	0	30	0.38	0	5±2	0	0	0	19.74
19	0	28	0.46	20	5±2	0	0	0	0
20	0	28	0.42	66	5±2	0	0	0	0
21	607	31	0.62	20.7	5±2	0	0	0	0
22	605	29	0.58	21	5±2	0	0	0	0
23	604	31	0.62	20.7	5±2	0	0	0	0
24	0	28	0.58	14	5±2	0	0	0	0
25	605	29	0.58	21	5±2	3	0	0	0
26	210	28.8	0.53	20	5±2	4.5	0	0	0
27	320	31	0.63	15.51	5±2	0	0	0	0
28	0	27.3	0.38	0	5±2	0	0	52.6	0
29	0	30	0.6	20.68	5±2	2.01	0	0	0
30	210	28	0.51	20	5±2	4.5	0	0	0
31	400	32.2	0.55	30.5	5±2	0	0	0	0
32	163	30.5	0.62	15.3	5±2	0	0	0	0
1	0.00	0.00	0.00	3839.59	144.52	187.02	23.34	7.20	194.22
2	0.00	0.00	0.00	4066.74	145.16	335.01	27.39	7.20	342.20
3	0.00	0.00	0.00	3831.33	145.36	204.84	24.07	7.20	212.03
4	0.00	0.00	0.00	3831.05	145.35	204.82	24.06	7.20	212.02
5	0.00	0.00	0.00	4023.59	145.49	215.63	25.04	7.20	222.82
6	0.00	0.00	0.00	4009.59	144.40	314.29	26.55	7.20	321.48
7	0.00	0.00	0.00	3801.59	144.88	172.10	23.20	7.20	179.29
8	0.00	0.00	0.00	3826.18	144.62	213.82	23.45	7.20	221.01

No	Coarse Aggregate 2	Mixing Water	Water cement ratio	Water Reducer	Air Percent	Air Entertainer	Set Accelerator	Super Plasticizer	Special Additive A
9	0.00	0.00	0.00	3831.39	145.28	204.85	24.07	7.20	212.04
10	0.00	0.00	0.00	4040.14	144.50	187.34	24.32	7.20	194.54
11	0.00	0.00	0.00	3702.27	146.92	213.51	22.11	7.20	220.70
12	0.00	0.00	0.00	4182.75	153.41	422.52	30.28	7.20	429.71
13	0.00	0.00	0.00	4061.97	145.53	187.44	24.08	7.20	194.64
14	0.00	0.00	0.00	3840.84	146.07	213.66	23.73	7.20	220.85
15	0.00	0.00	0.00	3843.75	144.63	210.46	24.38	7.20	217.66
16	0.00	0.00	0.00	3746.63	144.31	189.37	23.18	7.20	196.57
17	0.00	0.00	0.00	3670.83	153.20	189.35	23.29	7.20	196.54
18	0.00	0.00	0.00	4064.73	147.60	293.77	26.39	7.20	300.97
19	0.00	0.00	0.00	4065.05	146.43	229.26	25.79	7.20	236.45
20	0.00	0.00	0.00	4070.93	143.31	247.15	25.96	7.20	254.35
21	0.00	0.00	0.00	4048.14	144.61	187.36	24.35	7.20	194.56
22	0.00	0.00	0.00	3859.46	144.95	189.65	23.67	7.20	196.84
23	0.00	0.00	0.00	4038.14	144.57	187.34	24.30	7.20	194.54
24	0.00	0.00	0.00	4038.68	146.09	181.25	24.05	7.20	188.45
25	0.00	0.00	0.00	3859.65	144.96	189.66	23.68	7.20	196.85
26	0.00	0.00	0.00	3835.01	144.97	204.83	24.06	7.20	212.03
27	0.00	0.00	0.00	4000.82	144.62	186.70	24.48	7.20	193.89
28	0.00	0.00	0.00	4092.24	148.74	270.03	26.07	7.20	277.22
29	0.00	0.00	0.00	3819.92	143.98	186.88	23.63	7.20	194.08
30	0.00	0.00	0.00	3828.33	145.35	204.83	24.06	7.20	212.03
31	0.00	0.00	0.00	4008.78	143.47	219.46	25.65	7.20	226.66
32	0.00	0.00	0.00	4022.63	144.87	184.58	24.48	7.20	191.77

No	Special Additive B	Special Additive C	Retarder	Mass	Density	GWP_A1	GWP_A2	GWP_A3	GWP Total
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No	Special Additive B	Special Additive C	Retarder	Mass	Density	GWP_A1	GWP_A2	GWP_A3	GWP Total
1	0.00	0.00	0.00	3839.59	144.52	187.02	23.34	7.20	194.22
2	0.00	0.00	0.00	4066.74	145.16	335.01	27.39	7.20	342.20
3	0.00	0.00	0.00	3831.33	145.36	204.84	24.07	7.20	212.03
4	0.00	0.00	0.00	3831.05	145.35	204.82	24.06	7.20	212.02
5	0.00	0.00	0.00	4023.59	145.49	215.63	25.04	7.20	222.82
6	0.00	0.00	0.00	4009.59	144.40	314.29	26.55	7.20	321.48
7	0.00	0.00	0.00	3801.59	144.88	172.10	23.20	7.20	179.29
8	0.00	0.00	0.00	3826.18	144.62	213.82	23.45	7.20	221.01
9	0.00	0.00	0.00	3831.39	145.28	204.85	24.07	7.20	212.04
10	0.00	0.00	0.00	4040.14	144.50	187.34	24.32	7.20	194.54
11	0.00	0.00	0.00	3702.27	146.92	213.51	22.11	7.20	220.70
12	0.00	0.00	0.00	4182.75	153.41	422.52	30.28	7.20	429.71
13	0.00	0.00	0.00	4061.97	145.53	187.44	24.08	7.20	194.64
14	0.00	0.00	0.00	3840.84	146.07	213.66	23.73	7.20	220.85
15	0.00	0.00	0.00	3843.75	144.63	210.46	24.38	7.20	217.66
16	0.00	0.00	0.00	3746.63	144.31	189.37	23.18	7.20	196.57
17	0.00	0.00	0.00	3670.83	153.20	189.35	23.29	7.20	196.54
18	0.00	0.00	0.00	4064.73	147.60	293.77	26.39	7.20	300.97
19	0.00	0.00	0.00	4065.05	146.43	229.26	25.79	7.20	236.45
20	0.00	0.00	0.00	4070.93	143.31	247.15	25.96	7.20	254.35
21	0.00	0.00	0.00	4048.14	144.61	187.36	24.35	7.20	194.56
22	0.00	0.00	0.00	3859.46	144.95	189.65	23.67	7.20	196.84
23	0.00	0.00	0.00	4038.14	144.57	187.34	24.30	7.20	194.54
24	0.00	0.00	0.00	4038.68	146.09	181.25	24.05	7.20	188.45
25	0.00	0.00	0.00	3859.65	144.96	189.66	23.68	7.20	196.85

No	Special Additive B	Special Additive C	Retarder	Mass	Density	GWP_A1	GWP_A2	GWP_A3	GWP Total
26	0.00	0.00	0.00	3835.01	144.97	204.83	24.06	7.20	212.03
27	0.00	0.00	0.00	4000.82	144.62	186.70	24.48	7.20	193.89
28	0.00	0.00	0.00	4092.24	148.74	270.03	26.07	7.20	277.22
29	0.00	0.00	0.00	3819.92	143.98	186.88	23.63	7.20	194.08
30	0.00	0.00	0.00	3828.33	145.35	204.83	24.06	7.20	212.03
31	0.00	0.00	0.00	4008.78	143.47	219.46	25.65	7.20	226.66
32	0.00	0.00	0.00	4022.63	144.87	184.58	24.48	7.20	191.77

No	ODP_A1	ODP_A2	ODP_A3	ODP_Total	AP_A1	AP_A2	AP_A3
1	2.25758E-06	8.87589E-10	5.18306E-07	2.77588E-06	0.76	0.16	0.05
2	3.79463E-06	1.04156E-09	5.18306E-07	4.31293E-06	1.34	0.2	0.05
3	2.43698E-06	9.15217E-10	5.18306E-07	2.95529E-06	0.83	0.17	0.05
4	2.4369E-06	9.14921E-10	5.18306E-07	2.95521E-06	0.83	0.17	0.05
5	2.56677E-06	9.5201E-10	5.18306E-07	3.08507E-06	0.87	0.18	0.05
6	3.57569E-06	1.00964E-09	5.18306E-07	4.094E-06	1.26	0.19	0.05
7	2.0996E-06	8.82114E-10	5.18306E-07	2.61791E-06	0.7	0.16	0.05
8	2.53588E-06	8.91783E-10	5.18306E-07	3.05418E-06	0.86	0.16	0.05
9	2.43698E-06	9.15281E-10	5.18306E-07	2.95529E-06	0.83	0.17	0.05
10	2.27931E-06	9.24861E-10	5.18306E-07	2.79762E-06	0.76	0.17	0.05
11	2.53064E-06	8.40697E-10	5.18306E-07	3.04894E-06	0.86	0.16	0.05
12	4.44851E-06	1.15129E-09	5.18306E-07	4.96681E-06	1.69	0.22	0.05
13	2.28755E-06	9.15764E-10	5.18306E-07	2.80586E-06	0.76	0.17	0.05
14	2.53535E-06	9.02352E-10	5.18306E-07	3.05365E-06	0.86	0.17	0.05
15	2.49254E-06	9.27164E-10	5.18306E-07	3.01084E-06	0.85	0.17	0.05
16	2.26945E-06	8.81475E-10	5.18306E-07	2.78776E-06	0.76	0.16	0.05
17	2.27597E-06	8.85564E-10	5.18306E-07	2.79428E-06	0.76	0.16	0.05
18	3.3774E-06	1.00327E-09	5.18306E-07	3.89571E-06	1.18	0.19	0.05

No	ODP_A1	ODP_A2	ODP_A3	ODP_Total	AP_A1	AP_A2	AP_A3
19	2.71031E-06	9.80614E-10	5.18306E-07	3.22862E-06	0.92	0.18	0.05
20	2.89281E-06	9.87079E-10	5.18306E-07	3.41112E-06	0.99	0.18	0.05
21	2.28048E-06	9.25734E-10	5.18306E-07	2.79879E-06	0.76	0.17	0.05
22	2.28534E-06	9.0014E-10	5.18306E-07	2.80364E-06	0.77	0.17	0.05
23	2.27929E-06	9.23879E-10	5.18306E-07	2.79759E-06	0.76	0.17	0.05
24	2.2223E-06	9.14332E-10	5.18306E-07	2.74061E-06	0.73	0.17	0.05
25	2.28539E-06	9.00337E-10	5.18306E-07	2.8037E-06	0.77	0.17	0.05
26	2.43659E-06	9.1474E-10	5.18306E-07	2.9549E-06	0.83	0.17	0.05
27	2.26525E-06	9.31035E-10	5.18306E-07	2.78356E-06	0.76	0.17	0.05
28	3.13113E-06	9.91406E-10	5.18306E-07	3.64944E-06	1.09	0.19	0.05
29	2.24952E-06	8.9847E-10	5.18306E-07	2.76782E-06	0.75	0.16	0.05
30	2.43659E-06	9.1474E-10	5.18306E-07	2.9549E-06	0.83	0.17	0.05
31	2.59473E-06	9.75177E-10	5.18306E-07	3.11303E-06	0.88	0.18	0.05
32	2.24709E-06	9.30844E-10	5.18306E-07	2.7654E-06	0.75	0.17	0.05

No	AP_Total	EP_A1	EP_A2	EP_A3	EP_Total	POCP_A1	POCP_A2	POCP_A3	POCP_Total	PEC_A1	PEC_A2
1	0.8	0.08	0.01	0.01	0.09	12.93	4.63	0.22	13.15	1438.42	320.07
2	1.38	0.14	0.01	0.01	0.15	22.82	5.68	0.22	23.04	2525.54	375.59
3	0.87	0.09	0.01	0.01	0.1	14.12	4.8	0.22	14.34	1567.5	330.03
4	0.87	0.09	0.01	0.01	0.1	14.12	4.79	0.22	14.33	1567.16	329.93
5	0.92	0.09	0.01	0.01	0.1	14.86	5	0.22	15.08	1649.94	343.3
6	1.3	0.14	0.01	0.01	0.14	21.43	5.48	0.22	21.65	2371.56	364.08
7	0.74	0.08	0.01	0.01	0.08	11.93	4.57	0.22	12.15	1328.11	318.1
8	0.91	0.09	0.01	0.01	0.1	14.72	4.68	0.22	14.94	1636.11	321.58

No	AP_Total	EP_A1	EP_A2	EP_A3	EP_Total	POCP_A1	POCP_A2	POCP_A3	POCP_Total	PEC_A1	PEC_A2
9	0.87	0.09	0.01	0.01	0.1	14.12	4.8	0.22	14.34	1567.67	330.06
10	0.8	0.08	0.01	0.01	0.09	12.97	4.81	0.22	13.19	1444.23	333.51
11	0.91	0.09	0.01	0.01	0.1	14.69	4.44	0.22	14.91	1630.37	303.16
12	1.74	0.19	0.01	0.01	0.2	28.15	6.33	0.22	28.37	3518	415.16
13	0.81	0.08	0.01	0.01	0.09	12.98	4.76	0.22	13.2	1446.24	330.23
14	0.91	0.09	0.01	0.01	0.1	14.72	4.73	0.22	14.94	1632.82	325.39
15	0.89	0.09	0.01	0.01	0.1	14.49	4.87	0.22	14.71	1608.02	334.34
16	0.81	0.08	0.01	0.01	0.09	13.07	4.61	0.22	13.29	1452.42	317.87
17	0.81	0.08	0.01	0.01	0.09	13.08	4.63	0.22	13.29	1451.74	319.34
18	1.22	0.13	0.01	0.01	0.13	20.08	5.4	0.22	20.3	2221.23	361.79
19	0.97	0.1	0.01	0.01	0.11	15.77	5.17	0.22	15.99	1750.78	353.62
20	1.04	0.11	0.01	0.01	0.11	16.97	5.23	0.22	17.18	1887.13	355.95
21	0.8	0.08	0.01	0.01	0.09	12.98	4.81	0.22	13.19	1444.58	333.83
22	0.81	0.08	0.01	0.01	0.09	13.1	4.7	0.22	13.32	1457.54	324.6
23	0.8	0.08	0.01	0.01	0.09	12.97	4.8	0.22	13.19	1444.25	333.16
24	0.78	0.08	0.01	0.01	0.09	12.58	4.73	0.22	12.8	1399.79	329.71
25	0.81	0.08	0.01	0.01	0.09	13.1	4.7	0.22	13.32	1457.77	324.67
26	0.87	0.09	0.01	0.01	0.1	14.12	4.79	0.22	14.34	1567.39	329.86
27	0.8	0.08	0.01	0.01	0.09	12.93	4.83	0.22	13.15	1436.92	335.74
28	1.14	0.12	0.01	0.01	0.12	18.58	5.28	0.22	18.8	2072.97	357.51
29	0.8	0.08	0.01	0.01	0.09	12.91	4.68	0.22	13.13	1435.53	323.99
30	0.87	0.09	0.01	0.01	0.1	14.12	4.79	0.22	14.34	1567.39	329.86
31	0.93	0.1	0.01	0.01	0.1	15.1	5.13	0.22	15.32	1677.01	351.66
32	0.79	0.08	0.01	0.01	0.09	12.79	4.83	0.22	13.01	1422.18	335.67

No	PEC_A3	PEC_Total	NRE_A1	NRE_A2	NRE_A3	NRE_Total	RE_A1	RE_A2	RE_A3	RE_Total	NRM_A1	NRM_A2
1	121.34	1559.76	1288.68	320.07	113.39	1402.07	149.74	0	7.95	157.69	1778	0
2	121.34	2646.88	2261.11	375.59	113.39	2374.5	264.43	0	7.95	272.38	2000.32	0
3	121.34	1688.84	1404.19	330.03	113.39	1517.58	163.32	0	7.95	171.27	1800.05	0
4	121.34	1688.5	1403.84	329.93	113.39	1517.23	163.32	0	7.95	171.27	1800.05	0
5	121.34	1771.28	1477.9	343.3	113.39	1591.29	172.05	0	7.95	179.99	1888.03	0
6	121.34	2492.9	2123.25	364.08	113.39	2236.64	248.32	0	7.95	256.27	1954.12	0
7	121.34	1449.45	1190.15	318.1	113.39	1303.55	137.96	0	7.95	145.91	1765.49	0
8	121.34	1757.45	1465.79	321.58	113.39	1579.18	170.32	0	7.95	178.26	1843.03	0
9	121.34	1689.01	1404.35	330.06	113.39	1517.74	163.32	0	7.95	171.27	1800.05	0
10	121.34	1565.57	1293.98	333.51	113.39	1407.38	150.25	0	7.95	158.19	1869.65	0
11	121.34	1751.71	1459.94	303.16	113.39	1573.33	170.44	0	7.95	178.39	1784	0
12	121.34	3639.34	3209.85	415.16	113.39	3323.24	308.16	0	7.95	316.1	2089.18	0
13	121.34	1567.58	1295.66	330.23	113.39	1409.06	150.58	0	7.95	158.53	1883.31	0
14	121.34	1754.16	1462.59	325.39	113.39	1575.98	170.23	0	7.95	178.17	1852.2	0
15	121.34	1729.36	1440.42	334.34	113.39	1553.81	167.6	0	7.95	175.54	1801.28	0
16	121.34	1573.76	1301.1	317.87	113.39	1414.5	151.32	0	7.95	159.26	1731.2	0
17	121.34	1573.08	1300.23	319.34	113.39	1413.62	151.51	0	7.95	159.45	1753.04	0
18	121.34	2342.57	1988.49	361.79	113.39	2101.88	232.74	0	7.95	240.69	1986.5	0
19	121.34	1872.12	1568.12	353.62	113.39	1681.52	182.65	0	7.95	190.6	1915.36	0
20	121.34	2008.47	1690.89	355.95	113.39	1804.28	196.24	0	7.95	204.19	1944.08	0
21	121.34	1565.92	1294.3	333.83	113.39	1407.69	150.28	0	7.95	158.23	1873.53	0
22	121.34	1578.88	1305.79	324.6	113.39	1419.19	151.74	0	7.95	159.69	1790.39	0
23	121.34	1565.59	1294	333.16	113.39	1407.39	150.25	0	7.95	158.2	1868.68	0
24	121.34	1521.13	1254.18	329.71	113.39	1367.57	145.61	0	7.95	153.56	1894.35	0
25	121.34	1579.11	1306.02	324.67	113.39	1419.41	151.74	0	7.95	159.69	1790.39	0

No	PEC_A3	PEC_Total	NRE_A1	NRE_A2	NRE_A3	NRE_Total	RE_A1	RE_A2	RE_A3	RE_Total	NRM_A1	NRM_A2
26	121.34	1688.73	1404.08	329.86	113.39	1517.48	163.31	0	7.95	171.25	1798.59	0
27	121.34	1558.26	1287.38	335.74	113.39	1400.77	149.54	0	7.95	157.49	1849.97	0
28	121.34	2194.31	1859.66	357.51	113.39	1973.05	213.31	0	7.95	221.26	1997.67	0
29	121.34	1556.87	1286.13	323.99	113.39	1399.52	149.4	0	7.95	157.34	1766.77	0
30	121.34	1688.73	1404.08	329.86	113.39	1517.48	163.31	0	7.95	171.25	1798.59	0
31	121.34	1798.35	1502.32	351.66	113.39	1615.72	174.69	0	7.95	182.64	1855.42	0
32	121.34	1543.52	1274.2	335.67	113.39	1387.59	147.98	0	7.95	155.93	1862.52	0

No	NRM_A3	NRM_Total	RM_A1	RM_A2	RM_A3	RM_Total	CBW_A1	CBW_A2	CBW_A3	CBW_Total
1	0.57	1778.58	4.95	0	0.1	5.05	0	0	0.12	0.12
2	0.57	2000.89	8.88	0	0.1	8.98	0	0	0.12	0.12
3	0.57	1800.62	5.42	0	0.1	5.52	0	0	0.11	0.11
4	0.57	1800.62	5.42	0	0.1	5.52	0	0	0.11	0.11
5	0.57	1888.6	5.71	0	0.1	5.81	0	0	0.12	0.12
6	0.57	1954.69	8.33	0	0.1	8.43	0	0	0.13	0.13
7	0.57	1766.06	4.55	0	0.1	4.65	0	0	0.11	0.11
8	0.57	1843.6	5.66	0	0.1	5.76	0	0	0.11	0.11
9	0.57	1800.62	5.42	0	0.1	5.52	0	0	0.11	0.11
10	0.57	1870.22	4.95	0	0.1	5.06	0	0	0.12	0.12
11	0.57	1784.58	5.66	0	0.1	5.76	0	0	0.11	0.11
12	0.57	2089.75	10.37	0	0.1	10.47	0	0	0.1	0.1
13	0.57	1883.88	4.96	0	0.1	5.06	0	0	0.12	0.12
14	0.57	1852.77	5.65	0	0.1	5.76	0	0	0.1	0.1
15	0.57	1801.85	5.57	0	0.1	5.67	0	0	0.11	0.11
16	0.57	1731.77	5.01	0	0.1	5.11	0	0	0.12	0.12

17	0.57	1753.61	5.01	0	0.1	5.12	0	0	0.06	0.06
18	0.57	1987.07	7.79	0	0.1	7.89	0	0	0.12	0.12
19	0.57	1915.94	6.07	0	0.1	6.17	0	0	0.11	0.11
20	0.57	1944.65	6.53	0	0.1	6.64	0	0	0.11	0.11
21	0.57	1874.11	4.95	0	0.1	5.06	0	0	0.12	0.12
22	0.57	1790.96	5.02	0	0.1	5.12	0	0	0.11	0.11
23	0.57	1869.26	4.95	0	0.1	5.06	0	0	0.12	0.12
24	0.57	1894.92	4.79	0	0.1	4.9	0	0	0.11	0.11
25	0.57	1790.96	5.02	0	0.1	5.12	0	0	0.11	0.11
26	0.57	1799.17	5.42	0	0.1	5.52	0	0	0.11	0.11
27	0.57	1850.54	4.94	0	0.1	5.04	0	0	0.12	0.12
28	0.57	1998.24	7.12	0	0.1	7.22	0	0	0.11	0.11
29	0.57	1767.34	4.94	0	0.1	5.04	0	0	0.12	0.12
30	0.57	1799.17	5.42	0	0.1	5.52	0	0	0.11	0.11
31	0.57	1855.99	5.81	0	0.1	5.91	0	0	0.13	0.13
32	0.57	1863.09	4.88	0	0.1	4.98	0	0	0.12	0.12

No	CWW_A1	CWW_A2	CWW_A3	CWW_Total	TW_A1	TW_A2	TW_A3	TW_Total	CHW_A1	CHW_A2	CHW_A3
1	0	0	0.11	0.11	0.51	0	0.22	0.74	0.02	0	0.64
2	0	0	0.11	0.11	0.8	0	0.23	1.03	0.03	0	0.64
3	0	0	0.11	0.11	0.54	0	0.22	0.76	0.02	0	0.64
4	0	0	0.11	0.11	0.54	0	0.22	0.76	0.02	0	0.64
5	0	0	0.11	0.11	0.57	0	0.23	0.8	0.02	0	0.64
6	0	0	0.11	0.11	0.77	0	0.24	1.01	0.03	0	0.64
7	0	0	0.11	0.11	0.47	0	0.22	0.69	0.02	0	0.64
8	0	0	0.11	0.11	0.55	0	0.22	0.77	0.02	0	0.64

No	CWW_A1	CWW_A2	CWW_A3	CWW_Total	TW_A1	TW_A2	TW_A3	TW_Total	CHW_A1	CHW_A2	CHW_A3
9	0	0	0.11	0.11	0.54	0	0.22	0.76	0.02	0	0.64
10	0	0	0.11	0.11	0.52	0	0.23	0.75	0.02	0	0.64
11	0	0	0.11	0.11	0.55	0	0.22	0.77	0.02	0	0.64
12	0	0	0.11	0.11	0.88	0	0.21	1.09	0.04	0	0.64
13	0	0	0.11	0.11	0.52	0	0.23	0.75	0.02	0	0.64
14	0	0	0.11	0.11	0.55	0	0.21	0.77	0.02	0	0.64
15	0	0	0.11	0.11	0.56	0	0.22	0.78	0.02	0	0.64
16	0	0	0.11	0.11	0.52	0	0.23	0.74	0.02	0	0.64
17	0	0	0.11	0.11	0.46	0	0.17	0.63	0.02	0	0.64
18	0	0	0.11	0.11	0.72	0	0.23	0.95	0.03	0	0.64
19	0	0	0.11	0.11	0.59	0	0.22	0.81	0.02	0	0.64
20	0	0	0.11	0.11	0.62	0	0.22	0.84	0.02	0	0.64
21	0	0	0.11	0.11	0.52	0	0.23	0.75	0.02	0	0.64
22	0	0	0.11	0.11	0.52	0	0.22	0.74	0.02	0	0.64
23	0	0	0.11	0.11	0.52	0	0.23	0.75	0.02	0	0.64
24	0	0	0.11	0.11	0.5	0	0.22	0.72	0.02	0	0.64
25	0	0	0.11	0.11	0.52	0	0.22	0.74	0.02	0	0.64
26	0	0	0.11	0.11	0.54	0	0.22	0.76	0.02	0	0.64
27	0	0	0.11	0.11	0.52	0	0.23	0.75	0.02	0	0.64
28	0	0	0.11	0.11	0.66	0	0.22	0.88	0.03	0	0.64
29	0	0	0.11	0.11	0.51	0	0.23	0.74	0.02	0	0.64
30	0	0	0.11	0.11	0.54	0	0.22	0.76	0.02	0	0.64
31	0	0	0.11	0.11	0.58	0	0.23	0.82	0.02	0	0.64
32	0	0	0.11	0.11	0.51	0	0.23	0.74	0.02	0	0.64

No	CHW_Total	CNHW_A1	CHNW_A2	CNHW_A3	CNHW_Total	Initial_cost_items
1	0.66	0.19	0	6.67	6.86	123
2	0.67	0.34	0	6.67	7.01	124
3	0.66	0.21	0	6.67	6.87	120
4	0.66	0.21	0	6.67	6.87	120
5	0.66	0.22	0	6.67	6.89	120
6	0.67	0.32	0	6.67	6.99	120
7	0.66	0.17	0	6.67	6.84	120
8	0.66	0.21	0	6.67	6.88	120
9	0.66	0.21	0	6.67	6.87	120
10	0.66	0.19	0	6.67	6.86	123
11	0.66	0.21	0	6.67	6.88	118
12	0.68	0.4	0	6.67	7.07	122
13	0.66	0.19	0	6.67	6.86	123
14	0.66	0.21	0	6.67	6.88	120
15	0.66	0.21	0	6.67	6.88	130
16	0.66	0.19	0	6.67	6.86	112
17	0.66	0.19	0	6.67	6.86	112
18	0.67	0.3	0	6.67	6.97	118
19	0.66	0.23	0	6.67	6.9	112
20	0.66	0.25	0	6.67	6.92	112
21	0.66	0.19	0	6.67	6.86	117
22	0.66	0.19	0	6.67	6.86	117
23	0.66	0.19	0	6.67	6.86	117
24	0.66	0.18	0	6.67	6.85	112
25	0.66	0.19	0	6.67	6.86	112

26	0.66	0.21	0	6.67	6.87	122
27	0.66	0.19	0	6.67	6.86	106
28	0.66	0.27	0	6.67	6.94	108
29	0.66	0.19	0	6.67	6.86	120
30	0.66	0.21	0	6.67	6.87	122
31	0.66	0.22	0	6.67	6.89	122
32	0.66	0.18	0	6.67	6.85	122

APPENDIX E. INVENTORY VALUES FOR TRUCKS USED IN THE TRANSPORTATION MODULE

This section presents the inventory values used for the trucks presented in the transportation module.

Table E1 Transport, single unit truck, diesel powered per (ton.km) data

Details for Transport, single unit truck, diesel powered				
Flow	Category	Flow Type	Unit	Amount
Outputs				
Carbon dioxide, fossil	air/unspecified	Elementary	kg	1.71E-01
Carbon monoxide, fossil	air/unspecified	Elementary	kg	2.46E-04
Methane, fossil	air/unspecified	Elementary	kg	4.13E-06
Nitrogen oxides	air/unspecified	Elementary	kg	1.22E-03
Particulates, < 10 um	air/unspecified	Elementary	kg	2.35E-05
Sulfur oxides	air/unspecified	Elementary	kg	3.77E-05
VOC, volatile organic compounds	air/unspecified	Elementary	kg	8.42E-05

Table E2 Single unit truck, long-haul, diesel powered per (ton.km) data

Details for Transport, single unit truck, long-haul, diesel powered				
Flow	Category	Flow Type	Unit	Amount
Outputs				
Ammonia	air/unspecified	Elementary	kg	7.84E-06
Carbon dioxide, fossil	air/unspecified	Elementary	kg	3.23E-01
Carbon monoxide, fossil	air/unspecified	Elementary	kg	8.23E-04
Methane	air/unspecified	Elementary	kg	1.00E-05
Nitrogen dioxide	air/unspecified	Elementary	kg	1.77E-04
Nitrogen oxides	air/unspecified	Elementary	kg	1.71E-03
Nitrous oxide	air/unspecified	Elementary	kg	9.31E-07
Particulates, < 10 um	air/unspecified	Elementary	kg	9.10E-05
Particulates, < 10 um	air/unspecified	Elementary	kg	4.19E-06
Particulates, < 10 um	air/unspecified	Elementary	kg	2.10E-05
Particulates, < 2.5 um	air/unspecified	Elementary	kg	5.49E-06
Particulates, < 2.5 um	air/unspecified	Elementary	kg	1.00E-06
Particulates, < 2.5 um	air/unspecified	Elementary	kg	8.82E-05
Sulfur dioxide	air/unspecified	Elementary	kg	5.02E-06
VOC, volatile organic compounds	air/unspecified	Elementary	kg	2.06E-04

Table E3 Combination truck, gasoline powered per (ton.km) data

Details for Transport, combination truck, gasoline powered				
Flow	Category	Flow Type	Unit	Amount
Outputs				
Carbon dioxide, fossil	air/unspecified	Elementary	kg	6.18E-02

Carbon monoxide, fossil	air/unspecified	Elementary	kg	1.23E-03
Methane, fossil	air/unspecified	Elementary	kg	8.90E-06
Nitrogen oxides	air/unspecified	Elementary	kg	3.38E-04
Particulates, < 10 um	air/unspecified	Elementary	kg	1.48E-06
Sulfur oxides	air/unspecified	Elementary	kg	1.48E-05
VOC, volatile organic compounds	air/unspecified	Elementary	kg	5.53E-05

Table E3 Single unit truck, gasoline powered per (ton.km) data

Details for Transport, single unit truck, gasoline powered				
Flow	Category	Flow Type	Unit	Amount
Outputs				
Carbon dioxide, fossil	air/unspecified	Elementary	kg	1.32E-01
Carbon monoxide, fossil	air/unspecified	Elementary	kg	2.38E-03
Methane, fossil	air/unspecified	Elementary	kg	2.85E-05
Nitrogen oxides	air/unspecified	Elementary	kg	7.75E-04
Particulates, < 10 um	air/unspecified	Elementary	kg	3.79E-06
Sulfur oxides	air/unspecified	Elementary	kg	3.16E-05
VOC, volatile organic compounds	air/unspecified	Elementary	kg	1.77E-04

Table E4 Single unit truck, long-haul, gasoline powered per (ton.km) data

Details for Transport, single unit truck, long-haul, gasoline powered				
Flow	Category	Flow Type	Unit	Amount
Outputs				
Ammonia	air/unspecified	Elementary	kg	1.31E-05
Carbon dioxide, fossil	air/unspecified	Elementary	kg	3.11E-01
Carbon monoxide, fossil	air/unspecified	Elementary	kg	1.01E-02
Methane	air/unspecified	Elementary	kg	1.57E-05
Nitrogen dioxide	air/unspecified	Elementary	kg	9.83E-05
Nitrogen oxides	air/unspecified	Elementary	kg	1.16E-03
Nitrous oxide	air/unspecified	Elementary	kg	1.44E-05
Particulates, < 10 um	air/unspecified	Elementary	kg	4.49E-06
Particulates, < 10 um	air/unspecified	Elementary	kg	3.34E-06
Particulates, < 10 um	air/unspecified	Elementary	kg	1.75E-05
Particulates, < 2.5 um	air/unspecified	Elementary	kg	4.59E-06
Particulates, < 2.5 um	air/unspecified	Elementary	kg	4.14E-06
Particulates, < 2.5 um	air/unspecified	Elementary	kg	8.01E-07
Sulfur dioxide	air/unspecified	Elementary	kg	5.77E-06
VOC, volatile organic compounds	air/unspecified	Elementary	kg	4.71E-04

APPENDIX F. LCCA FOR TEXAS

Age	Activity	Quantity	Unit	Unit price \$	Total \$
Maintenance and repair					
15	Diamond grinding existing surface	0	yd ²	5.6	0
15	Full depth pavement design	32	yd ²	200	6400
15	MOT at 5%				320
15	Design cost at 10%				640
15	Construction inspection services at 10%				640
	Total				8000
Major maintenance					
25	Diamond grinding existing surface	22293	yd ²	5.6	124840.8
25	Full depth pavement repair	4.8	yd ²	200	960
25	MOT at 5%				6290
25	Design cost at 10%				12580
25	Construction inspection services at 10%				12580
25	Total				157250.8
Minor maintenance					
40	Diamond grinding existing surface	0	yd ²	5.6	0
40	Full depth pavement repair	4	yd ²	200	800
40	MOT at 5%				40
40	Design cost at 10%				80
40	Construction inspection services at 10%				80
	Total				1000
Major rehabilitation					
60	Milling	0	yd ²	3.5	0
60	Full depth pavement repairs	184	yd ²	150	27600
60	Place asphalt tack coat (9 yd ² /gal)	2477	gallon	1.7	4210.9
60	2 inch HMA binder	2475	tons	65	160846
60	2 inch HMA surface	2475	tons	65	160846
60	MOT at 5%				17675

60	Design cost at 10%				35350
60	Construction inspection services at 10%				35350
	Total				441877.9
	Salvage value				-75,002
	Overall Total (all items)				608,129

VITA

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