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A DECISION-MAKING TOOL FOR INCORPORATING CRADLE-TO-GATE SUSTAINABILITY INTO PAVEMENT DESIGN

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A DECISION-MAKING TOOL FOR INCORPORATING CRADLE-TO-GATE
SUSTAINABILITY INTO PAVEMENT DESIGN

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Construction Management

by
Sujata Subedi
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TABLE OF CONTENTS

ACKNOWLEDGEMENT	ii
ABSTRACT.....	v
CHAPTER 1. INTRODUCTION	1
1.1. Problem Statement	3
1.2. Objectives.....	4
1.3. Scope	4
1.4. Research Approach	5
1.5. References	8
CHAPTER 2. LITERATURE REVIEW	9
2.1. Pavement Sustainability	9
2.2. Pavement Life Cycle	10
2.3. Pavement Sustainability Measurement.	16
2.4. Environment Product Declaration (EPD).....	47
2.5. The relation between LCA, EPD, and PCR	54
2.6. Pavement Design and Sustainability	55
CHAPTER 3. Decision-Making Tool for Incorporating Cradle-To-Gate Sustainability Measures into Pavement Design.....	64
3.1. Introduction	64
3.2. Background	65
3.3. Objectives.....	68
3.4. Methodology	68
3.5. Data Sources.....	71
3.6. Environmental Impact Analysis	74
3.7. Economic Analysis.....	78
3.8. Overall Performance Score	79
3.9. Decision-Making Tool: A Windows-Based Software	80
3.10. Demonstration of the Decision-Making Tool in Case Studies.....	82
3.11. Results and Analysis	85
3.12. Summary and Conclusions.....	89
CHAPTER 4. SUMMARY AND CONCLUSIONS	93

4.1. Future Work	95
Appendix. COPYRIGHT PERMISSION	96
VITA	97

ABSTRACT

The need to continually maintain an aged and crumbling national roadway network, together with a growing demand for upgrading has resulted in major environmental and economic impacts around the nation. This has led to an interest in developing a structured framework to quantify the sustainability performance of pavements by balancing economic and environmental performance against engineering criteria. This study developed an Environment Product Declaration (EPD) based, decision-making framework to quantify the sustainability of pavement design alternatives. In this study, the sustainability of pavement is described in tandem with Environmental and Economic performance criteria. First, the Environmental analysis was inclusive of EPD and transportation module, where the first module quantifies environmental performances from raw material extraction to the manufacturing of pavement concrete mixes, and later measures the environmental burden associated with the transportation of concrete mixes from plant to the job site. Then, the economic module measures the cost value of a pavement alternative. Lastly, the computed economic and environmental performances were combined to define the overall performance, which in turn represents the cost-effective and environmentally preferable alternative. The developed framework was integrated into the current pavement design method, which in turn presents a decision-support system. To assist both designers and decision makers, the decision-support system can either benchmark or compare the sustainability of multiple pavement design/mixes, thereby assisting the decision makers to select the most sustainable alternative.

CHAPTER 1.

INTRODUCTION

In recent years, different agencies have embraced sustainable practices for their activities and business. The necessity to embrace the principle of sustainability garners more importance as human activities jeopardize both the environment and human health on a global scale. For instance, greenhouse gas (GHG) emissions plays a vital role in climate change, thereby impacting ecosystems and human health (Van Dam et al., 2015). The transportation sector (aircraft, ship, car, pipelines, rail, and trucks) alone contributes to 27% of the total in human-caused GHG emissions (EPA, 2013). Further, in GHG emissions, construction of transportation amenities also has an important role. Therefore, incorporating any sustainable practices in the transportation industry will carry a substantial impact on the global amount of GHG emissions. As an example, pavement system, as a main component of the nation's transportation industry, wields a major influence as an economic, social, and environmental component. The pavement system provides smooth and safe traveling for vehicles and users (FHWA, 2017).

Increased demand for a national roadway network, in tandem with a persistent upswing in the price of pavement materials, has aroused the need for an implementation of innovative and tenable technologies for the paving industry. In recent years, stakeholders tend to focus on the enhancement of pavement performance. However, only a few appear to be concerned with the overall sustainability of the pavement. A sustainable pavement must balance between three components of sustainability, i.e., its economic, environmental, and social components (Van Dam et al., 2015).

Over the years, various sustainability assessment methods have been developed to quantify pavement sustainability. Life Cycle Assessment (LCA) presents a structured methodology to quantify the environmental impacts in regards to the pavement life cycle (Kendall, 2012). LCA, also referred to as a cradle-to-grave framework, was introduced during late 1990's as a sustainability measurement tool for pavement. Since then, LCA has been the most commonly used sustainability tools in the pavement. Yet, even after three decades of LCA integration into the pavement, there remains a lack of standard methodology to measure pavement sustainability (Harvey et al., 2016).

The main challenge associated with LCA is data availability and reliability. The LCA framework covers all life-cycle stages of a product, i.e. from the raw material acquisition to the end-of-life. Therefore, the collection of the data for all these phases for analysis is time-consuming and difficult. Further, the accuracy of the LCA result depends on data quality. The time-consuming nature, coupled with data availability, brings into question the accuracy of LCA results. Further, LCA represents an evolving science, complete with a set of adopted assumptions, methodologies, interpretations and limitations which also vary among stakeholders. Such variations result in different impact values for the same pavement design. In essence, the results from LCA may not be consistent. Therefore, the use of LCA for decision-making might mislead the results (Santos, Thyagarajan, Keijzer, Flores, & Flintsch, 2017).

A new sustainable assessment approach for tools developed recently, is known as the Environment Product Declaration (EPD). EPD is a cradle-to-gate sustainability assessment method which applies industry standard rules in order to quantify the environmental burden associated with a product's a) raw material extraction, b) transportation of extracted materials from extraction site

to plant location, and c) production (Schenck, 2009). Placed another way, EPD reports the environmental impact of a product which is standardized and verified by a third party. Therefore, EPD addresses industry concerns with the limitation of LCA.

The standard rules on which EPDs are developed are Product Category Rules (PCR). PCR are developed by program operators; the process follows the cradle-to-gate frameworks as per ISO 14025 specification (Del Borghi, 2013). EPD quantifies the environmental performance by following standard rules, thus providing a basis for the comparison of the products at all levels. Also, the ready availability of inventory data in EPD lowers the time and effort necessary for data collection as required with LCA (Harvey et al., 2016).

While uncertainties associated with the LCA process slow its implementation in decision-making, the incorporation of an EPD based decision support system seems to be a more reliable choice for sustainability measures of pavement design. Since EPD only addresses the environmental performance of pavement products, implementation of economic performance into an EPD framework will potentially address a need for an analysis tool to incorporate environmental and economic aspects into pavement design decision making.

1.1 Problem Statement

Over the years, pavements have undergone many advancements to enhance performance. However, most of these innovative technologies focused on a single factor of sustainability: engineering performance. Therefore, to meet the needs of the concrete paving industry, a rational and comparable sustainability tool becomes necessary which can be integrated into an existing pavement design. A robust sustainability tool, which considers both environmental and economic

aspects of concrete mixes in pavement design selection, would thus enable pavement industry stakeholders to select the most sustainable pavement design alternative.

1.2 Objectives

The objective of the study was to develop an EPD framework to quantify the sustainability performances of a concrete pavement design/mix alternative. The developed framework could be integrated into a current pavement design such as Mechanistic-Empirical Pavement Design Guide (MEPDG) or the American Association of State Highway and Transportation Officials (AASHTO 93) in order to develop a decision-making tool. The tool would both compare and benchmark the overall sustainability by considering the environmental and economic performance of pavement alternatives and by optimizing the concrete mixes. The developed tool measures environmental performance based on the Environmental Product Declaration (EPD) as it declares impact data based on standard industry rules. The cradle-to-gate decision-making tool would be used by stakeholders, designers, and decision-makers to provide a comparison and benchmark as an alternative pavement design/ product.

1.3 Scope

The study integrated a cradle-to-gate framework into a current pavement design method and developed a sustainability measurement tool, which in turn identifies the most sustainable pavement design alternative by means of balancing engineering, economic, and environmental performances. The tool evaluates the sustainability of pavement alternatives based upon a cradle-to-gate framework, where gate references a construction site. The environmental and economic performances are quantified, based on an EPD and cost database. The EPD database provides environmental impact data for different concrete products that are used nation-wide, while the cost database provides economic data for all the corresponding products in the EPD database. The

database allows the user to modify the cost and EPD database, established on regional values, which in turn increases the accuracy of the developed tool.

The developed tool may be used by the decision makers and pavement agencies, and the like, either to benchmark or to compare pavement design/products. The first one averages the environmental and cost data of all the selected mixes (that satisfy the design) to quantify the environmental and economic performances. The latter one evaluates individual selected products to select the most eco-friendly and cost-effective product.

1.4 Research Approach

To achieve the aforementioned objectives, the proposed research activities consisted of 8 different tasks categorized into three project phases.

Phase 1: Develop Environment Impact Analysis Framework

Task 1: Development of the EPD database

Task 2: Collection of concrete mixes used in Louisiana pavement projects

Task 3: Collect inventory data from USLCI for different vehicle classification

Task 4: Develop EPD Module and Transportation Module

Phase 2: Develop Economic Analysis Framework

Task 5: Collect material cost data for all mixes and collect initial construction cost for Louisiana concrete mixes

Task 6: Compute the economic value of design/ product

Phase 3: Evaluate overall sustainability

Task 7: Combine economic and environmental framework

Task 8: Integrate the framework into pavement design to develop a decision-making tool

The first phase of the study was to develop an environmental analysis framework to quantify the impact associated with raw material acquisitions, transportations to plant, combining various concrete mixes, and transportation of those mixes to the job site. Initially, an EPD data was collected from different sources. Then, the EPD database was developed by compiling the data collected from an individual EPD database as well as the average data for Louisiana industry. Although individual EPD data were collected from different companies located nationwide, industry average data was solely for Louisiana-based mixes. Based on the plant location of the mixes, the EPD database was categorized into three different regional levels: 1) Statewide region (Louisiana), 2) Southern region (Louisiana, Oklahoma, Florida, and Texas) and the 3) Nationwide region (California, Washington, Louisiana, Oklahoma, Florida, and Texas).

Next, the EPD module was developed to quantify the impacts in a selected functional unit, i.e., m^3 per lane-km. Further, a transportation database was developed, which consisted of the emission data for different categories of trucks, i.e., Light duty truck, medium duty truck, and heavy-duty truck. For each category of the truck, emission data for two different fuel types, diesel, and gasoline, were collected. Lastly, this phase, developed a transportation module to quantify the impact associated with the concrete mix transportation from plant location to the job site.

The second phase of the study was to develop a framework for economic analysis. For this, the cost data i.e., material costs and the initial construction costs were collected. The material cost was

collected for the individual EPD by contacting the corresponding company, whereas the initial construction cost was collected for the Louisiana-based mixes. The initial construction cost was collected from the Louisiana Department of Transportation bid history database. The material cost was used to evaluate the economic performance for individual EPD mixes, whereas an initial construction cost was used to compute the economic performance for Louisiana mixes. All the costs were estimated in functional units, representing economic performance.

The final phase of the study was an evaluation of the overall sustainability of the pavement design/mix alternative. For this, the calculated environmental and economic performance was converted into relative scores. The relative scores were then weighted and summed to compute the overall sustainability score of the pavement design/mix alternative. Thus, a developed framework was then integrated into the pavement design, referred to as a decision-making tool.

The developed framework was based on a well-defined cradle-to-gate system boundary. It should be noted that the impacts due to the construction, use, maintenance, and end-of-life of pavement were not considered. Even though sustainable pavement balances the performance between economic, environmental, and social performances, the existing gaps associated with the quantification and assessment of the social performance of pavement limits its inclusion in the analyses.

The developed methodology was incorporated to develop the Windows-based software, the Sustainable Pavement Design Tool (SPD). The software allows the user to compare the design with the mix alternative. Moreover, the user can select the method of analysis in the software – either by benchmarking or product comparison. The first option provides a baseline result by averaging the impacts, whereas the latter compares the products individually.

1.5 References

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CHAPTER 2.

LITERATURE REVIEW

2.1 Pavement Sustainability

Sustainability may be defined as a human-originated system that has the ability to meet present human needs without degrading the larger system where it exists and functions (WCED, 1987). In pavement, the sustainability concept is broader; there is no single definition for pavement sustainability. However, sustainable pavement, as illustrated in Figure 2.1, refers to pavement characteristics which have the ability to preserve and restore the surrounding ecosystem, achieves engineering functionality, meets basic human needs, and consumes a minimal human, financial, and environmental resources (Harvey et al., 2016). Further, pavement sustainability considers three different components (economic, environmental, and social) in decision-making (Van Dam et al., 2015). These factors together are termed as a “triple-bottom” line. Over the years, the economic factor was the main factor in decision making. However, with an increased concern for environmental and social impacts associated with the pavement system, an increased number of stakeholders embrace different aspects of placing sustainability into the pavement.

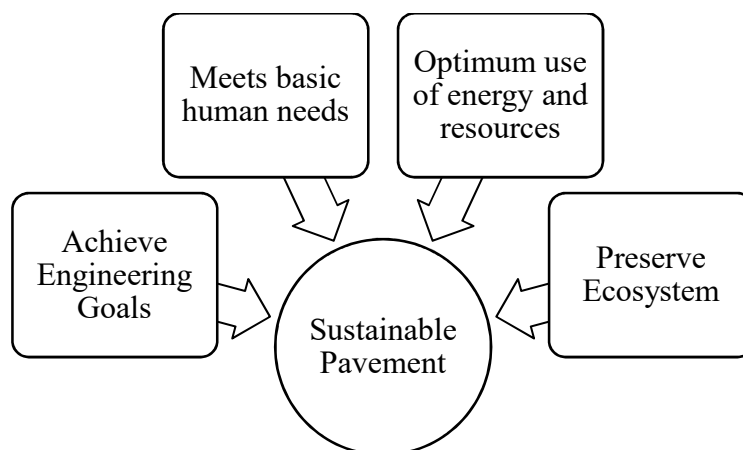


Figure 2.1. Characteristics of a sustainable Pavement (Harvey et al., 2016)

2.2 Pavement Life Cycle

To integrate sustainability measures into the pavement, it is essential to have a clear concept on pavement life-cycle. The six phases of the pavement life-cycle are presented in Figure 2.2. The section describes a different pavement-related process in each phase and how they are related. Sustainability approach may be integrated to each of these phases or can only include few phases (AzariJafari, Yahia, & Amor, 2016).

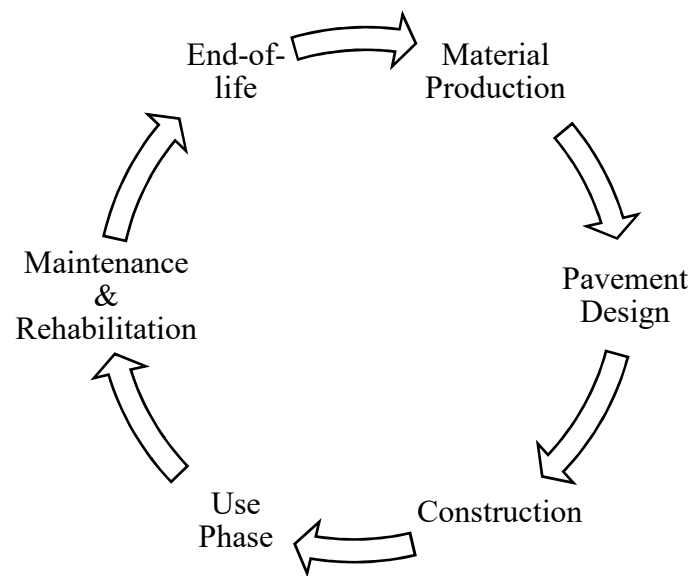


Figure 2.2. Pavement life cycle stages (Harvey et al., 2016)

2.2.1 Material Production

In pavement life-cycle, the initial phase includes raw material acquisition, transportation to the plant site, manufacturing of the finished product, production of the pavement mixes, and transportation to the construction site (Harvey et al., 2016). It is also termed as to as a cradle-to-gate framework system. Different studies have been conducted to investigate the environmental impact accompanying due to the extraction and production of pavement materials. Horvath and Hendrickson (1998) compared environmental impact due to the material production of steel-reinforced pavement against the asphalt pavement. The study concluded that asphalt pavement

consumes 40% more energy than the reinforced concrete (Horvath & Hendrickson, 1998). In asphalt pavement, the environmental impact is mainly associated with feedstock energy. For instance, the study conducted by Häkkinen and Mäkelä (1996) reported that while considering feedstock energy, the asphalt pavement, in the first phase of a pavement, approximately consumes two times more renewable energy than a normal concrete pavement (Häkkinen & Mäkelä, 1996). However, if feedstock energy is not considered, the impact due to two different pavement system would be the same. Further, a study by Nisbet (2001) reported that the concrete pavement requires less energy and have lower emissions during the raw material extraction and production (Nisbet, Marceau, VanGeem, & Gajda, 2001). In addition, the study also claimed that on asphalt pavement feedstock energy has a significant impact.

2.2.2 Pavement design

Pavement design involves determining the structural and functional demands based on the given environmental and traffic conditions. The structural and functional demand of the pavement is addressed by governing the pavement materials, a number of pavement layers, and their corresponding thickness. Different sustainable measures have been adopted by the Department of Transportation (DOTs) to enhance the environmental and economic benefits of pavement. Few sustainable measures adopted in the pavement design phase are:

- Using recycled concrete aggregate (RCA), recycled asphalt pavement (RAS), and recycled asphalt shingles (RAS) in the base layer.
- Using polymer-modified binder, stiffer materials such as RAP, RAS (recycled asphalt shingles) to extend the pavement life.
- Using industrial by-products such as slag, fly ash to reduce the cement consumption, and increase the durability of concrete.

- Incorporating environmental impact assessment methods in design criteria.
- Use of innovative technologies, such as rolling compacted concrete, fiber-reinforced concrete to increase the strength of concrete pavement and requires less maintenance and rehabilitation.

2.2.3 Construction.

This phase refers to all the activities and equipment works related to the pavement construction such as laying, compaction, transportation, and usage of equipment, etc. (Harvey et al., 2016). Various sustainability factors such as human health, water quality, project cost and time, etc. is being affected by aforementioned activities. Apart from these direct impacts of construction, it is necessary to quantify impact associated with other indirect factors such as energy required for night construction, impact due to traffic delay during construction, rerouting, etc. Different researchers have investigated the impact of these parameters on the environment during pavement construction. Striple (2001) investigated the impact of different types of construction equipment, such as excavators and pavers, on the environment during the construction phase (Stripple, 2001). The study concluded that the emissions during the operation of equipment in the construction phase are significantly higher than the emission during material extraction and production. Yet, the study didn't consider the impact associated with the construction delay, which limits the reliability of this study. Furhter, Zhang et al. (2005) used a tool to convert the delay caused during construction into environmental impact (H Zhang, Keoleian, & Lepech, 2008). The study concluded that the CO₂ emission and energy consumption associated with the traffic delay, during the construction phase, is higher than the all other phases considered in the study. However, the result from this study contradicts with the study performed by Chan (2007). Chan (2007) concluded that the energy consumption during material production is highest among all other

phases, yet, the emission during use phase (traffic) is comparable to impact due to material extraction and production phase (Chan, 2007). Apart from the research, recently different efforts, listed in Table 2.1, have been integrated to reduce the impact due to pavement construction.

Table 2.1. Sustainable practices in construction phase (Van Dam et al., 2015)

Objectives	Sustainability Practices	Environmental Impact	Economic Impact	Societal Impact
Reduce Fuel Consumption and Emission	Minimize haul distances	Decrease in GHG emissions and air pollutant	Decrease in fuel costs	
	Use of suitable equipment	Decrease in GHG emissions and air pollutant	Decrease in GHG emissions and air pollutant	
	Idling reduction	Decrease in GHG emissions and air pollutant	Reduction in fuel costs	Better air quality
	Use alternative fuels	Reduction in emission	Varies	Better air quality
	Decrease haul distances	Decrease in GHG emissions and air pollutant	Reduction in fuel costs	
Reduce Noise	Restriction in Construction time	May increase emissions	Can reduce in construction productivity	Less noise
	Proper condition of equipment	None	Increased capital investment	Less noise
Accelerate Construction	Effective traffic control strategies	Reduction in emission due to delays	Reduction in fuel cost (users & agency)	Less traffic disturbance
	Use project management software	Reduction in emission due to delays	Reduction in fuel cost (users & agency)	Less traffic disturbance
	Use of intelligent transportation warning systems	Reduction in emission due to delays	Increased agency costs	Less traffic disturbance and enhance safety
Control Erosion, Water Runoff, and Sedimentation	Use perimeter control barriers	Reduction in sedimentation, and degradation of water quality	May increase project costs	May reduce water pollution
	Apply erosion control blankets	Reduction in sedimentation	May increase project costs	Reduction in impact

2.2.4 Use Phase

When the pavement is in service it is termed as the use phase. In this phase, the traffic and environment are interacting with pavement i.e. from completion of pavement construction until its end-of-life. There are number of factors that determines the impact associated with the use phase such as vehicular characteristics (tire width, tire type, axle load etc.) and pavement characteristics such as (roughness, heat capacity, structural responsiveness, permeability, macrotexture, albedo and conduction (Babashamsi, Md Yusoff, Ceylan, Md Nor, & Salarzadeh Jenatabadi, 2016). These factors influence sustainability metrics such as GHG emissions, vehicle operating costs, fuel economy, energy use, human health, radiative forcing etc. (Van Dam et al., 2015). As there are many parameters in this phase, quantification of impacts due to this phase is complex and the least considered in most of the pavement sustainability studies. Zaniweiski (1989) studied the influence of pavement structure on fuel consumption by considering different pavement and vehicle type. The author concluded that the difference in fuel consumption by asphalt and concrete pavement is insignificant i.e. the later one consumes 1% less fuel (Zaniewski, 1989). Regarding the effect of pavement roughness, Sandberg (1990) investigated 20 different existing roads with different level of roughness. The study concluded that fuel consumption due to the roughness varies up to 11% from smooth to rough asphalt pavement (Sandberg, 1990). Another environmental impact associated with the use phase is noise-induced due to pavement vehicle interaction. Bennert (2005) conducted a comparison study on noise-induced due to two different type of asphalt pavement: dense graded asphalt and Stone Mastic Asphalt (SMA). The study concluded that the SMA produced less noise in comparison to the dense graded asphalt pavement (Bennert, Hanson, Maher, & Vitillo, 2005). The reduction in noise in SMA is related to the pavement roughness and materials.

2.2.5 Maintenance and Rehabilitation

The activities performed in order to maintain the structural and functional capacity of a pavement is referred to as a Maintenance and Rehabilitation (M&R) activities. Overlays, patching, chip sealing, seal coats, milling, in-place recycling, etc. are some examples of M&R activities. The type and frequency of M&R are dependent upon multiple factors such as pavement design, traffic, type, and environmental conditions. M&R activities influence sustainability factors such as durability, material use, performance life etc. (Harvey et al., 2016). Over the years, only initial construction cost has been considered in the economic analysis, however, with the increase in interest on the impact due to the pavement M&R, recently, this phase is considered for both economic and environmental analysis. In the context of environmental impact as well, many researchers investigated the environmental impact induced due to pavement maintenance and rehabilitation. Chan (2007) compared the environmental impact due to the M&R of asphalt and concrete pavement by quantifying the GHG emissions and energy consumption by M&R activities of both pavements. The study concluded that the concrete pavement rehabilitation consumed less energy when compared to the asphalt pavement rehabilitation activities. The author also mentioned that the energy consumed by flexible pavement during M&R activities is only 10% of the initial cost (Chan, 2007). Similarly, Athena Institute (2006) also compared the environmental burden associated with the concrete and asphalt M&R alternatives. The study was detailed as it included most of the M&R activities for both types of pavement such as overlay, milling, full reconstruction, etc. The study concluded that the energy consumed by the asphalt pavement M&R activities were higher when compared to the rigid pavement (Institute, 2006).

2.2.6 End-of-life

The phase when the pavement is not useful anymore, and requires either final disposal, reuse or recycling process is referred to as end-of-life. FHWA has classified Recycle materials (RAP, RCA), full-depth reclamation, and landfilling as end-of-life considerations (Harvey et al., 2016). The main challenge in this phase is associated with allocation i.e., how much benefits and impacts should be allocated and partitioned between the original pavement and the proposed new pavement (Horvath, 2003). If the materials are not recycled, then the impacts associated with the transportation of the removed pavement materials to the disposal or landfill site should be considered (Harvey et al., 2016). Ekvall and Tillman (1997) conducted an experiment with an objective to make the allocation procedure effect oriented. The authors reported the problems associated with the ISO allocation method, and then proposed eight different allocation methods. The study suggested that the allocation method should be aligned with the goal and scope of the study, and therefore, didn't recommend any rigid procedure to conduct allocation (Ekvall & Tillman, 1997). A similar investigation on allocation was conducted by Nicholson et al. (2009). The study recommended 5 different allocation method but suggested that the allocation method should be selected based on the overall goal and scope. The study further recommended that the end-of-life has a significant (may be positive or negative) effect on the environment and therefore should be considered on any environmental impact analysis (Nicholson, Olivetti, Gregory, Field, & Kirchain, 2009).

2.3 Pavement Sustainability Measurement.

With the increase in demand for national roadway system, in tandem with increasing interest in sustainability, sustainability measurement is widely investigated, both in transportation and pavement. Further, the pavement system exists and functions in a larger system, therefore, it is

imperative to measure the impact imposed by pavement to the surrounding system. The measurement of pavement sustainability would assist both in benchmarking and comparing pavement design alternatives. There are distinctive ways to deal with pavement sustainability measurement. However, due to discrepancies in system boundaries, definitions and valuation among pavement stakeholders, it is difficult to compare different measurement efforts (Van Dam et al., 2015). Currently, there are four general measurement tools to measure different pillars of sustainability: Sustainability rating system, life-cycle cost analysis (LCCA), performance assessment and life cycle assessment (LCA). Each of these tools has its very own qualities and shortcomings. Based on the methodology, these tools can be categorized as qualitative and quantitative. A qualitative measurement tool, sustainability rating system, depends on conceptual approaches to gather and accumulate data on monetary, environmental, and social performances of pavement system framework (Babashamsi, Md Yusoff, et al., 2016). These databases are then used to give a rating or score to the pavement alternatives, which in turn mirrors the sustainability of the corresponding alternative. On the other hand, the quantitative technique is a rational method which uses either developed models or observational equation (empirical formula) for sustainability quantification. The quantified value reflects the impact related with different pavement life-cycle phases. However, it should be noted that all quantitative tools do not consider the overall pavement life cycle to quantify the impact. Some quantitative tool system boundaries may be a cradle-to-gate framework (only material production), whereas some consider cradle-to-grave framework or even cradle-to-cradle framework. However, the choice of inclusion or exclusion of each life cycle is dependent upon time constraint, availability of funds, characteristics, and demands of the project. Performance assessment, LCCA, and LCA are the most commonly used quantitative sustainability measurement tool.

2.3.1 Sustainability rating system

The sustainability rating system also referred to as qualitative approach, is an assembly of practices or features that modify nature, economy, or social qualities, combined with a uniform technique of measurement score, usually a point (Van Dam et al., 2015). Till date, there are different sustainability rating techniques. The nature of the rating framework and the objective of a project determines the most reliant sustainability rating system. For a rating of different pavement alternatives, information on the type, their impacts and possible range imposed by the pavement systems are gathered. The gathered data, in tandem with sustainability practices as defined by the rating framework, is then used to acquire the complete sustainable rating or score of a pavement design, which thereby reflects their relative effects. Currently, there is numerous international and national rating system available in the pavement community. ENVISION, The Sustainability tracking, Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), Green roads, Assessment and Rating System (STARS), BE2ST-in-highways, Green Highway Partnership (GHP), I-LAST, Sustainable Infrastructure Project Rating System (SIPRS), Sustainable Transportation Environmental Engineering and Design (STEED), are examples of national and global rating systems that have been created (Hirsch, 2011). Some of these sustainability rating systems may be a self-evaluation-based or third-party evaluation. In self-evaluation, there is no user or agency cost as users evaluate their own projects. Third-party evaluation, on the other hand, requires certification of the scores and official recognition from other agency. The third-party evaluation will cost extra money to an agency or users. A summary of the normally utilized sustainability rating systems are listed in Table 2.2.

Table 2.2. Summary of sustainability rating system (Barrella, Amekudzi, Meyer, Ross, & Turchetta, 2010) (Soderlund, Muench, Willoughby, Uhlmeier, & Weston, 2008)

Type of rating	Tool Name	Developed by (Launch Date)	Features
Self-Evaluation	GreenLITES	New York State Department of Transportation (2008)	<ul style="list-style-type: none"> • Transportation-specific rating system • Used internally by NYDOT
	GHP	FHWA, EPA, and MDSHA	<ul style="list-style-type: none"> • Pavement-specific rating system • Based on three principle aims: safety, project environmental streamlining, and congestion reduction
	I-LAST	Illinois DOT (2009)	<ul style="list-style-type: none"> • Performance-based approach, the pavement-specific rating system • Focuses mainly on beginning, construction, and end of the phase
	INVEST	FHWA's Sustainable Highways (2010)	<ul style="list-style-type: none"> • Transportation-specific rating system • Scoring and documentation web-based
	ENVISION	Institute for Sustainable Infrastructure	<ul style="list-style-type: none"> • The broad-based infrastructure rating system • Scoring and documentation web-based
Third-Party Certification	Greenroads	University of Wisconsin, Washington State DOT (2012), and CH2M Hill	<ul style="list-style-type: none"> • Transportation-specific rating system • Applicable to all type of roadway projects
	STARS	A public-private team from Oregon and Washington (2010)	<ul style="list-style-type: none"> • Transportation-specific rating system • Focuses mainly on the use phase

One of the benefits of using sustainability rating system is that it covers extensive variety of elements and practices, like wastes from pavement construction, disruption to neighboring land due to construction, use of recycled materials into the new pavement system, pedestrian accessibility, ecosystem connectivity, stormwater runoff, use of locally available materials and resources, etc. (Zietsman, Ramani, Potter, Reeder, & DeFlorio, 2011). In a simple analysis, a rating

system assigns equal value to every best practice (i.e. all are equivalent to one point). However, in a complex form, best practices are weighed in a rating system (based on their priority or impact on sustainability). The latter one is more useful in case of constrained finances or scope because it assists in choosing the foremost impactful practices. Yet, in the simplest form, a common metrics are assigned to a broad aspect of sustainability practices, which may sometimes generate conflict on which aspects to incorporate or exclude.

The weakness of this method is that it doesn't quantify full environmental impacts as in quantitative methods. Recently, Leadership in Energy and Environmental (LEED) system, modified the sustainability certification criteria to quantification of the environmental impacts rather than scoring. This has motivated agencies and organizations to progressively transfer from qualitative measures to quantitative ones.

2.3.2 Performance Assessment

Performance Assessment, a sustainable quantification tool, evaluates pavement performance of a proposed pavement by comparing it against intended performance and assesses the functional and structural attributes that are necessary to meet the intended function (Van Dam et al., 2015). Metrics to represent the performance assessment vary from organization to organization, yet, most of them include traditional distress ratings (e.g. cracking, faulting, rutting, etc.), pavement structural capacity, composite condition rating system, material design parameters (such as gradation, thickness, compressive strength, etc.), along with the mechanisms to compare the expected design parameters to these attributes (Harvey et al., 2016). Since performance is evaluated by comparing the proposed function of a pavement against their intended function, there is no need for different guidelines for this assessment, instead, a standard practice is followed. For example, if a plain concrete pavement lasts for 25 years after construction, the value of proposed

alternative concrete materials (e.g. fiber reinforced, steel reinforced) are assessed as per their proposed service life as compared to standard 25 years. The main criterion for evaluating pavement performance is that it should at least perform better than the current standard practice. Since this method is easily applicable, different DOT's have adopted this methodology to compare different pavement alternatives. Figure 2.3 presents the list of different states that have integrated performance assessment at a different phase of pavement life cycle.

Planning and programming	<ul style="list-style-type: none"> • Wisconsin, California Department of Transportation (Caltrans) • Metropolitan Transportation Commission (MTC) • Denver Regional Council of Governments (DRCOG) • North Jersey Transportation Planning Authority(NJTPA), • States: Maryland, Minnesota, Ohio, Wisconsin, Florida, Washington, Oregon
Project development	<ul style="list-style-type: none"> • Caltrans and NJPTA
Construction	<ul style="list-style-type: none"> • New York State Department of Transportation (NYSDOT), • States: Wisconsin, California, Washington
Maintenance and Rehabilitation operations.	<ul style="list-style-type: none"> • New York Metropolitan Transportation Authority (NYMTA), • States: California

Figure 2.3. Performance assessment adopted by different state and agencies in different pavement life-cycle phase (Grant, 2011)

2.3.3 Life Cycle Cost Analysis

Over the years, initial construction cost has been the main criterion for the selection of the pavement alternative. However, with the rise in value associated with pavement maintenance and rehabilitation, in tandem with the restricted quantity of funds, pavement decision makers have integrated cost analysis tools to select the foremost cost-efficient pavement alternative. Life-

cycle cost analysis (LCCA) presents a cradle-to-grave framework, illustrated in Figure 2.4, to determine the overall cost of the pavement by accounting all pavement life-cycle stages (Lamprey, Ahmad, Labi, & Sinha, 2005). ISO 15686-5 defines LCCA as a cost analysis tool for estimating and evaluating economic performance by incorporating all the pertinent economic factors (both initial and future costs) of various assets that meet the structural, functional, operational, and different necessities (ISO, 2008). LCCA evaluates economic performance by considering that benefits associated with different alternatives are same that the benefits of all considered alternatives are the same, and thus only differential cost should be considered (Van Dam et al., 2015). Since LCCA accounts only for the economic component, it is recommended that along with LCCA, LCA should be performed as well.

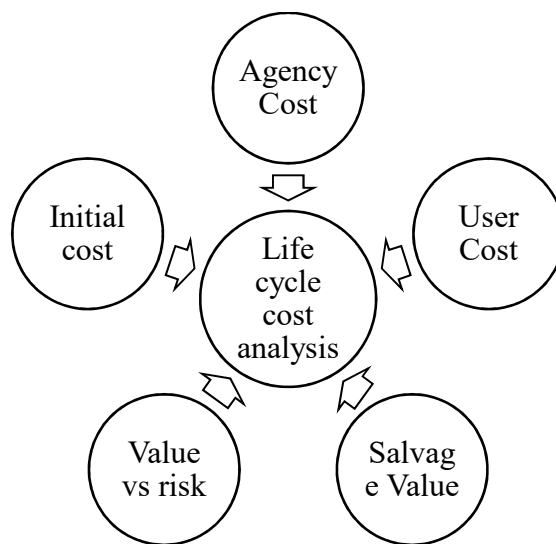


Figure 2.4. Life Cycle Cost Analysis Framework

There are three different categories of LCCA, namely, 1) conventional, 2) societal, and 3) environmental (Swarr et al., 2011). The conventional LCCA, which is the most common one, accounts for monetary values covered by the user or producer throughout the pavement life cycle. LCCA, where the environmental damage is quantified and monetized is referred to as an

environmental LCCA (Lamprey et al., 2005). Environmental LCCA is a complex process, and due to the lack of a standard practice to conduct an environmental LCCA or technique for monetization of environmental impact, they are not often used. Lastly, societal LCCA is conducted by extending the analysis into the macro-economic system level i.e. by including the costs for the society (Lamprey et al., 2005). All categories of LCCA can be quantified by two approaches, deterministic LCCA, and probabilistic LCCA. While the deterministic approach utilizes fixed discrete values for each LCCA input variables, input variables in a probabilistic approach are defined by a frequency (probability) (FHWA, 2002). Since deterministic LCCA approach uses discrete value for the input variable, it doesn't account for the uncertainties associated with it. However, in the probabilistic LCCA approach, uncertainties are accounted as it provides a range of values for a variable (FHWA, 2002). As, deterministic approach estimates in a fixed value, there is a high chance that values may not be accurate and might mislead during the decision-making. Therefore, when the deterministic approach is adopted, it is necessary to conduct a sensitivity analysis to investigate if a change in input variables alters the estimations. Since the probabilistic approach gives the results in a range and the confidence levels, it addresses the limitation of the deterministic approach (Van Dam et al., 2015). Life-cycle cost, quantified either by the deterministic or probabilistic approach, properly weights for present cost and future costs, and it is imperative that all costs should be compared in an equivalent time frame. This is usually performed determined by Equivalent Uniform Annual Cost (EUAC), Incremental Benefit-Cost (IBC) analysis, Net Present Value (NPV), etc. NPV is determined by discounting all project costs to a base, or present year. EUAC is evaluated by converting all costs of the project to an equal recurring annual cost over the analysis period. EUAC is appropriate for projects whose budgets are established on an annual basis.

Over past few decades, LCCA has gained wide range of popularity and are used as a “decision-support tool” in various applications. National Highway System (NHS) Designation Act of 1995 states that if a project segment cost equals or exceeds \$25 million, it is necessary to implement LCCA (Kane, 1996). The NHS act recommended LCCA to be used as a decision-support tool. In the same act, it is also stated project investment should determine the detail level of LCCA analysis i.e. major to minor as per the larger and smaller level of investment (Kane, 1996). However, due to lack of proper guidance on using LCCA, later in the 1998 Transportation Equity Act for the 21st Century (TEA-21) the NHS act was reversed (Olson, 2000). Yet, different agencies and government agencies utilize LCCA for financial analysis (e.g. OMB circular No. A-94, Executive order 13123) (Van Dam et al., 2015). In addition, the Federal Highway Administration (FHWA) recommends incorporating LCCA in all major investments i.e. projects that have a wide range of influence (Guyen, Rangaraju, & Amirkhanian, 2008).

The first implementation of LCCA in the pavement can be recorded in 1991 by ISETA, which considered LCCA in the design and construction of pavements (Van Dam et al., 2015). Further, a mandatory rule, applied by Executive order no. 12893 “Principles of Federal Infrastructure Investment” in January 1994, stated that for all infrastructure investment decision, the cost-benefit analysis should be directed by considering the overall life cycle (Van Dam et al., 2015). Till date, the use of LCCA to evaluate the economic performance of pavements is common. For some of the states, LCCA been the important factor in pavement selection over the years. Therefore, different state DOT’s have adopted different economic practices (presented in Table 2.3). From Table 2.3, it can be observed that the FHWA’s *RealCost* Software is widely used in comparison to other tool (Van Dam et al., 2015).

Table 2.3. Economic practices adopted by different states (Wazi, 2016)

LCCA Tool	State	Analysis Period (Years)	Discount Rate (%)	User Costs Included
RealCost	California	20, 35, 55	4	Yes
	Colorado	40	Determined manually	Yes
	Florida	40	3.5	Optional
	Indiana	At least 50 (for new)	4	Yes
	Oregon	40 (new) 50 (Interstate)	4	Optional
	Washington	50	4 (based on OMB)	Yes
Custom Spreadsheet	Georgia	30, 40	3	Yes
	Minnesota	35 to 50	Determined annually	No
	Pennsylvania	50	4	Yes
DARWin and custom software	Michigan	10 to 20	Determined annually	Yes
Custom software	Texas	30	Not specified	Yes

There are a number of studies that have integrated LCCA in pavement projects either to determine the overall cost of pavement or to compare and select different pavement alternatives. The FHWA in the State of Utah adopted LCCA to assess the cost-effectiveness of different pavement M&R strategies. The LCCA analysis was conducted based on a framework which consists of four phases: 1) pavement analysis module, (2) selection of alternative M&R strategies (3) ranking of M&R alternatives based on their corresponding cost-effectiveness (4) selection of the M&R with highest ranking (Anderson, Peterson, Sheppard, & Sy, 1979). However, the main limitation of this study is that it only considered the cost-effectiveness of each alternative but didn't consider their environmental impact. Similarly, Corvetti and Owusu-Ababio (1999) did research on the

feasibility of pavement design alternatives for Wisconsin DOT. The result of their research revealed the deficiencies of the LCCA conducted by WisDOT. The conclusion was drawn according to some types of asphalt and concrete pavement designs that been missed through conducting the LCCA program in this state (Croveti & Owusu-Ababio, 1999). Smith et al. (1993) have done some “LTPP (The Long-Term Pavement Performance) and SHRP (The Strategic Highway Program)” studies, with the purpose of creating a tool reflects the accurate characterization of the pavement and would not rise the economic resources consumption significantly (Smith, Freeman, & Pendleton, 1993). The framework for pavement LCCA is presented in Figure 2.5.

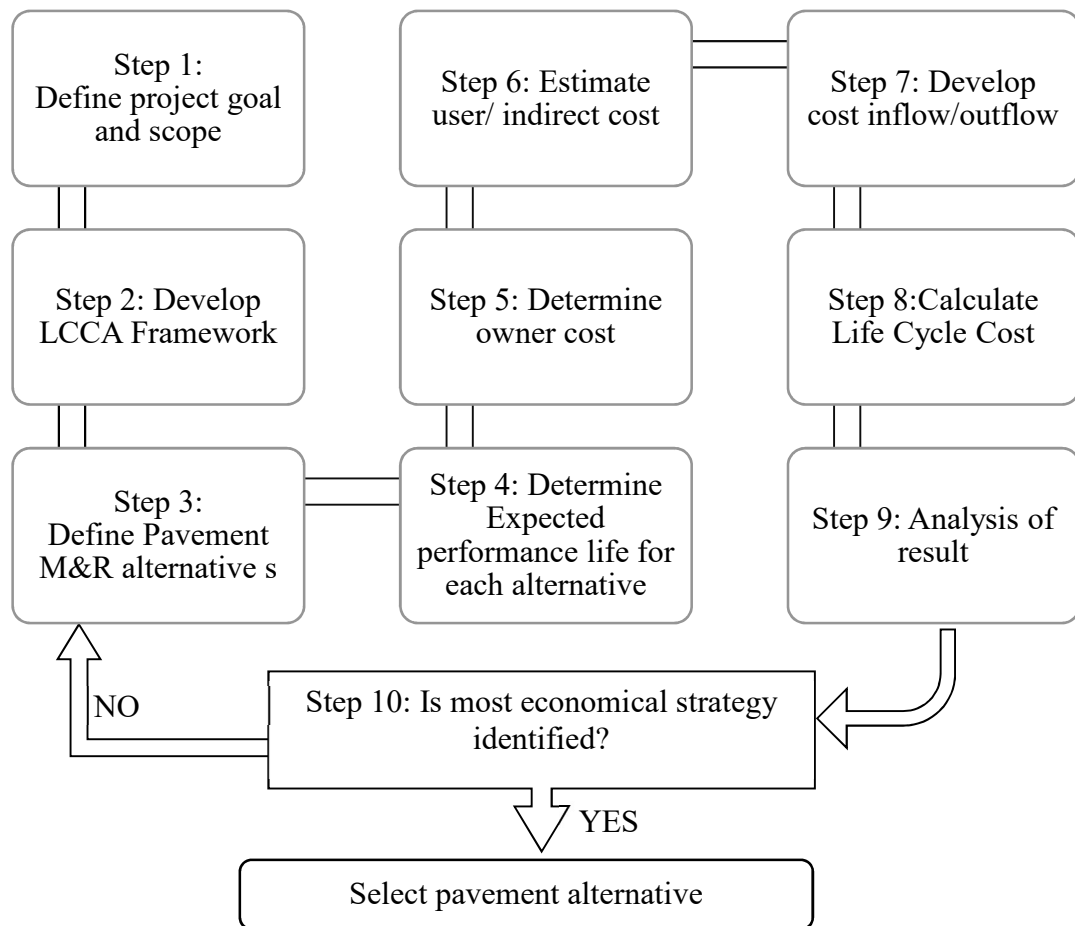


Figure 2.5. Methodology to consider a pavement LCCA (Babashamsi, Yusoff, Ceylan, Nor, & Jenatabadi, 2016)

Even though LCCA considers all the phases of pavement and provides many benefits, its use has been limited as it doesn't account for the performance level. Therefore, LCCA is not suitable to compare and select pavement alternatives with different level of performance, it will not provide a reliable result. Another drawback of LCCA is that it doesn't account for environmental and social performances. Therefore, it should be noted that an alternative with the lowest LCC is not necessary to be sustainable too. Hence, it is recommended that LCA should be integrated with LCCA in pavement alternative selection. Further, a variable such as user cost, discount rate, and end-of-value parameters have different conflicting points. Due to this, the LCC of similar pavement varies from one study to another. Due to the aforementioned limitation of LCCA, it is

recommended LCCA to be used as a support tool while selecting pavement alternative rather than being the decision-making tool.

2.3.4 Life Cycle Assessment

Life Cycle Assessment (LCA), also referred as a cradle-to-grave analysis tool, determines the potential environmental impacts of a product over its life-cycle. As illustrated in Figure 2.6, an LCA requires the input of energy and resource consumption and in return will provide a range of environmental impacts categorized into different impact categories across the overall life-cycle of a product (Harvey et al., 2016). During the late 1990s, LCA was recognized as an impact assessment method when ISO standardized LCA methods (SAIC 2006). Since then LCA has been used by different industry stakeholders and agencies to quantify the environmental impact related to their product. In addition, LCA quantifies the impact due to each phase, therefore, it benefits the user to easily track product phase that has a substantial impact on the environment. In addition, LCA also allows user and consumers to relate the environmental performances of different product alternatives, and therefore would assist in decision-making. Due to these characteristics, LCA is the widely used sustainability quantification tool.

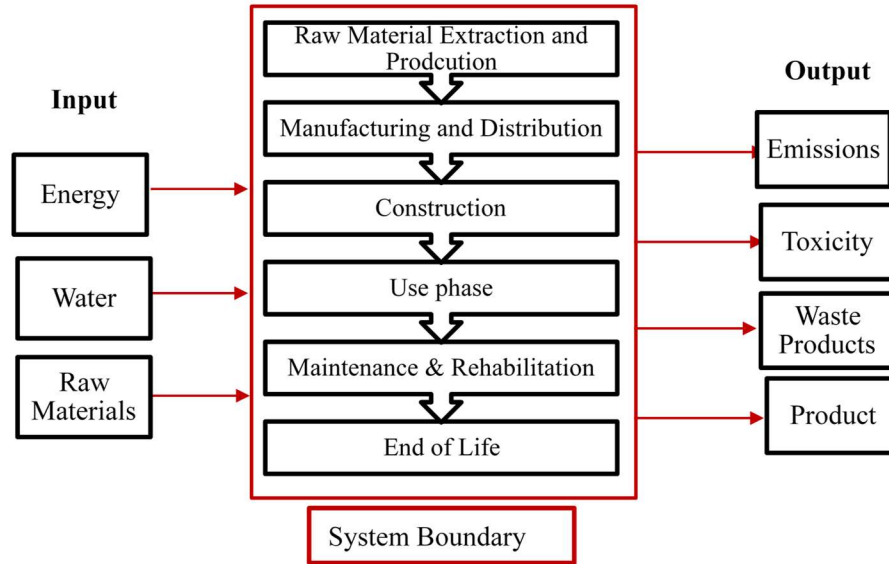


Figure 2.6. LCA framework (Harvey et al., 2016)

2.3.4.1 LCA Framework

The LCA framework, presented in Figure 2.7, consists of a) Goal and Scope definition, b) Life-cycle Inventory (LCI), c) Life-cycle impact assessment (LCIA), and d) Interpretation (João Santos, Flintsch, & Ferreira, 2017)

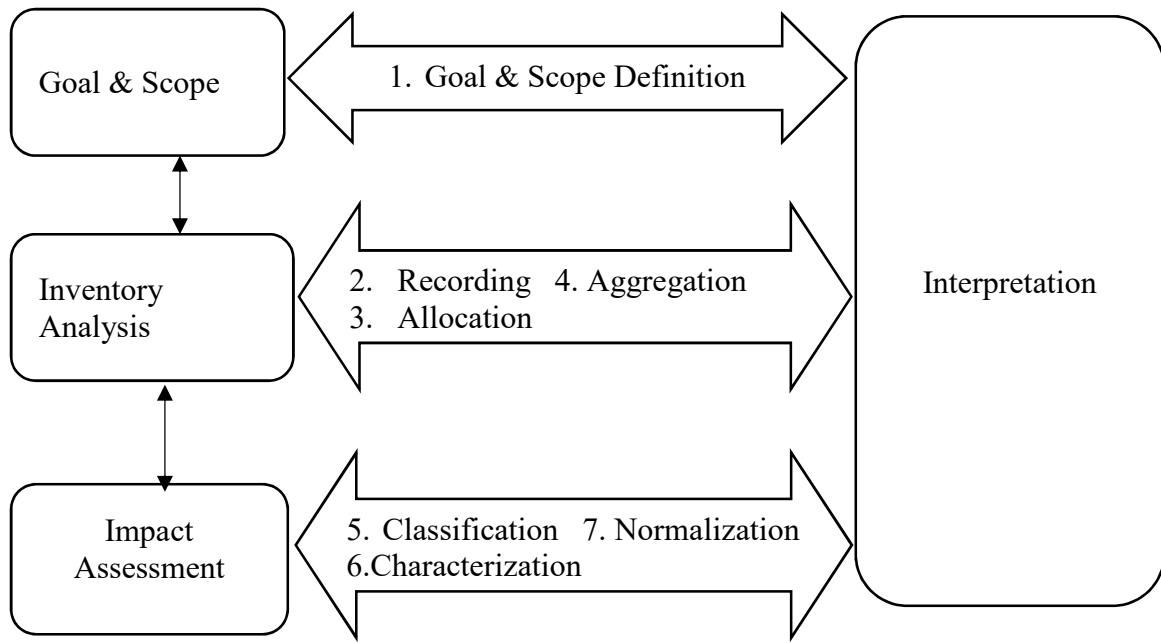


Figure 2.7. Four Phases of LCA (Harvey et al., 2016)

a) Goal and Scope: In any LCA analysis, the initial step is to set its goal and scope. In other words, a clear statement on what is the purpose of the study, system analysis boundary, a required level of accuracy, allocation method, and type of LCA (attributional or consequential) is required. For a reliable and accurate LCA, it is necessary that the scope should be in accordance with the purpose of LCA. In context to the pavement LCA, the goal of pavement LCA can be either benchmarking, comparing different pavement types, assessment of different pavement M&R strategies, etc. A literature review of past studies shows that the most of the studies were conducted to compare different types, whereas few of them were conducted to select the most eco-friendly M&R alternative for same pavement type (Loijos, 2011; Mroueh et al., 2013; Spielmann & Scholz, 2005).

There are two main types of LCA i.e. attributional and consequential. Attributional LCA quantifies the environmental impacts associated with a specific process or service. However, consequential LCA evaluates the difference in the environmental impacts due to a change in a system or a

decision. Next, in this phase a functional unit should be selected to represent the quantified performance of a product or system. Functional unit are reference unit as per which all the input and output of energy/ material data are collected. While conducting a comparative LCA, the functional unit for both of the system, on which comparison is to be made, should be the same. Most of the previous pavement LCA studies have used lane-miles, lane-kilometers as a functional unit. Yet, few studies also used 5km, 10km, square meter. For pavement, it is important that the functional unit should include indicators of pavement performance, the criteria of performance distress ratings, performance index, physical dimensions physical dimensions (length, width, or thickness). A studied conducted by Berthiaume and Bouchard (1999) compared the exergy output for different pavement surface types by using traffic volume as a functional unit (Berthiaume & Bouchard, 1999). Some of the studies adopted structural capacity as a functional unit as well. For instance, a study performed by Liu et al. (2014) adopted carbon intensity per unit of structural capacity as a functional unit. The study investigated the sustainability of 20 different projects in various states (California, Alaska, and Texas) by quantifying the carbon emissions. Since the energy and resource input/ output is affected by material properties, the structural capacity was used as a functional unit (Liu, Cui, & Schwartz, 2014).

Another important task in the initial phase is defining system boundaries. The system boundary is limitations that define what processes of a product system is included in LCA analysis. As per ISO 14044 system boundary is defined as a limit or criteria that defines the unit process that are inclusive in a product system (ISO, 2006). It has been reported that omitting processes and improper way of defining system boundaries can lead up to 50% error (Lenzen & Dey, 2000). Most of the past studies have considered material production, construction, and M&R phase (Loijos, 2011; Mroueh et al., 2013). Due to the complexity and limited availability of data, use

phase as well as end-of-life are not usually considered in LCA analysis. Most of the studies assumed that the impact associated with this phase is the same, irrespective of the pavement type, and didn't consider in the analysis. However, a study conducted by Wang et al. reported that the impact of the use phase and end-of-life varies from one pavement to another since it is dependent upon pavement characteristics and pavement-vehicle interaction. Therefore, it is recommended to quantify the impacts associated with this phase when an accurate result is needed. In addition, the level of detail i.e. unit processed or industry average data also determines the accuracy of result.. Each of the data types is described in section 2.4. However, the main challenge in unit process data is data unavailability, whereas, for industry average, the main concern is that it is not representative of a single process.

In addition, this phase should define the required data quality. As per ISO 14044, the data quality requirement should define as per the geographical coverage, data precision, time dependency coverage, technology coverage, and representative, the population of interest, technology coverage, reproducibility, and completeness.

2.3.4.1.1 Life cycle Inventory (LCI)

Life cycle inventory, the second phase of LCA, accumulates all the input and output flows from the environment and system. In pavement LCA, inventory data should be collected for all activities associated with the different phase of pavement such cement/ asphalt production, hauling of aggregate, concrete or asphalt mix production, removal of asphalt/ concrete pavement and other different activities (Harvey et al., 2016).

Based on the inventory data, LCA can be classified as Input-output LCA, process-based LCA and Hybrid LCA. The Input-output based LCA (I-O LCA), also known as a top-down approach, reports the material and resource consumption, and environmental emissions based on economic activities.

In this LCA, the information on industrial-transactions from one company to another company along with the environmental emission from each industry is used to estimate the emission in the overall supply chain. In process-based LCA, for each individual process in a product or service, within the defined system boundary, an environmental emission is quantified. Since process-based data is a detailed analysis method and time consuming, users only select some processes only, which results in truncation error (Lave, Cobas-Flores, Hendrickson, & McMichael, 1995; Lenzen & Dey, 2000; João Santos et al., 2017). Both types of LCA has its own strength and weakness, therefore, a hybrid LCA is used to combine both process-level data and integration of the economic sector.

Further, the data collection in this phase should be performed in accordance with the level of details defined as per defined goal and scope. In addition, the location-specific data should be based on the overall goal of the project i.e. either national average data or local data. Portland Cement Association (PCA) and National average databases i.e. ISO 14040 are some of the national average data. However, most of the previous studies have used national average data, due to the unavailability of local data. Most of the past studies used national data and only a few used state-level data. For example, a study conducted by Weiland (2008) used state-level inventory data from Washington State, Wang et al. (2012) used a state-level inventory database from California, and Cass and Mukherjee (2011) used inventory data from Michigan. In context to the National average data, inventory database for Portland Cement Association (PCA) and ISO 14040 are commonly used as life cycle inventories (Weiland & Muench, 2010).

Unit process is the smallest element in LCA analysis for which the inflow and outflow data is determined. When multiple unit processes are grouped together they are termed as an aggregated unit processes which in turn represent a complex process. It is necessary that LCI should cover all

the unit process aggregated unit process which are within defined system boundaries as established in the goal and scope phase (Harvey et al., 2016). Therefore, for a proper LCI, a flowchart diagram showing all the flows from and to the unit process should be developed. In LCI, the input includes material or energy flow into the unit process, whereas, the output includes material or energy flow, products, co-products (such as atmospheric emissions, emission to soil, waterborne emissions, and solid wastes) (Institute, 2006). All of these data can be categorized as primary data and secondary data. The data collected from a specific process of a certain system is termed as a primary data whereas secondary data are the one in which inventory data for a specific process is obtained by assuming that the process considered in the study is similar to the industry distributions or averages. Irrespective of the data type, it is important to check the data quality. Representation, reproducibility, precision, and consistency are some of the methods for checking data quality. The first LCA study that accounted for data uncertainty was initiated by Horvath and Hendrickson (1998). In this study, wide range of data resources were collected, in order used to determine input factors of chemical, waste, and air emissions (Horvath & Hendrickson, 1998). Results proved that the incorporation of uncertainty enhanced the comparison of outcomes.

The main challenge associated with LCI is the allocation procedure. Defining the portion of the impact on the main product and side product is referred to as an allocation procedure. Since pavement nowadays have been using RAP, RAS, and RCA, it is important to perform allocation precisely (Harvey et al., 2016). Lastly, at the end of this phase, all the information on energy and resources consumption and their outcome in the form of emission, wastage should be well documented. The assumption and limitation, if made any during data collection should be stated as well. If the targeted audience of the proposed LCA study is public, it is necessary that LCI be reviewed by the third party.

2.3.4.1.2 Life-Cycle Impact Assessment (LCIA)

In Life-cycle impact assessment phase, all the data collected from LCI is converted into human and environmental impacts by using an impact chain. There are many categories to represent the impact, therefore this phase requires the selection of a set of impact categories, a characterization model, and impact category indicator to represent the environmental impact associated with a certain product. For each selected category, a characterization model along with the factor value is used to account how much of each impact category indicator will contribute to the impact categories. Then, by multiplying the adopted characterization factor and emission values collected from LCI will quantify the impact for each category (Harvey et al., 2016).

EPA has identified the following impact categories based on three main groups of environmental impacts (human health, resource reduction, and ecological health) 1. Global warming potential, 2) acidification 3) land and water use 4) resource depletion 5) eutrophication and 6) energy consumption (Bare, 2011). In case of pavement LCA, GHG emissions and energy consumption are easily understood by pavement stakeholders and do not cause over-complexity. Therefore, they are considered as the main emissions in pavement LCA studies (Akbarian, Moeini-Ardakani, Ulm, & Nazzal, 2012). Besides considering energy and GHG, other air pollutants and wastes should be considered. For example, emissions such as CH₄ and N₂O contribute to 6-16% of GHG emissions leading to different environmental impacts (such as acidification, photochemical smog, air pollutants, etc.). Different studies have considered these impacts, however, the findings of different studies, in terms of emission amounts, varied. Since the impacts depend on the selection of the scope and system boundary, the discrepancy in these parameters among different studies have resulted in the discrepancy. Weiland and Muench (2010) conducted an LCA to quantify the air pollutants associated with different pavement overlay alternatives. The study concluded that

(HMA) replacements emitted higher amounts of NO_x than PCC (Weiland & Muench, 2010). Yet the study of Zhang et al. (2010a) concluded unlike quantities of NO_x as compared to that reported by Weiland and Muench (2010) (Han Zhang, Keoleian, Lepech, & Kendall, 2010).

The impact assessment can be calculated and visualized either by midpoint and endpoint indicators. The impact which selected before the end of a supply chain are midpoint indicators (such as global warming potential, eutrophication, photo chemical smog etc.) whereas the one that considers full chain is called endpoint indicators (such as skin cancer related to the UVB radiation, rise in sea level, etc.) (Harvey et al., 2016) Further, it is imperative that the geographic scope of each indicator should be identified. Some can be local (i.e. particulate from the traffic, air quality measures, etc.) and some can be global (global resource depletion, global warming potential, etc.) The first one has better result and precision whereas the later one has a wide application but may underestimate the impact). Regional/local impacts are more recommended rather than global impacts (Harvey et al., 2016). However, impacts defined by TRACI assessment methodology developed by EPA are most widely used. Till date, all the impact categories are not considered in the LCA. In most of the previous studies, human health and resource depletion have not been considered. In addition, noise is one of the important environmental burden, which is often ignored by most of the LCA studies. For example, the noise initiated by different types of pavement is different such as more noise is induced by stiffer pavement. Roadways contribute to noise during the construction, use, maintenance, and rehabilitation phases and such noise has effects on human health. Along with the impact categories, it is necessary to report resource use, resource renewability, resource origin, and feedstock energy. In North America it is a common practice to separate the feedstock energy from the overall energy consumption.

For interpretation of LCIA results, three different methods are commonly used: Normalization, Grouping, and weighting. The calculated impact categories are in non-commensurate units, such as acidification in sulphur dioxide equivalent and eutrophication in nitrogen equivalent, therefore, Normalization is performed to harmonize all the impacts calculated in different units such as global warming potential in KgCO₂eq, acidification in hydrogen ion equivalents, etc. into a common scale based on a reference value (Bare, 2011). Mathematically, the formula for calculating normalization is presented by Equation 2.1. Till date, different reference has been developed based on the location (either global, regional or local). In North America, TRACI normalization value which is expressed as impact per capita per year is widely used.

$$\text{Normalized value} = \frac{\text{Impact A}}{\text{Normalizarion factor for Impact A}} \quad (2.1)$$

Grouping is another method for LCIA. In grouping, the considered impact categories are assigned into more sets based on either their scale of impact or the as per the unit process. This method also tends to rank or sort the indicators based either their characteristics or by classifying them as low, medium, or high categories (Harvey et al., 2016).

In LCIA, weighting is a procedure of converting an impact category into different value by assigning a numerical factor. It can be performed either on the indicator results or the normalized value. It should be noted that the weights are based on a perspective or value judgment. Therefore, when a decision is to be made based upon the weighted value, precaution should be adopted. However, it is recommended that, even if the weighted value is used for further analysis, normalized value for impact categories should be presented as well (Harvey et al., 2016). There are different weighting criteria developed by different organization/ agencies for their own purpose. For instance, in 2011 a list of different environmental impacts was developed by EPA's

Science Advisory Board (SAB) to allocate their own resources (Bare, 2011). Further, BEES transformed EPA's weighting factor into their own set of weighting criteria for interpreting LCA. The National Institute of Standards and Technology (NIST) provided volunteering stakeholders to develop their own EPD.

2.3.4.1.3 Interpretation

In the last phase of LCA, all the impact categories, calculated as per the functional unit is reported and well documented. Further, the impact associated with each phase of the product is quantified and the major impacts are identified. Further, based on either LCI or LCIA results, this phase determines the significant issues by anomaly assessment and dominance analysis of anomaly assessment (Harvey et al., 2016). Further, this phase checks the consistency, sensitivity, and completeness of the results. Based on the results, this phase checks if the results meet the goal defined in the initial phase of a study. If it didn't meet the defined goals, the LCA should be repeated to achieve the goal. Therefore, LCA is sometimes referred to as an iterative process as well. Also, the last phase determines if there are any uncertainties in the result by assessing the final data quality by checking the mean, variability, and data distribution. Based on the result, the study should also provide recommendations for future applications (Harvey et al., 2016).

2.3.5 Review of Past Studies in Pavement LCA

The section provides a detail explanation on the benefits and in-depth understanding of the previous LCA studies. Even though the goal of pavement LCA is to compute the environmental impact associated with the pavement life cycle, the time and data limitations restricted some researchers from considering important phases in LCA. For instance, Zapata and Gambatese (2005) conducted an LCA analysis to compare an asphalt pavement and continuously reinforced concrete pavement (CRCP) by considering life-cycle stages from raw material acquisition,

manufacturing to construction. Other life-cycle phases were not considered in the comparison (Zapata & Gambatese, 2005). Since the study compared two different types of pavement which have different M&R type and frequency and different pavement-vehicle interaction, it is necessary that these phases should be included in the analysis. The study concluded that cement production had a significant environmental impact than the asphalt production. For asphalt pavement, the dominant process for energy consumption was drying and mixing of aggregate (Zapata & Gambatese, 2005). In addition, the study reported that feedstock energy of asphalt binder has a significant role in defining the energy consumption of asphalt pavement which in turn may cause a large difference in sustainability aspects of two types of pavement. Similar, comparison between asphalt and the concrete pavement was performed by Chan (2007) (Chan, 2007). The author reviewed 13 different pavement projects in Michigan. The study conducted two main tasks. First, the study determined the limitations of LCA, second, the study investigated the techniques to integrate the impact of pollution in the LCA framework (Chan, 2007). The study used environmental data from mix design information from a combination of sources, such as the Athena Sustainable Materials Institute, SimaPro 6.0, Portland Cement Association (PCA), and the IVL Swedish Environmental Research Institute, to quantify the impacts related to different types of surface materials (Chan, 2007). The most significant contribution of this study is to include construction caused traffic delays in LCA analysis. The LCA analysis showed that there is not significant difference in energy consumption and CO₂ emission in the pavement mix production and construction phase. Further, if the energy for asphalt binder processing is considered then the energy consumption during asphalt pavement construction is more than the concrete pavement construction, if not then there are no significant differences in energy consumption by two types of pavement.

All of the above-mentioned studies didn't consider the entire phases of a pavement life-cycle. However, a study conducted by Häkkinen and Mäkelä covered entire phases of pavement life-cycle, with an exception of the end-of-life phase. The objective of this study was to measure and compare the environmental impact of a Jointed Reinforced Concrete Pavement (JPCP) and Stone-Mastic Asphalt (SMA) by considering eight different environmental categories i.e. energy consumption, CO₂ emissions, heavy metal releases, and air pollutants (Häkkinen & Mäkelä, 1996). The analysis was conducted on a kilometer of pavement with an ADT of 20,000. For construction phase, the fuel consumption (related to the paving equipment) was the only factor considered, however, in addition to fuel consumption, factors such as "road salting" and "studded tires" were considered in pavement design, use, and M&R phase. Further, noise, fuel consumption, lighting, concrete carbonation, and dust impact categories were considered too in the use phase. However, this study didn't account for the traffic delay occurred due to the initial construction as well as maintenance activities. The LCA study, by considering 50 years of pavement life, concluded that the emission associated with the use phase was nearly two times greater than the total emissions through all other phases of a pavement (Häkkinen & Mäkelä, 1996). Similarly, the study also reported that the fuel consumption can decrease in the range of 0.1-0.5% due to change in pavement characteristics. In context to the comparison of asphalt and concrete pavement, the study showed that the rate of emission production such as NO_x, CO, CO₂, and mercury (Hg) was 40 to 60% higher in the concrete pavement when compared to asphalt pavement during production, paving, lighting, and maintenance. However, if the processing of asphalt is considered, the environmental impact due to the asphalt pavement is 2 times more than that of a concrete pavement. The higher energy consumption of asphalt pavement is associated with the non-renewable energy consumed by asphalt pavement. However, there is marginal difference in other

impact categories between the two pavements (Häkkinen & Mäkelä, 1996). Mroueh et al. determined the impact of using industrial by-products in pavement construction. The LCA was conducted on seven different pavement structures along 1 km of road with 7,000 ADT (14% heavy trucks), where by-products (such as blast furnace slag, coal ash, crushed stone waste) were used as a substitute to virgin materials (Mroueh et al., 2013). The study considered a material acquisition, construction, M&R phase only. The impact categories considered for the analysis was CO₂ emission, Sulphur dioxide, usage of fuel and other energy, raw materials and secondary products consumption, NO_x, SO₂, carbon monoxide, VOC, particulates, noise, and infiltration of compounds into underground sources. In this study, the maintenance and rehabilitation were considered the same for both types of pavement. Since this is not the case in actual pavement life, this questions the accuracy of the results in this study. The final score, which in turn represented environmental performance, was obtained by summing up the different environmental weights. The weight was assumed in such a way that the energy and material consumptions were higher than the weight of other environmental impact categories i.e. noise, VOC and particulates, etc. However, the study recommended to incorporate end-of-life phase LCA study, since using recycled materials in new construction reduces the consumption of virgin material thereby providing more sustainable pavement in construction (Mroueh et al., 2013).

2.3.5.1 LCA based sustainable quantification tool

ATHENA. Athena institute developed an Athena pavement LCA tool which reports impact associated with the materials extraction and manufacturing, pavement construction and future maintenance activities. Further, this tool also allows users to estimate the impacts associated with the use phase by including the built-in pavement-vehicle interaction algorithms (J Santos, Thyagarajan, Keijzer, Flores, & Flintsch, 2017). This software provides the flexibility to the users

by allowing them to input pavement design, construction, and M&R parameters. Based on the input parameters, the software estimates the impact by using the databases from the US LCI database and from Athena Institute which includes inventory data for materials, transportation, equipment, and energy. The tool reports energy consumption and material flow, emissions to air, land, and water (J Santos et al., 2017).

DuboCalc. DuboCalc, an LCA software developed by Rijkswaterstaat RWS (Netherlands), quantifies the environmental impact of a pavement or a product by estimating all the energy and resources consumed over the entire lifetime of a pavement. The quantification is based on an environmental and modeling database which in turn is linked to the material, processes, and equipment inventory data (J Santos et al., 2017). In this software, the environmental impacts are quantified into 11 categories. The overall environmental performance of the design is represented by converting 11 impact categories into a single number, Environmental Cost Indicator Value (ECI Value), such that the product with lowest ECI value is the most cost-effective and environment-friendly (J Santos et al., 2017).

Project Emission Estimator (PE-2): PE-2 is a web-based tool that quantifies the carbon footprint related with the pavement construction and rehabilitation work (Mukherjee & Cass, 2012). The tool quantifies emission due to 4 phases of pavement which are raw material acquisition, manufacturing, construction, and M&R. The web-based tool, which was developed by Michigan Technological University, provides decision makers to assess project carbon emission and compare emission associated with different construction alternatives. The tool was initially developed to quantify the environmental impacts for 14 highway construction, M&R, and reconstruction projects in Michigan (Mukherjee & Cass, 2012). Michigan Department of Transportation and contractors adopted PE-2 tool to quantify the overall emissions during

pavement life-cycle. The tool required the user's input for pavement parameters such as pavement type, thickness, and estimated hours of operation of different types of equipment. Based on this input, the carbon emission associated with the given pavement design is evaluated. Even though this tool is developed to compare the pavement materials in general, it provides the user with an informed decision on which materials and methods are appropriate for a given highway project (Mukherjee & Cass, 2012). The PE-2 tool can be accessed at https://www.construction.mtu.edu/cass_reports/webpage/index.html.

Building for Environmental and Economic Sustainability (BEES). The BEES assists in selecting the most sustainable building product by quantifying the economical as well as environmental impact. This software, developed by the National Institute of Standard and Technology (NIST) during the late 1990s, encompasses inventories data for 230 building products. Based on user selection of products from the pre-existing database, the overall sustainability is computed by accounting for all stages of a product (Lipiatt, 2007). It measures the environmental impact by adopting LCA approach as specified in the ISO 14040 series, whereas, economic performance is evaluated by using life-cycle cost analysis. The environmental performance is categorized into 12 categories, which are then normalized, weighted, and summed to convert into a single number. The unit for thus calculated environmental performance is impacted per capita per year. However, the economic performance, calculated based on LCCA, is a monetary value. Since two performances are in the non-commensurate unit, it is necessary to harmonize them into a single unit. Therefore, a relative scale for each performance criteria was calculated following the ASTM standard for performing multiattribute decision analysis. Then, the software then weighs and sums up the calculated relative scale to represent the overall sustainability score, such that, the lower the score more sustainable is the product (Lipiatt, 2007).

Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE):

PaLATE, developed by University of California, Berkley, is a free excel add-on to evaluate sustainability of a pavement. The sustainability is defined in terms of both the environmental and economic effects of pavements. The tool was developed at the Department of Civil and Environmental Engineering, University of California, Berkeley (Nathman, 2008). As presented in Figure 2.8, The tool requires the user input on pavement characteristics, such as design, construction, maintenance, type of equipment and use, and costs for pavement, and, subsequently provides the environmental results, cost results and leachate information on roadway materials. The environmental impacts calculated in PaLATE are NO_x emissions, CO₂ emission, SO₂ emissions, CO emissions, PM₁₀ emissions, and energy consumption (Nathman, 2008). The environmental performance is computed based on a hybrid life-cycle analysis. For economic performance, all calculated costs are presented in net present value. This tool can be used by the transportation agency decision-makers, researchers, pavement designers, and civil engineers. It will assist the user in selecting an optimum pavement design that results in the least environmental and economic impact (Nathman, 2008).

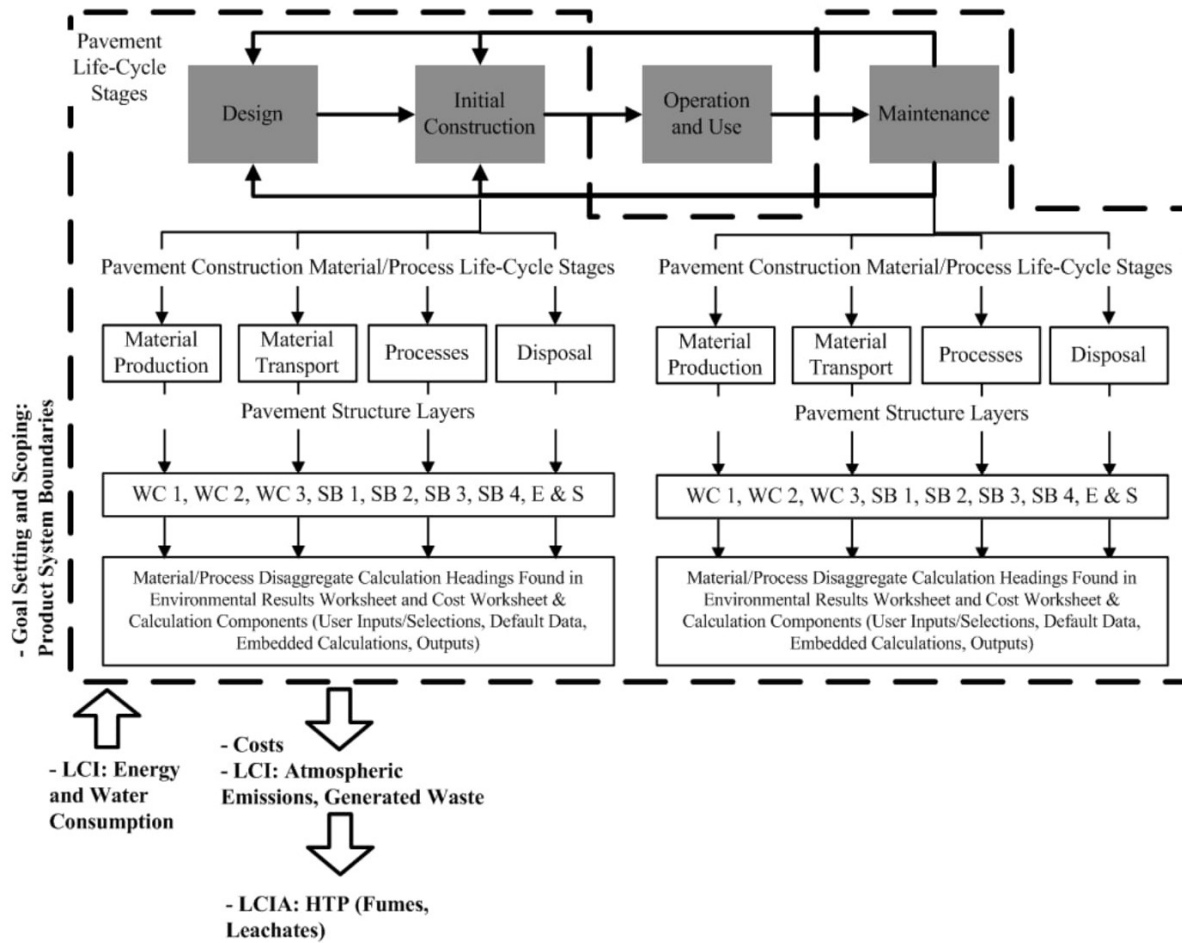


Figure 2.8. PaLATE analysis Framework (Nathman, 2008)

2.3.5.2 Limitation and Research Gaps in Life-Cycle Assessment

Even though LCA presents a methodical technique which quantifies the environmental impact related to pavement by considering the overall pavement life-cycle, there are numeral deficiencies and limitation associated with LCA. As mentioned previously, to quantify the environmental burden of pavement, it requires data collection from a wide range of sources such as primary and secondary source of data. First, primary data are time-consuming and may be inappropriate for small scale application, second, a collection of secondary data from existing database and commercial software may question its accuracy as the assumptions and limitations are not known (Harvey et al., 2016). Also, secondary data may be inaccurate, biased, outdated, incomplete, and

sometimes expensive to use as well. As there is a direct relationship between data availability and accuracy of results, it is imperative to determine data accessibility, monetary resources, and availability of resources and compare it against the benefits of applying the collected data in LCA. Another limitation associated with implementing LCA for decision-making in pavement is due to the lack of standard practices to conduct pavement LCA (Subedi et al., 2018). From previous studies, it can be observed that each study has adopted their own sets of assumptions, the inclusion, and exclusion of different pavement life-cycle phase was objective to the researcher choice, and the methods of interpretation varied from one study to another. Due to this, different results are obtained for similar pavement type i.e. some researcher reported that the drying and mixing of aggregate consumed significant energy, whereas some claimed that the asphalt processing had a significant role in environmental impact. Hence, due to these discrepancies, it limits the use of LCA as a decision-making tool.

Further, LCA methodology quantifies the environmental performance and doesn't estimate the economic functionality of a product. Therefore, an appropriate method to select the sustainable product is to combine LCCA and LCA together which in turn presents the comprehensive decision-making process. The product selected from the combined methodology presents a product that is eco-friendly and economically feasible. Considering the limitations of LCA, future research/work should focus on the following statements (Prashant V. Ram & Van Dam, 2017)

- The data related to any phase of the pavement should be properly documented.
- The end-of-life has a great impact on pavement
- Pavement containing Recycled Asphalt pavement (RAP), RAS, etc. therefore, every analysis should be performed to quantify their benefits.

- Pavement condition depreciation or decay should be considered during pavement maintenance and rehabilitation phase.
- Whenever possible regional or local data should be used in the analysis.
- Pavement condition decay should be included during maintenance and rehabilitation phases.
- Integrate sustainable construction practices that can be used for both concrete and flexible pavement.
- Human health, water pollution impact categories should be quantified in LCA, in addition to common impact categories such as GHG emissions, particulate emission, etc.
- The LCA analysis, in the future should consider pavement performance as well.

2.4 Environment Product Declaration (EPD)

As mentioned earlier, LCA identifies areas for improvement in their environmental attributes, together with adoption of more sustainable business approaches. Yet for complex system like pavement, LCA possesses challenges for consistent methodologies across both stakeholders and industries, and therefore, provides no comparable result in regard to the impact between the supply and value chain (Mukherjee & Dylla, 2017) i.e. if two products vary in a system boundary, functional unit, life cycle phase, and many more dissimilarities, the products would be difficult to compare. Therefore, LCA provides no benefit when a stakeholder wants to choose a selection among the various pavement products available, i.e., a selection of concrete mixes either from company A or company B. As an emerging tool, Environment Product Declaration (EPD), provides an environmental impact data by following a set of industry-wide standard rules for a specific material/ product. Therefore, EPD declares and defines environmental impact data that is consistent and comparable (Harvey et al., 2016). The standard rules, in connection with the

availability of inventory data, alleviates the data collection procedure as compared to LCA. The environmental impact data in EPD is based on a cradle-to-gate framework, i.e., the reported data is drawn from the raw material acquisition, transportation from extraction to the plant site, and finally, the manufacturing of the product.

In order to create a reliable EPD, LCA must meet specific requirements; hence, information is needed concerning challenges in modeling the product, the type of data to be used, and the environmental impact categories which should be included. To answer these questions, involved industries must develop Product Category Rules (PCRs) for different types of products. PCR provides a systematic protocol to compare identical products of various companies in terms of environmental impacts, thus allowing the data to be utilized in a life-cycle assessment (Schmincke & Grahl, 2007). Even though EPD are developed by using a standard rule (PCR), a verification from the third party is required to support the consistency of data, collection, analysis and reporting requirements.

There are two major benefits of creating EPDs for different types of products. First, EPD provides companies awareness of different aspects of environmental impacts related to their product. Second, customers such as highway agencies could compare and select those products with lower impact (Schenck, 2009). The two major benefits may be referred to as the Business to Business EPD's and Business to Consumer EPDs. The Type III EPD was developed for business-to-business comparison and communication, which can be the tool to collect and provide environmental information in business. As a tool, Type III EPD can be useful for procurement and marketing, and to provide LCA data in the value chain. Another use is in business-to-consumer communication. Consumer demands have increased for companies to be transparent and to take responsibility for the entire supply chain of their products. EPDs are based on an LCA perspective

and hence can provide comparable and verified results to consumers. In this regard, EPD is suitable for Business to Consumer communication. The standard ISO 14025 accords additional requirements to EPDs that either are intended for business-to-consumer (B2C) communication, or are likely to be adopted by consumers. On the one hand, B-to-C EPD is found at the end of the supply chain, and on the other hand B-to-B EPDs are mid-stream in the supply chain (Mukherjee & Dylla, 2017). In addition, recently LEEDv4 and the green construction code require building materials to submit EPDs of their products, in order to verify their environmental performance (Sakai & Buffenbarger, 2014). With this change, LEEDv4 rating criteria now assign two points for the projects that can document one. The projects show 50% in costs of their products, thereby demonstrating lower impacts than industry baselines through EPDs, and two. The projects present 20 products/materials with EPDs (Gelowitz & McArthur, 2016).

Currently, there are 40,000 EPDs available for different products listed in the United Nations Standard Products and Services Code (UNSPSC), a database holding the names of the different products (Schenck, 2009). It is noted that aggregated data of a company cannot be used as a primary source for creating individual EPDs. Such data solely represent an average EPD of the same company, rather than illustrating an EPD specific to the product. However, such aggregated data may be used as a secondary data source for another company's EPD.

2.4.1 Development of EPD

The procedure for developing EPD is presented in Figure 2.9. As illustrated in Figure 2.9, EPD is developed when the need for the environmental impact is identified by industry for a specific product. After the EPD development identification, a program operator is appointed, which then finds or creates a PCR that is applicable to the particular product category. PCR defines the reporting and calculation requirements for creating Life cycle assessments and EPDs (Harvey et

al., 2016). Next, a comprehensive LCA analysis of a product is conducted by an LCA agent to report the cradle to gate analysis. The conducted LCA is verified by the third party to ensure that the analysis meets the requirements as per PCR, ISO 14040, and ISO 14044. The EPD is then developed based on the results of LCA. Next, the developed EPD is reviewed and verified by the independent third party. After the review, if acceptable and verified, EPD is finally published (Harvey et al., 2016).

The U.S. faces many issues for the advance and use of EPD. First, the current infrastructure is inadequate to support the development and use of EPD. Second, there exists almost no legislation requiring the use of EPD, making the use of EPDs optional. It is highly recommended that the EPA takes a lead in developing a strong-life-cycle inventor (Schenck, 2009). Third, there is no support for PCR. The precise development of LCA, these PCR should first be well developed (Schenck, 2009). Currently, EPDs are not used in decision making. However, there is an ambition to implement this approach in decision making when EPDs are fully developed.

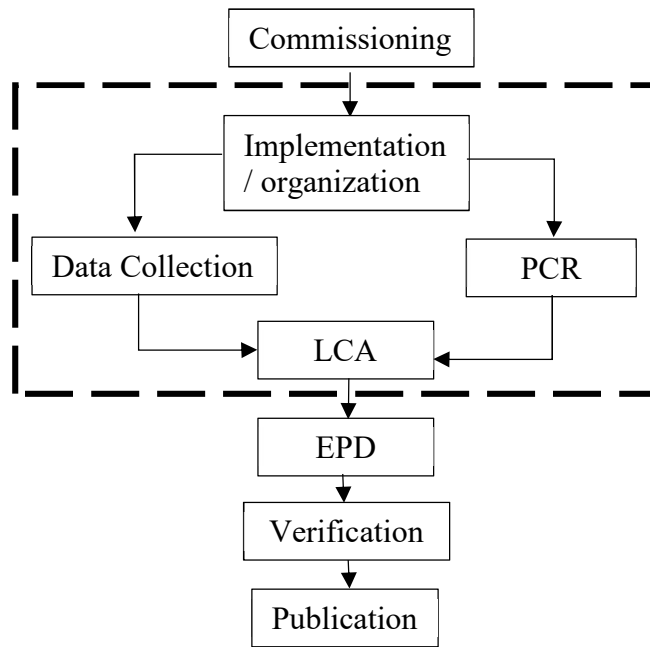


Figure 2.9. EPD Development Process (GreenSpec, 2019)



2.4.2 Individual and Industrial-wide EPD

The inventory data used in the development of EPD defines if it is an individual EPD or industry-wide EPD. If an individual company uses its own inventory data to develop EPD then it is termed as an individual EPD of the corresponding company. However, if an inventory data from different companies, of a certain region, are used and aggregated to represent an average impact in a cradle-to-gate framework, it is then referred to as an industry-wide average EPD. This industry-average data is encouraged to be used where there is a limit of data availability. This industry-average are generally used as a secondary data source for another company's EPD.

2.4.3 EPD in Pavement Construction

As mentioned previously, EPD addressed some of the limitations of LCA and therefore provides a comparable result. Hence, pavement stakeholders are exploring different ways to apply EPD in pavement construction (FHWA, 2017). This initiative has resulted in the development of EPD for pavement products used in pavement project. The EPD for pavement materials is developed either

by a group of manufacturers, a specific producer, or a group of manufacturers. Figure 2.10 presents an EPD developed by the Central Concrete Supply Company, which in turn defines the environmental impact associated with the production of 1m³ of concrete.

Summary of Environmental Product Declaration		Environmental Impacts 		
Central Concrete		Impact name	Unit	Impact per m3
Mix	340PG9Q1	Total primary energy consumption	MJ	2,491
San Jose Service Area		Concrete water use (batch)	m3	6.66E-2
EF V2 Gen Use P4000 3" Line 50% SCM		Concrete water use (wash)	m3	8.56E-3
Performance Metrics 		Global warming potential	kg CO2-eq	271
		Ozone depletion	kg CFC-11-eq	5.40E-6
		Acidification	kg SO2-eq	2.26
		Eutrophication	kg N-eq	1.31E-1
28-day compressive strength	4,000 psi	Photochemical ozone creation	kg O3-eq	46.6
Slump	4.0 in			35.7

A sample EPD for a concrete mix design by Central Concrete Supply Co.

Credit: Central Concrete Supply

Figure 2.10. A sample of EPD for a concrete mixture (FHWA, 2017)

Concrete and asphalt represent the main paving materials in the U.S. in relation to corresponding PCRs already developed. The PCR for asphalt is developed by the National Asphalt Pavement Association (NAPA) EPD program, whereas Portland cement and concrete, known as PCR, is developed by the Product Category Rules Task Group and the National Ready Mixed Concrete Association (NRMCA) EPD program. Both programs have outlined five years as a validity period of EPD; after that, EPD requires a review. Both of the programs require ISO 14020, ISO 14025, ISO 14040, and ISO 14044 as a standard to be followed for developing EPD and PCR. However, NRMCA EPD is required to follow an additional ISO 21930 standard (Marceau, Bushi, Meil, & Bowick, 2012). The main objective of these programs is to develop EPDs that provide relevant and comparable data for the concrete and asphaltic materials. These EPDs will also assist the

consumer to compare different products from different companies to select the one that fits their needs, and which provides the least environmental impact. Therefore, EPD addresses both business-to-business and business-to-consumer applications (Gelowitz & McArthur, 2016). EPD also provides better transparency in material performance and assists in tracking the consistency of materials selected by using the ISO 140025 (standard document).

2.4.3.1 NRMCA industry-wide EPD

After publication of PCR, different cement and concrete companies have developed their own EPDs to benchmark their product. To date, there are thousands of individual and industry-wide EPDs for cement and concrete products. NRMCA conducted a cradle-to-gate LCA, and thus produced an industry-wide (average) EPD. EPD was developed for 72 ready mix concrete products from different companies. The NRMCA industry-wide EPD program was conducted according to the requirements defined in Carbon Leadership Forum (CLF) PCR for ISO 1425 Type III EPD for concrete. This EPD may be used by pavement stakeholders to compare different pavement product/ mixes against a baseline value or in other words, the industry-wide EPD may be used by different companies as a baseline to benchmark environmental impacts of their product. The industry average EPD also can be used by a concrete producer when a project submittal process requires EPD.

Further, for concrete product EPD to meet the requirements of LEEDv4, the corresponding concrete producer should have participated in the NRMCA industry-wide average program to provide data to the LCA (Gelowitz & McArthur, 2016).

2.4.4 Limitation of EPD

Even though EPD addresses the major limitations of LCA, there still exists some constraint regarding this tool. In a consideration of environmental performance alone, and not accounting for

other components of sustainability, either economic or social impact accounts for one of the limitations of EPD. In addition, most of the published EPDs account for GHG emissions, energy consumption, acidification, eutrophication, and the like. However, due to data gaps and uncertainty, EPD includes no environmental impact categories, such as human health. Further, EPD is not appropriate in comparing products with different levels of performance and different service life. For example, a comparison of pavement design with a service life of 20 years against one with 30 years using EPD is not reliable. Further, EPD cannot be applied to compare two different products, since their standard rules (PCRs) are different. For instance, a comparison between concrete and asphalt pavement incorporating EPD is not currently feasible. Lastly, the development of individual data for all scales of the industry is not feasible, as it requires both resources and time. This results in an implementation of industry average data to estimate an environmental impact which may be less accurate. Therefore, these limitations of EPD should be well understood and properly addressed before a final decision is made while using EPD.

2.5 The relation between LCA, EPD, and PCR

LCA, PCR, and EPD together provides an environmental performance of a product from a cradle-to-gate framework, see Figure 2.11. The system boundary conditions along with the data and system inputs are identified in PCR. Based on the PCR, an LCA is performed to quantitatively determine the environmental performances of a corresponding product. The EPD reviewed and approved by the third-part is then publicize the outcome of LCA for stakeholders and the public (Schenck, 2009). A detailed justification of environmental impact is provided by the combination of these three elements together.

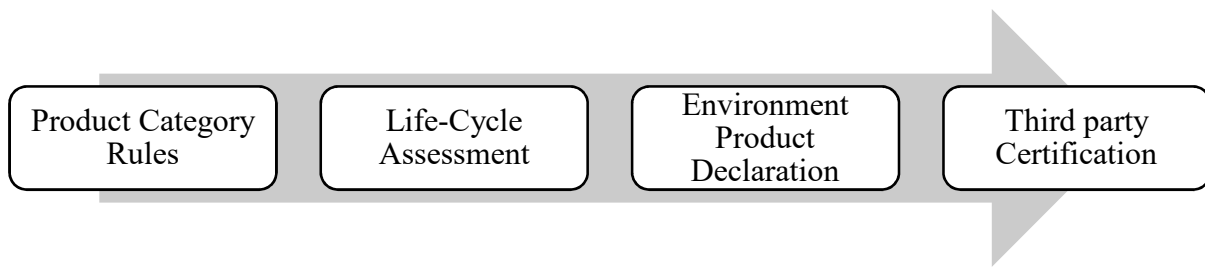


Figure 2.11. The relationship between LCA, EPD, and PCR (Harvey et al., 2016)

2.6 Pavement Design and Sustainability

The aim of a pavement design is to deliver a strong, smooth, safe, and economical pavement system. The pavement design process will result in the development of pavement structure alternatives (different types of layers with different thicknesses), pavement materials specifications required to meet the performance objectives of each layer together with the whole pavement system, and construction specifications which are required for the pavement to achieve its intended performance (Van Dam et al., 2015). Currently, “the American Association of State Highway and Transportation Officials (AASHTO 93) guide for the pavement design and the Mechanistic-Empirical Pavement Design Guide (MEPDG) are two pavement design methods used by pavement stakeholders. Both design methods focus more on the engineering performance of pavement and the accompanying results in pavement alternatives that meet the engineering criteria. Thus, the economic aspect is considered while selecting among different alternatives. However, as mentioned at the beginning of this chapter, a sustainable pavement should meet engineering performance criteria, should be economically feasible, and should have a minimal impact on the environment. The first two criteria are addressed in pavement design and pavement design selection procedure. However, the current state-of-pavement design method does not account for environmental performance (Harvey et al., 2016).

The selection of the final pavement design determines the overall sustainability of the pavement. Therefore, the structural and functional requirement, economic aspect, and environmental aspect should be considered while selecting pavement design. Use of all these criteria will result in a more comprehensive idea of sustainability. Therefore, it becomes necessary to quantify the environmental impact of each alternative design to be assessed. The environmental impact may be assessed by a sustainability rating tool since it converts the sustainability measure into a common point. However, these tools tend to neglect some sustainability aspects during evaluation, and therefore a precaution should be adopted. Another sustainability measurement tool, LCA, is used to compute the environmental impact of different pavement design alternatives. However, the existing limitations of LCA (inconsistent methodology, data availability, etc.) will question the reliability of the end results. In this context, EPD data provides a consistent and reliable environmental impact and addresses some limitations of LCA, appropriate for an evaluation of the environmental performance of pavement material. The pavement material (concrete and asphalt mixes) EPD data may be integrated into the pavement design method so that it can be weighed against environmental and economic criteria. As mentioned previously, EPD doesn't account for the economic performance of a pavement alternative; therefore, to measure the economic aspect, some economic analysis tools should be considered as well.

Integrating the EPD to measure environmental performance and an economic analysis to measure the economic performance of pavement alternatives to meet engineering performance criteria not only will present a decision support system in a current design method but will also assist in achieving the overall sustainability of pavement system. Decision-support is defined as a measurement done to achieve quantification or to acquire qualities that will assist organizations or designers for project decisions.

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CHAPTER 3.

DECISION-MAKING TOOL FOR INCORPORATING CRADLE-TO-GATE SUSTAINABILITY MEASURES INTO PAVEMENT DESIGN¹

3.1 Introduction

While the economic and social importance of the national transportation network is indisputable, there is a growing recognition that highway construction and maintenance have major environmental impacts (Hassan, 2008). Some of these environmental impacts occur during the construction, operational, and maintenance/rehabilitation phases. During the construction phase, the ecosystem could be affected through possible vegetation removal, erosion and sedimentation, soil compaction, and noise, as well as aesthetic disturbance, contamination, and toxicity, among other concerns (Southerland, 1994; WDOT, 2005). Highway construction operations may also affect the environment through non-renewable energy use, emission, noise, etc. Since transportation activities are expected to continue to grow, it is imperative that sustainable technologies be introduced in order to reduce the impacts on the environment and social life, while optimizing the cost of maintaining the transportation network.

The environmental impacts of pavement may be analyzed and quantified using Life-Cycle Assessment (LCA). The LCA framework consists of four major steps (ISO, 2006a, 2006b) (i) goal and scope definition, (ii) Life-Cycle Inventory (LCI) analysis, (iii) Life-Cycle Impact Assessment (LCIA), and (iv) Interpretation (Harvey et al., 2016). The application of LCA to the pavement is challenging since it is not only time-consuming but also requires a wide range of resources to compile the required data. There is also a direct relationship between data availability

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and the accuracy of the results. Furthermore, the variation in the assumptions, methodologies and interpretation technique among stakeholders results in different impact values for the same pavement product (Del Borghi, Strazza, Gallo, Messineo, & Naso, 2013). Due to these reasons, the comparison of pavement alternatives using LCA is a challenging task.

Environment Product Declarations (EPD), an emerging sustainable measurement tool, address some of the limitations of LCA by certifying the transparent and reliable communication among various stakeholders in the pavement community (Mukherjee & Dylla, 2017). It applies consistent and industry defined standards while providing meaningful metrics that can be used for the comparison of products at the local and state levels (Mukherjee & Dylla, 2017). The inventory database provided in EPDs alleviates the data-collection burden (Harvey et al., 2016). An EPD, obtained from life cycle assessment in accordance with the international standard ISO 14025 (Type III Environmental Declaration) (ISO, 2006c), presents a standardized, third party, verified document that reports the product's environmental impacts (Gelowitz & McArthur, 2016). Product Category Rules (PCR) define the EPD compilation rules, which in turn are followed by the program operators as per ISO 14025 specifications (Mukherjee, 2016), thus considering the cradle-to-gate cycle of a product. One drawback of EPDs their lack of consideration of the economic aspect of the product/design. Therefore, the present study combined EPD with economic criteria, which would provide an effective approach in the selection of a design/product alternative.

3.2 Background

Extraction and transportation of pavement materials, as well as construction and maintenance activities, cause significant impacts on the environment (Southerland, 1994). Hence, an alternative pavement with minimal environmental burden is preferable in reducing these impacts. Multiple sustainable quantification tools were developed to follow a logical and systematic approach for

quantifying the environmental impacts of pavement. ATHENA, ROAD-RES, Project Emission Estimator (PE-2) are LCA based tools, that quantify the environmental impacts associated with the manufacturing, construction, maintenance, and end-of-life stages of a pavement (Birgisdottir & Christensen, 2005; Haapio & Viitaniemi, 2008; Mukherjee & Cass, 2012).

The ATHENA Pavement LCA tool, developed by the Athena Sustainable Materials Institute, reports environmental impacts for materials manufacturing, roadway construction, and maintenance of life cycle stages. The software is based on databases from the Athena Institute and the US LCI Database (Haapio & Viitaniemi, 2008). ROAD-RES, developed by the Technical University of Denmark, focuses on quantifying the environmental benefits of recycling waste materials in construction projects (Birgisdottir & Christensen, 2005). PE-2, an interactive web-based tool developed by Michigan Technological University, can be used by contractors and highway agencies to evaluate and benchmark the carbon dioxide footprint of highway construction projects (Mukherjee & Cass, 2012). However, the goal of the PE-2 platform is not to compare different pavement materials but rather to make informed decisions on which materials and methods to select in different projects (Mukherjee, 2013).

The aforementioned tools may be used to quantify the environmental burdens of a pavement. However, while many are concerned about the environmental impacts of a pavement, few are willing to pay more in order to reduce such impacts. Therefore, a balance should be reached between environmental and economic performances in the selection of a sustainable pavement design/product. Quantification software, such as Dubocalc, the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE), and the Building for Environmental and Economic Sustainability (BEES) were developed to implement a well-defined and organized

methodology for selecting pavement and construction products to achieve an optimum balance between environmental and economic performances (Lipiatt, 2007).

Dubocalc, developed by Rijkswaterstaat RWS, Netherlands, provides a software modeling database and an environmental database, which are connected to a list of equipment, materials, and processes. It calculates and converts 11 different environmental impacts into one valued number: the Environmental Cost Indicator Value (ECI Value). The lower the ECI value, the better the project is considered (Santos, Thyagarajan, Keijzer, Flores, & Flintsch, 2017). Since this tool was developed in the Netherlands, the software is not directly applicable to quantify the sustainability of pavement products/designs in the United States. PaLATE, a free Excel add-on, developed and designed by the Consortium on Green Design and the University of California-Berkeley, evaluates both the life-cycle costs and environmental impacts using hybrid life-cycle analysis of different pavement alternatives (Nathman, 2008). Users input pavement parameters and the tool calculates the net present value, emissions, and leachate information (Liu, Cui, & Schwartz, 2014). The main deficiency of this tool is the utilization of obsolete data, such as the 1992 I-O-LCA models in most environmental calculations.

The BEES model, a Windows software developed by the National Institute of Standards and Technology (NIST), provides a systematic methodology to select sustainable construction alternatives in order to balance environmental and economic factors (Lipiatt, 2007). An overall performance score combines the two performance criteria by using the ASTM standard for Multi-Attribute Decision Analysis (MADA) (Lipiatt, 2007). The product with the lowest overall score is the most cost-effective and environmentally friendly alternative.

The aforementioned issues related to LCA such as data quality and accuracy, the difference in system boundaries and assumptions among stakeholders, make LCA-based tools less consistent

and reliable. As EPD addresses these limitations, incorporation of these declarations in a cradle-to-gate framework would provide more reliable and accurate metrics to measure sustainability.

3.3 Objectives

The objective of this study was to conceive and to develop a decision-making tool for evaluating the sustainability of pavement designs and products, based on a cradle-to-gate analysis. This tool is based on EPD in order to enhance the reliability of the analysis. It was developed such that it may be integrated with a state-of-the-art pavement design method such as the Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO, 2008), as well as the AASHTO 1993 (AASHTO, 1993) pavement design method. The proposed tool was developed for pavement designers and decision makers in the evaluation of alternative designs and products by optimizing pavement mixes.

3.4 Methodology

To address the aforementioned objectives, the framework for this research included an environmental analysis carried out in conjunction with an economic analysis to quantify the sustainability of pavement products and design alternatives. Even though sustainability is balancing environmental, economic, and social needs, this study addressed only the first two components due to the limitations associated with quantifying the social component. The boundaries for the environmental impact assessment, presented in Figure 3.1, included the activities associated with the following four phases: acquisition of pavement raw materials; transportation of raw materials; manufacturing of pavement mixes; and transportation of mixes to the site location. Although other construction activities contribute significantly to the environmental and economic analysis, this study focused on the optimization of pavement mix design/product for structural, environmental and economic performances. The system boundary,

illustrated in Fig. 1, represents an EPD and transportation from the plant to the construction site. Therefore, for environmental analysis, a precise and accurate EPD and transportation module were developed by using a compiled EPD database and transportation inventory data collected from various data sources. Similarly, a compiled database was developed and used to evaluate the economic performance of pavement alternatives. The two performance factors were combined into a single score to represent the overall performance and to quantify the relative differences in performances among the alternatives considered.

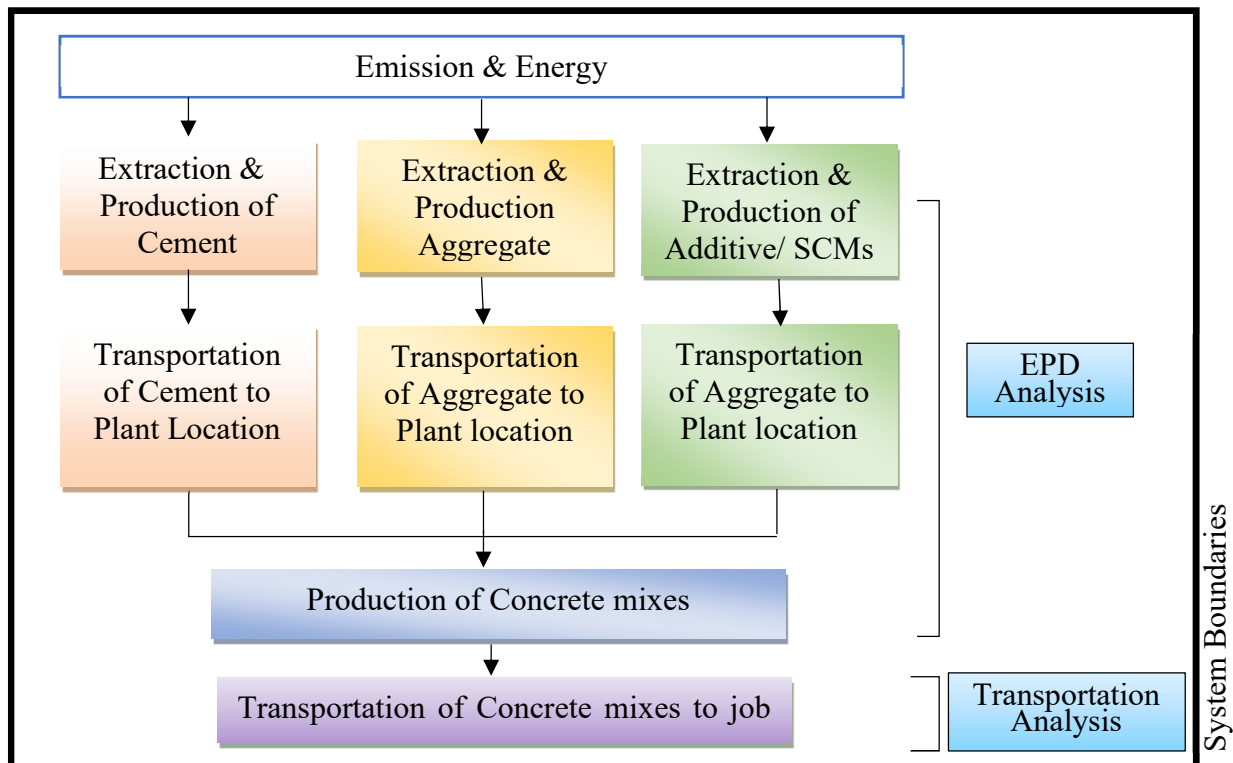


Figure 3.1. System Boundary

The developed methodology, presented in Figure 3.2, was designed to create a decision-making tool, which was incorporated into a Windows-based software. As shown in Fig. 2, the tool analyzes designs that satisfy engineering criteria based on environmental and economic performances. The results from each criterion were then combined to assess the overall performance of a

product/design. Finally, the products/design with the lowest overall performance score is considered the most sustainable pavement. As this study only considers pavement mix design to quantify sustainability, availability of accurate and coherent data for EPD and cost plays a significant role in the accuracy of the results. Since EPD is currently available for Portland cement concrete mixes, the developed methodology evaluates the overall performance of rigid pavements only. With the availability of EPD for asphalt concrete in the future, the tool can be expanded to quantify and compare flexible pavement designs/product alternatives.

The decision-making software allows for the evaluation of multiple concrete pavement designs and alternative products using two modes of analysis: benchmarking and product comparison. Benchmarking provides the baseline results by averaging the impact of multiple selected mixes to quantify the total environmental impacts of a design alternative. Product comparison compares multiple products for selecting the most sustainable product.

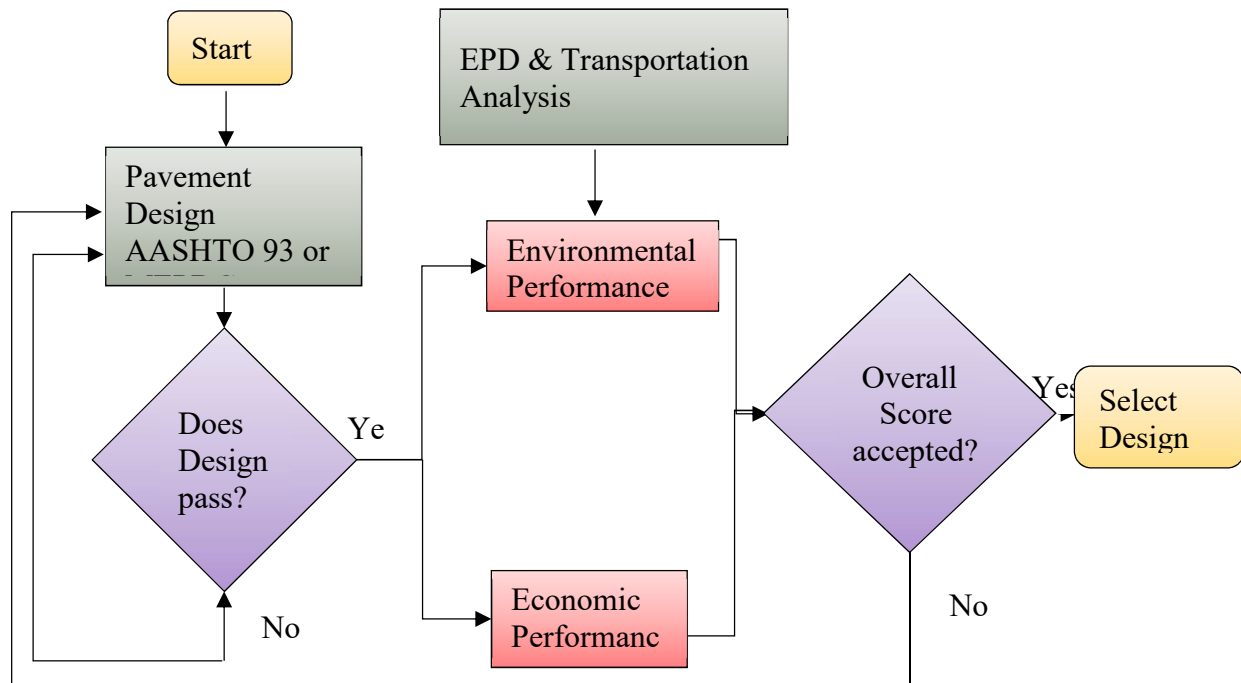


Figure 3.2. Analysis Framework

3.5 Data Sources

3.5.1 EPD Database

The EPD database describes the environmental impacts from raw material acquisition to the manufacturing of a unit volume of concrete products (mix designs). The EPD database is a compilation of different products collected from both the individual company EPD and the industry-wide average EPD. Environmental impacts for each product in the compiled EPD database are categorized into six impact categories: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP) and Non-renewable Energy Consumption. As per the plant location of products, EPD database was structured into three regional levels: 1) State wide region (Louisiana) with 132 mixes; 2) Southern region (Louisiana, Texas, Florida, and

Oklahoma) with 490 mixes; and 3) Nationwide (California, Washington, Louisiana, Texas, Florida, and Oklahoma) with 2,146 mixes.

3.5.1.1 Nationwide and Southern Region EPDs

Nationwide and Southern Region EPDs, except Louisiana, used individual EPDs collected from manufacturer websites, industry communications, and product data sheets. In the nationwide database, EPDs were compiled into a single database consisting of products from the states of California, Washington, Texas, Florida, and Oklahoma. The environmental impact data collected from these states were not categorized into three stages of EPD (i.e., a single value represents the environmental impact for each impact category).

3.5.1.2 Louisiana EPD

Pavement sustainability is an emerging concept in many states including Louisiana (LA); hence, there was no company in the State that had formally published an individual EPD. Since individual EPD sources were not available for Louisiana, a survey was conducted to assess whether industries/companies measure the environmental impacts or inventory of their products. The survey found that 48 plants (seven companies in LA) participated in an industry-wide average EPD. Among those seven LA companies, five companies with 16 plants were included in the study. The state industry-wide average data from those companies, together with mixes collected from nine districts of Louisiana, were provided to the Athena Institute to develop an industry-wide average EPD for the state. In the Louisiana database, EPD was divided into three stages, 1) Raw materials extraction (A1); 2) Transportation impacts from the supplier to the gate of the plant location (A2); and 3) Manufacturing process impacts (A3). The mixes represented 132 pavements identified from state pavement projects in the past five years.

3.5.2 Transportation Data Source

To quantify the total environmental impacts due to the transportation of concrete mixes from the plant location to the construction site, the transportation average emissions data were gathered from the United States Life Cycle Inventory database (LCI). The US LCI inventory data vary for different combinations of vehicle type and fuel. Hence, the Federal Highway Administration (FHWA) truck classification for three different truck types (Light, Medium, and Heavy Duty commercial trucks) and classification of fuel as diesel and gasoline were adopted in the transportation impact analysis. The inventory data quantified emissions in kg per ton/km traveled for each truck and fuel combination.

3.5.3 Economic Data Sources

Economic performance plays an important role in the selection of a pavement design. Therefore, cost data for each product in the EPD database were obtained from two different sources and were compiled in the cost database. For consistency, all the cost values were stored in the same unit as in the EPD database (i.e., per cubic yard volume of concrete mix).

3.5.3.1 Nationwide and Southern Region Cost Data

The first source of the cost data was the manufacturers associated with each EPD. As all other products in the EPD database, except Louisiana products, were individual EPD, corresponding company manufacturers were contacted to provide the initial mix design cost (material cost) for each product.

3.5.3.2 Louisiana

Since Louisiana products were from state projects, the first step was gathering manufacturers' contact information associated with each product in the Louisiana Department of Transportation and Development (LaDOTD) database. This process was followed by acquiring the material costs

from the associated manufacturers. In addition to the manufacturers, a second source, the LaDOTD bid history database, was used to acquire the initial construction cost for Louisiana concrete products. Initial construction cost accounts for material, equipment, overhead, labor costs, etc. The initial construction cost data were compiled into a single cost database, which also contains information on the year of construction, location, type, etc. for each project.

3.6 Environmental Impact Analysis

The goal of the environmental analysis was to quantify the environmental impacts of pavement design/product alternatives by incorporating six impact categories into a single environmental performance score. The analysis framework shown in Fig. 3 is based on the combination of EPD and transportation analysis to compute the overall environmental score.

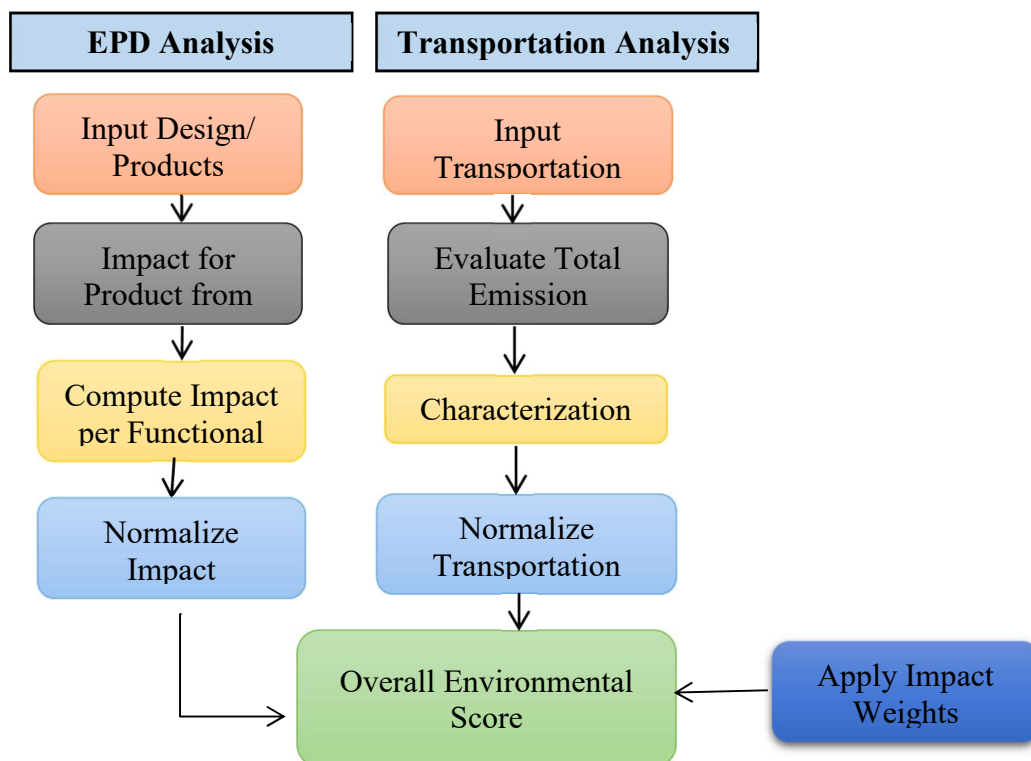


Figure 3.3. Environment Analysis Framework

3.6.1 EPD Analysis

EPD analysis is a cradle-to-gate system approach for quantifying environmental impacts. As presented in Fig. 3, the EPD analysis methodology developed in this research involves four steps. The first step defines the pavement design/products that meet the engineering performance criteria as defined by MEPDG or AASHTO 1993. The next step is the extraction of raw data for the selected products from the EPD database. However, these impacts were not quantified for the selected functional unit. Thus, the third step was the computation of impact per functional unit (m^3 per lane-km or “ yd^3 per lane-mile”) to quantify the environmental impact performance. Computed impacts were in non-commensurate units, i.e., GWP represented in KgCo_2eq , acidification in hydrogen ion equivalents, etc. Hence, the final step, normalization, quantified the computed impacts into a common scale. Reference values, developed by the U.S. Environment Protection Agency (EPA) Office of Research and Development, were used to normalize all the impacts into a common scale. The normalized impact values show the performances in terms of U.S. flows per capita per year.

3.6.2 Impacts of Transportation to Site

EPD analysis quantifies the impacts from three out of the four stages considered in this study. Transportation analysis represents the last phase of the environmental analysis, which quantifies the impacts due to transporting concrete mixes from a plant location to the job site. The impacts from this phase were added to the transportation phase impact from EPD, A2. Hence, A2 in the environmental analysis represents the combined transportation impacts of both phases.

For this analysis, the inventory data extracted from the US LCI database varies as per truck and fuel types. Therefore, defining the vehicle and fuel characteristics was an initial step in this analysis. Based on the defined vehicular characteristics, Equation (1) was used to quantify the

total emission for each impact indicator. To account for the principal-haul and back-haul distance, weight of a loaded truck and weight of an empty truck were considered. The number of trucks (N) depends upon the amount of pavement construction materials required per functional unit (m³ per lane-km or “yd³ per lane-mile”) and load carrying capacity of the truck. The distance traveled depends upon the plant and construction site location as presented in Equation 3.1:

$$T = E \times N \times D \times (W_{loaded} + W_{empty}) \quad (3.1)$$

where T= Total emission; E= average emission per truck and fuel type from US LCI database (kg/T.km); W_{loaded}= Total weight of loaded trucks; W_{empty}= Total weight of empty trucks; N= Number of trucks; and D= Distance travelled.

The computed total emissions for each impact indicator were converted into equivalent impact categories using characterization models. The analysis adopted the U.S. EPA characterization model and factor values to account for how much each indicator contributes to each impact category. The characterization factor is multiplied by the respective emission mass to determine the overall impact of each category. Equation 3.2 provides an example of a characterization model used to quantify the environmental impacts associated with GWP:

$$\text{Global Warming Index} = \sum m_i \times \text{GWP}_i \quad (3.2)$$

where Global warming index = a scaled index expressing the global warming potential of a product; m_i = mass in grams of inventory emission flow i; and GWP_i = global warming potential conversion factor from one gram of inventory flow i to CO₂.

As in the EPD analysis, each resulting impact category value was normalized with respect to the fixed U.S. scale impact values.

3.6.3 Overall Environmental Performance

The normalized values from EPD and transportation analysis were added to calculate the respective total impact score for each impact category. For example, Equation 3.3 shows the computation of the total impact score for global warming potential. Normalized impact performances were harmonized by weighting each impact category based on a set of weights, reflecting the relative importance to the overall environmental performance. By using Equation 3.4, the overall environmental score was obtained by adding all the weighted impacts scores of each category. The adopted weights were inclusive of the BEES stakeholder panel, EPA Science advisory, a set of default weights, and user-defined weights, which may vary according to the needs of the society and the public. Table 3.1 presents a summary of the weights and normalization values for the different impact categories used in the program.

$$\text{Total GWP} = \text{GWP}_{\text{EPD}} + \text{GWP}_{\text{Transportation}} \quad (3.3)$$

$$\begin{aligned} \text{Overall Weighted Environmental Performance} = & \text{GWP} \times W_{\text{GWP}} + \text{POCP} \times W_{\text{POCP}} + \text{AP} \times W_{\text{AP}} + \\ & \text{ODP} \times W_{\text{ODP}} + \text{EP} \times W_{\text{EP}} + \text{Fossil Fuel Depletion} \times W_{\text{FFD}} \end{aligned} \quad (3.4)$$

where W represents the relative weights of respective impact category.

Table 3.1 Weights and Normalization Value of Impact Categories
(Gloria, Lippiatt, & Cooper, 2007; Lippiatt, 2007; Ryberg, Vieira, Zgola, Bare, & Rosenbaum, 2014)

Output	BEES	EPA	Default	User Defined	Normalization Values
GWP	37	25	20	Specified by user	24000
AP	10	15	15		0.16
EP	13	15	15		91
ODP	10	15	15		22
POCP	12	15	15		1400
Fossil Fuel Depletion	18	15	20		288572.50

3.7 Economic Analysis

Cost data for each product were available in the EPD database along with well-established guidelines for evaluating economic performance. This analysis assumed the maintenance and rehabilitation costs to be similar to alternative products/designs since they all met the engineering criteria set forward in the design. Extraction of the material cost associated with the selected products from the EPD database was the only step for evaluating economic performance for the National and Southern Region products, except Louisiana.

Louisiana products had both materials and initial cost and thus monetary value for each product type could be calculated for each pavement alternative. For economic performance calculation, initial cost was used, as it is inclusive of materials, labor, equipment cost, etc. The initial costs assigned in the cost database per mix were categorized by the construction year of the corresponding project. Hence, the study considered the time value of money to convert the initial cost into present value by using a discount rate of 2.2% for the 12 months ending in April 2017 as published by the U.S. Department of Labor (Statistics, 2017). The inflation rate was varied per

location and per yearly cycle. Since initial cost values were for Louisiana products only, the current 2.2% inflation rate was adopted in the state analysis. The evaluated present value of each alternative represents the economic performance score while the lowest economic score represents the most cost-effective design/product.

3.8 Overall Performance Score

The overall performance combines the environmental and economic analysis into a single score. Since the environmental and economic performance scores were evaluated in different units, results were converted into a common scale. The relative scale for both performances was evaluated based on the ASTM standards for conducting Multi-Attribute Decision Analysis (MADA), which in turn characterizes the comparison of different attributes (Zavadskas, Liias, & Turskis, 2008). As presented in Equations 3.5 and 3.6, the respective economic and environmental scores for each alternative were computed by dividing the overall corresponding score of each alternative by the sum of corresponding scores for all the alternative products/designs considered in the analysis. This would result in a performance score of the economic and environmental factor of each alternative on a relative scale ranging from zero to 100. Thus, computed environmental and economic performance scores were synthesized by respective weights.

Environment performance score (E1) =

$$\frac{(\text{Weighted or Normalized impact of an alternative})}{(\text{Sum of weighted or normalized impact of all alternatives})} \times 100 \quad (3.5)$$

$$\text{Economic performance score (E2)} = \frac{\text{Total cost of specific alternative}}{\text{Sum of cost of all alternatives considered}} \times 100 \quad (3.6)$$

By using Equation 3.7, the two weighted scores were then combined into an overall performance score. As there is no standard weighting recommendation, this calculation is based on the values and perspective of each manufacturer/designer and/or consumer. The lower the score, the better

the design. The range of acceptable overall scores depends upon DOT specifications. Currently, LaDOTD has specified no range of acceptable score and therefore, an equal weight was assigned to both environmental and economic scores.

$$\text{Overall performance score} = E1 \times W1 + E2 \times W2 \quad (3.7)$$

where W1 and W2 are the relative weighting of environmental impact and economic value, respectively.

3.9 Decision-Making Tool: A Windows-Based Software

A robust user-friendly interface software was developed by implementing the described methodology, and following a systematic technique for selecting a cost-effective and environmentally preferable product/design alternatives. The software had two modes for quantifying the environmental/ economic burdens: benchmarking and product comparison.

Fig. 4 displays the user interface of the software; each tab addresses a main step in the analysis. As shown in Figure 3.4(a), the analysis begins by defining the purpose of the analysis (benchmarking or product comparison). The software then allows the user to define the pavement characteristics and thereby select the desired products from the list of different products, depending upon the respective region and compressive strengths (MPa or psi). The analysis requires user inputs, shown in Figure 3.4(b), for weights of economic and environmental performance criteria, as well as the weights in relation to environmental impact categories from the predefined weights in the program. To account for transportation analysis, vehicle characteristics and travel distances should be defined. As illustrated in Figure 3.4(c), the software can compute the distance either by supplier zip code via an internet connection or by entering the distance manually.

Finally, results for individual or all design/products may be viewed in a summary graph or life-cycle stage graph. A life-cycle stage graph shows the environmental impacts for the different phases, either for total environmental performance or for each impact category. The summary graph presents either the overall, environmental or the economic performance. In an environmental analysis, both non-weighted and weighted results may be accessed. The economic performance shows the initial cost and material costs separately for Louisiana. For other regions, the graph displays only material costs.

Sus Pav Des

Layer Information Weights Transportation Summary

Purpose of Analysis: **Select An Analysis Pur...** Project Location's Zip Code: 70820 [Need a help?](#)

Design 1 +

Design type: New pavement Pavement type: Rigid pavement

Layer 1 +

Thickness: 10.0 inch

Load Material

(a)

Sus Pav Des

Layer Information Weights Transportation Summary

Performance Weights

Environmental Performance(%) 50.0 Economic Performance(%) 50.0

Predefined Weights: **EPA Science Advisory Board-b...**

Global Warming Potential(%) 15.0 Depletion Potential(%) 15.0

Acidification Potential(%) 15.0 Energy Consumption(%) 15.0

Eutrophication Potential(%) 15.0

Sum(%) 100.0

(b)

Sus Pav Des

Layer Information Weights Transportation Summary

Transportation details: * Need a help?

Vehicle type: Light-Duty Trucks

Fuel type: Gasoline

Material Supplier Zip Code: 70808 **Calculate distance**

Estimated distance (miles): 6.442 **Compute**

(c)

Figure 3.4. User interface of the developed software

3.10 Demonstration of the Decision-Making Tool in Case Studies

3.10.1 Benchmarking Analysis - Case Study 1

3.10.1.1 Project Description

This project was constructed in 2013 in Calcasieu Parish with a total length of 0.21 km. The project was constructed for turn-lane improvement in I-210 with a designed Average Daily Traffic (ADT) of 4,257.

3.10.1.2 Pavement Structural Design

The road section consisted of three layers, a 300 mm thick cement-treated subgrade layer, a 225 mm Class II base course (Stone/ Recycled PCC), and an 275 mm thick top layer of Portland cement concrete (PCC). The modulus of rupture was 4.1 MPa, and the modulus of subgrade reaction (k) was 1481 MPa/m.

3.10.1.3 Original and Alternative Designs

The initial design of the pavement was 275 mm thick PCC with a compressive strength of 28.9 MPa. Following AASTHO 1993 (AASTHO, 1993) design guidelines, an alternative design was developed, based on the structural inputs of the actual design. Adoption of a compressive strength of 33.1 MPa and 37.9 MPa resulted in 250 mm and 225 mm thick PCC.

3.10.2 Benchmarking Analysis - Case Study 2

3.10.2.1 Project Description

The project was constructed in 2013 in Avoyelles Parish with a total length of 6.05 km. It is a reconstruction project for a road section on route LA1 with a designed ADT of 17,700.

3.10.2.2 Pavement Structural Design

The road section consisted of three layers, 300 mm thick treated subgrade layer, 300 mm Class II base course (Crushed Stone) and 250 mm thick top layer of PCC. The modulus of rupture was 4.1 MPa and the modulus of subgrade reaction (k) was 1851 MPa/m.

3.10.2.3 Original and Alternative Design

The initial design of the pavement was a 250 mm thick PCC (top layer) with a compressive strength of 54.1 MPa. Following the same design procedure for this case study, adopting a compressive strength of 48.2 MPa and 39.3 MPa resulted in 275 mm and 325 mm thick PCC.

3.10.3 Product Comparison - Case Study 1

3.10.3.1 Project Description

The project was constructed in 2014 in Tangipahoa Parish with a total length of 0.30 km. The road was constructed for interchange improvements in I-12 and U.S. 51 with a designed ADT of 29,900.

3.10.3.2 Pavement Structural Design

The road section consisted of three layers, 300 mm thick lime-treated subgrade layer, 200 mm Class II base course (Crushed Stone/ Recycled PCC), and a 275 mm thick top layer of PCC. The modulus of rupture was 4.1 MPa and the modulus of subgrade reaction (k) was 2036 MPa/m.

3.10.3.3 Original and Alternative Designs

The initial design of the pavement was 275 mm thick PCC (top layer) with a compressive strength of 28.9 MPa. An alternative design, constructed by assuming a compressive strength of 34.5 MPa, resulted in 250 mm thick PCC. As shown in Table 3.2, each design evaluated two different products (mix 1 and mix 2).

3.10.4 Product Comparison: Case Study 2

3.10.4.1 Project Description

The project was constructed in 2013 in Calcasieu Parish with a total length of 2.25 km. The road was constructed for clover lane and interchange improvements on I-210 with a designed ADT of 67,130.

3.10.4.2 Pavement Structural Design

The road section consisted of three layers, subgrade layer, 250 mm Class II base course (Stone/Recycled PCC), and a 325 mm thick top layer of PCC. The modulus of rupture was 4.1 MPa and the modulus of subgrade reaction (k) was 1851 MPa/m.

3.10.4.3 Original and Alternative Design

The initial design of the pavement was a 325 mm thick PCC (top layer) with a compressive strength of 41.4 MPa. An alternative design, constructed by assuming a compressive strength of 34.5 MPa, resulted in a 350 mm thick PCC. As shown in Table 3.2, each design evaluated two different products (mix 1 and mix 2).

3.10.5 Summary of Design inputs and different parameters for each case study

Table 3.2 presents a summary of the original and alternative designs (thickness and compressive strength) for each case study, together with the project location zip code. The weights for the impact categories, vehicle type, and fuel type for each case study are also provided in Table 3.2. Furthermore, for transportation impact analysis, the distance traveled for benchmarking case studies 1 and 2 was 48.2 and 40.2 km, respectively. However, for product comparison analysis, the plant location of corresponding mix product was adopted to calculate the distance traveled.

Table 3.2. Summary of design, products, and user defined parameters for case study

Case study	Product/design	Project zip code	Compressive strength (MPa)	Thickness (mm)	Weights	Vehicle type	Fuel type
Benchmarking, Case study 1	Design 1	70601 LA	28.9	275	EPA	Heavy duty	Gasoline
	Design 2		33.1	250			
	Design 3		37.9	225			
Benchmarking, Case study 2	Design 1	71350 LA	54.1	250	BEES	Light duty	Diesel
	Design 2		48.3	275			
	Design 3		39.3	325			
Product comparison, Case study 1	Design 1 Mix 1	70420 LA	28.9	275	EPA	Heavy duty	Gasoline
	Design 1 Mix 2			275			
	Design 2 Mix 1		33.1	250			
	Design 2 Mix 2			250			
Product comparison, Case study 2	Design 1 Mix 1	70605 LA	41.4	325	EPA	Medium duty	Diesel
	Design 1 Mix 2			325			
	Design 2 Mix 1		34.5	350			
	Design 2 Mix 2			350			

3.11 Results and Analysis

3.11.1 Performance Analysis

All case studies were evaluated with performance weights of 50% for economic and 50% for environmental. Table 3.3 illustrates the overall performance of each design and product for each case study. As shown in Table 3.3, for benchmarking analysis, Design 3 and Design 2 showed the least overall score for case studies 1 and 2, respectively. Hence, Design 3 and Design 2 were the most sustainable and economic alternatives. For product comparison, Design 2 (Mix 1) and Design 1 (Mix 1) had the least overall score for Case Studies 1 and 2, respectively. Therefore, those products were the most cost-effective and environmentally preferable product alternatives.

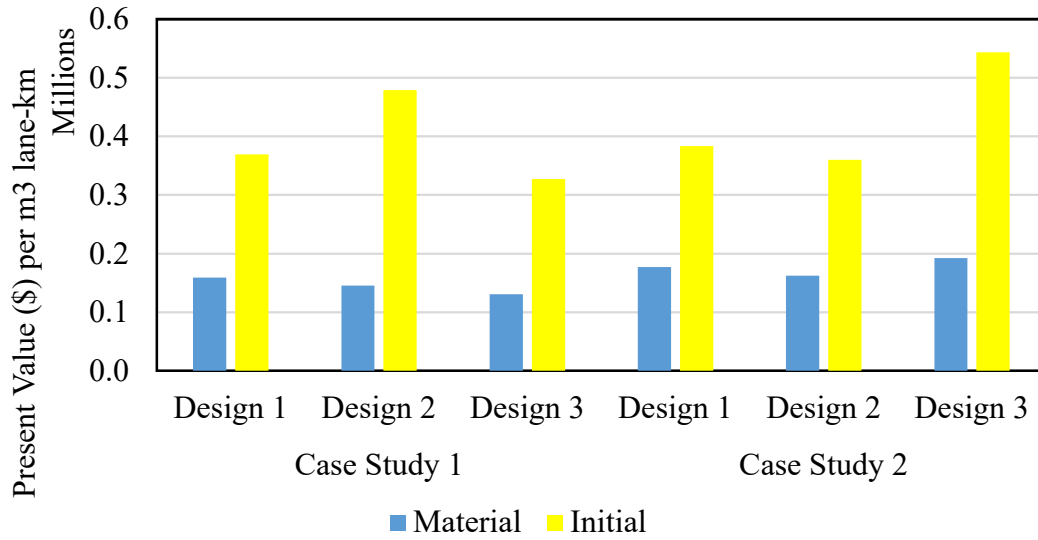
Table 3.3 Overall Performance of Case Study

Products/ designs	Economic	Environment	Total	Economic	Environment	Total
Benchmarking						
Design 1	15.7	17.8	33.5	14.9	16.3	31.2
Design 2	20.4	16.1	36.5	14.0	15.0	29.0
Design 3	13.9	16.2	30.1	21.1	18.7	39.8
Product comparison						
Design 1 Mix 1	15.1	5.6	20.7	9.8	12.1	21.9
Design 1 Mix 2	11.3	25.2	36.5	13.6	11.4	25.0
Design 2 Mix 1	9.8	9.6	19.4	16.1	13.2	29.3
Design 2 Mix 2	13.8	9.6	23.4	10.6	13.2	23.8

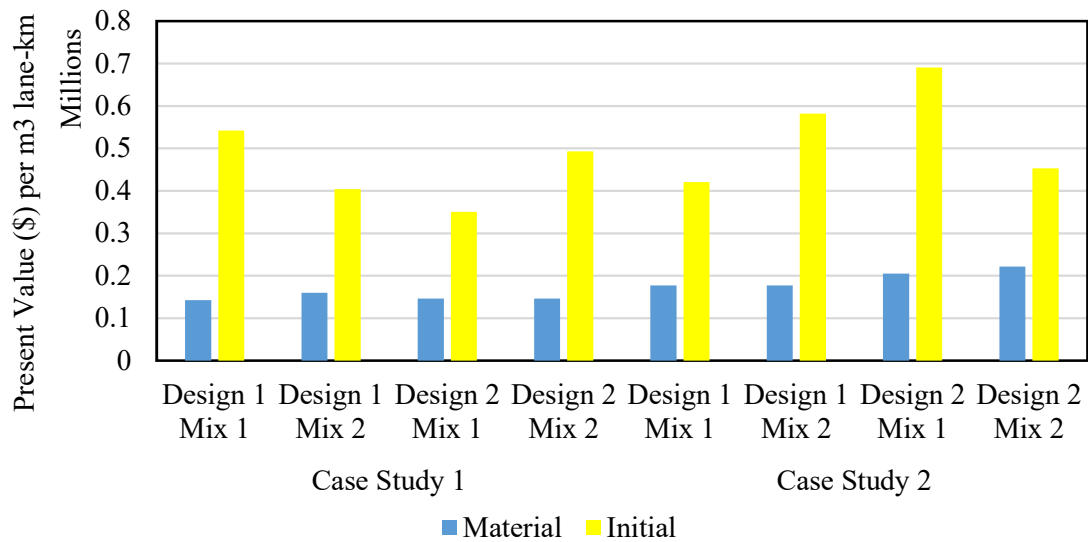
Note: Bold represents the lowest overall performance score among all the considered alternatives

3.11.2 Economic Performance

Figure 5(a) presents the total initial and material costs for each design for Case Studies 1 and 2 in the benchmark analysis. Design 3 and Design 2 provided the least present value for initial and material costs in Case Studies 1 and 2, respectively. From Figure 3.5(b), Design 2 (Mix 1) and Design 1 (Mix 1) provided the least present value for the initial cost for Case Studies 1 and 2, respectively. Even though the material cost for the two mixes of design 1 was the same for Case Studies 2, the initial cost varied. Since the initial cost accounts for equipment, labor, and overhead costs, etc., the least material cost does not necessarily mean least initial cost. Therefore, both costs should be evaluated concurrently.



(a)



(b)

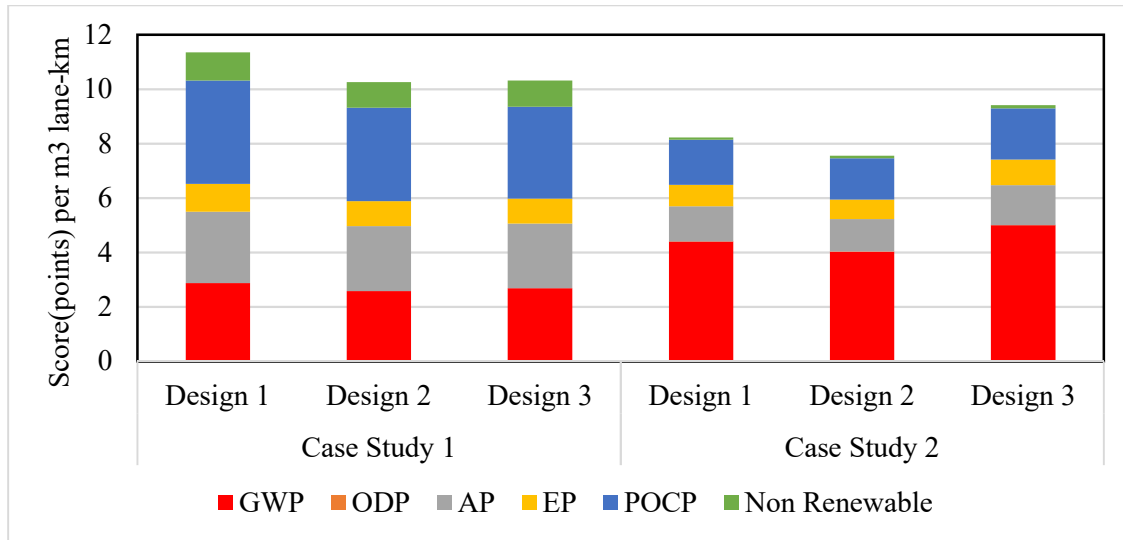
Figure 3.5. Economic Performance for (a) Benchmark Analysis and (b) Product Comparison

3.11.3 Overall Environmental Performance

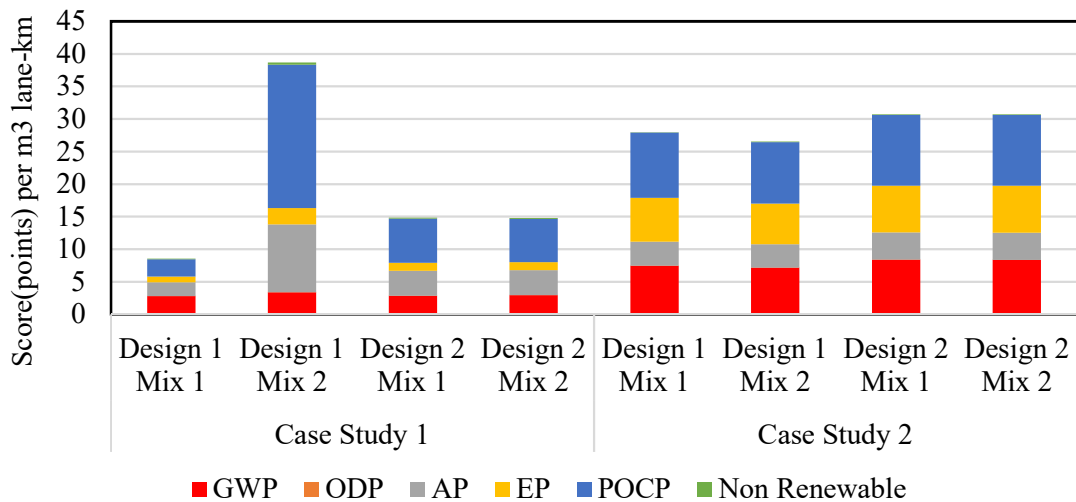
Figures 3.6a and 3.6b show the environmental scores for all impact categories and the total score of each design alternative in the benchmark and product comparison analyses, respectively. For benchmarking, the total environmental score for Design 2 was the least for both cases. The

Photochemical Ozone Creation Potential (POCP) accounted for a significant portion of the environmental burden, in comparison to other impact categories for Case Study 1. However, for Case Study 2, the Global Warming Potential (GWP) was slightly greater than POCP. This is due to the different weights assumed in each case study. EPA weights adopted in Case Study 1 account for 25% and 15% for GWP and POCP, whereas BEES weights adopted in Case Study 2 account for 37% and 12% for GWP and POCP, respectively.

From Figure 3.6(b), the total environmental score for Design 1 (Mix 1) and Design 1 (Mix 2) was the least for product comparison in Case Studies 1 and 2, respectively. EPA science advisory weights were used in both cases, supporting that POCP accounts for a significant portion of the environmental impacts in comparison with other impact categories.



(a)



(b)

Figure 3.6. Environmental Performance for (a) Benchmark Analysis and (b) Product Comparison

3.12 Summary and Conclusions

Adequate sustainability measurement tools are needed to provide a balance between the economic and environmental performances of pavements. Due to the increasing popularity of sustainability, there is a need for a tool, which can aid in decision-making by providing a comparison of different designs/products with respect to economic and environmental functionalities. This study

developed a framework to integrate sustainability measures into pavement design by developing a tool to assist in informed decision-making. The decision-making tool uses a cradle-to-gate analysis for environmental impacts, as well as initial costs for economic analysis. A user-friendly software was developed based on the proposed framework; it allows the user to define parameters such as performance weights and environmental impact category weights for which there is no standard consensus. The software may be used by the manufacturers to benchmark a product, by the designers to select cost-effective solutions, and by the consumers in selecting a product, that offers the best combination of environmental and economic aspects. The developed program will be expanded in the future to cover Life Cycle Cost Analysis (LCCA) in computing the economic score of alternatives.

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CHAPTER 4.

SUMMARY AND CONCLUSIONS

With an increased awareness regarding environmental impacts imposed by a pavement system, different stakeholders and agencies have incorporated sustainable practices in pavement design and construction. However, very few are willing to pay more in order to implement such practices. Therefore, an innovative, sustainable technology which tends to reduce both negative environmental impacts and costs is needed.

To date, Life-cycle assessment (LCA) has been the most popular assessment tool to quantify the environmental performance of the pavement. Due to the fact that LCA is an evolving science, there is no standard that defines the rules and methodologies for conducting LCA for a pavement. Further, the assumption and limitations made during the LCA analysis are not consistent in the industry. Due to these gaps, LCA results from one study may deviate from another for the same type of pavement. In addition, LCA quantifies only environmental performance while ignoring the cost performance. Therefore, there is a need for standard rules and methodologies to quantify the environmental and economic performances. The established standards would serve to select the most sustainable pavement design/alternative.

The aim of this study was to develop a framework to quantify the sustainability of pavement and thus conceive a sustainability measurement tool by incorporating the developed framework into the pavement design. The tool will assist pavement designers/ decision makers to compare and benchmark alternative pavement design/ products. The tool measures the economic and environmental functionalities of pavement based on a cradle-to-gate framework. The environmental analysis quantifies impacts associated with raw material acquisitions to material

production (mixes) and transportation of the mix from the plant site to the construction site. EPD, a consistent sustainable quantification tool, was used to compute the impact from raw material acquisitions to material production (mixes); whereas, a transportation module was developed to quantify the impact associated with the transportation of the mix from the plant site. In context to the economic performance, the process applied the same system boundary as in environmental analysis. For all pavement mixes, with an exception for the Louisiana based mixes, material cost was used to evaluate the economic performance. However, for Louisiana based mixes, initial construction cost (material cost plus material transportation cost, overhead, labor, and equipment) was used to evaluate economic performances. The economic and environmental performance was combined to estimate the overall performance of the pavement.

Based on the developed framework, windows-based software was developed to allow users to compare and benchmark their pavement design/product alternatives. The developed software allows the users flexibility to define the input parameters (pavement mixes/ design, performance weights, vehicular characteristics, and environmental impact category weights). Since the importance of environmental impact categories varies in perspective from users to users, the program provides the flexibility for users to input this parameter. The results for all the alternatives may be viewed either in the graphical or tabular form for non-weighted as well as weighted performances. Further, the results may be viewed either solely for environmental and economic performance, or for an overall combined performance. The developed decision-making tool would aid designers, consumers, and manufacturers to benchmark and compare different alternatives in order to select eco-friendly and cost-effective solutions.

4.1 Future work

4.2 Future Work

Even though the developed tool presents a promising way to assist in pavement decision-making, the framework works only on the cradle-to-gate framework. A well-established consensus is that other phases of pavement carry significant impacts to the triple components of sustainability. Although a lack of data and proper methodology restricted the integration of use-phase and end-of-life phase in the current study, sustainability may be achieved by balancing the economic, environmental, and social performances. This study considered no social components due to its complexity. Therefore, the recommendation is that for future studies all phases of pavement, together with the social component, should be considered in the sustainability analysis of pavement.

Recently, different developments have been made in the concrete pavement. Such as continuously reinforced pavement, fiber reinforced pavement are also used in pavement applications. Therefore, it is imperative to develop EPDs for these types of concrete as well. Further, comparison of rigid and asphalt pavement is one of the main issues in pavement decision-making. Since EPD for concrete and asphalt are developed based on different product category rules, the developed tool cannot be applied for the comparison of two types of pavement. Hence, a systematic methodology is needed to compare these two different types of pavement.

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