LCA: A TOOL TO STUDY FEASIBILITY AND
ENVIRONMENTAL IMPACTS OF
SUBSTITUTING ASPHALT
BINDERS

A Thesis
Submitted to
the Temple University Graduate Board

In Partial Fulfillment
of the Requirements for the Degree
MASTER OF SCIENCE
IN CIVIL ENGINEERING

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by
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May 2021

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ABSTRACT

Finding innovative technologies for building our roads has always been of paramount importance. From moving to warm mix asphalt to decrease our indulgence in high energy consumption to substituting fly ash for asphalt binders to reduce dependence on pure asphalt binders from petroleum, engineers have painstakingly tried to develop new ways to improve the ways that flexible pavements are made. The major problem facing the next generation of civil engineers is sustainable practices on the field.

Over the years, significant progress has been made in this regard on the impacts of building pavements on the environment. Characterizing these improvements tend to be difficult, and that is where Life Cycle Assessment (LCA) comes in. LCA is a technique used to analyze and quantify the environmental impacts of a product, system, or process. LCA shows where the significant impacts occur and how improvements can be made while recommending better practices. Even with its many advantages, its use is very constrained, especially in the United States, as it is still a very novel approach in design coupled with limited datasets and protocol for its operation.

With modern technologies of substitute materials for binders like bio-oil from food waste, reclaimed asphalt pavement (RAP), and fly ash, there is a need to understand their environmental impacts. Furthermore, in this regard is where LCA can help using three significant areas: selection of materials, normalization, and characterization. Characterization refers to the identification and quantification of the relationships between the life cycle results and the environmental impacts. This research explores the environmental impacts of substituting other materials for asphalt binders using LCA. With variations in modifying levels of substitutes, results show promising levels in emissions of harmful gasses to both the air and water. This study explores ways used in normalizing this process as well as setting up a pathway for other asphalt binder substitutes.

Keywords: Life-Cycle Assessment, LCA, RAP, Fly Ash, Asphalt Binders

ACKNOWLEDGMENTS

I am very thankful to even be in this position of being able to show my appreciation to the people who have supported me one way or the other over the years.

Firstly, I would like to express an utmost gratitude to my advisor, Dr. Ahmed Faheem for being an amazing mentor and a friend over my stay at Temple. I would also like to thank you for always pushing me to try to be my best self both in and out of the classroom. Your guidance and support over the last 5 years have been immeasurable and I would like you to know that. I would also like to thank the other members of my committee. Drs. Felix Udoeyo and Philip Udo-Inyang, I would like to thank you for your interest in my thesis and your contributions to the success of the study. I would also like to thank you for your guidance and support which helped to improve the quality of this research. To my friends, thank you for keeping me focused and for always encouraging me to strive and work harder. I would like to thank my Temple family especially Ms. Ross, Ms. Margie, Dr. Golriz Kermani, Hatim Osman, Ahmed Mohsen, Chidubem Ogugua, Patrick Chukwu, and Kemi Adeyemi. To my friends, Abiodun Abayomi, Aruna Adekunle, Pelumi Adebowale, and Sager Busari, I would like to thank you for being there to talk to whenever I need some motivation and for always reminding me the reason why I work so hard.

For trying to set the best footpath for you guys, I thank my nieces and nephews, Qaneetah, Salenah, Kamilah, Farhan and Zayn Adesokan. I would also like to thank my brothers and sisters for their continuous support and always having my back. Thank you Bukola Solebo, for To my aunts, uncles, and guardians, I would like to thank you for your guidance and support. To my mom and dad, I owe everything. For the life, love, support, and guidance that has been provided to me. I love you, mom.

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GLOSSARY

A.I. – Asphalt Institute

EPA – Environmental Protection Agency

EPD – Economic Product Declaration

FHWA - Federal Highway Administration

ISO - International Organization of Standardization

LCA - Life Cycle Assessment

NAPA - National Asphalt Pavement Association

PCC – Portland Cement Concrete

CH 1 – INTRODUCTION

1.1 Environmental Impacts of Asphalt Binders

Right from its production from refineries, asphalt poses adverse risks to the environment. The asphalt binder is the most vital component of the pavement industry. About 94 percent of the United States roadway relies on using this material to in construction. Asphalt binders are a by-product of refining crude petroleum to produce gasoline and other petroleum products. Being produced from the thick, heavy residue that remains after fuels and lubricants are removed from crude oil, it leads to many adverse effects right from the stage of production to its usage, leaving a trail of detrimental impacts across the supply chain. With a yearly demand for over 500 million tons of asphalt pavement, this can quickly add up the number of concerns for its impact.

It will be a considerable bias not to tell the economic effectiveness of asphalt pavements in comparison to other materials currently used (Portland Cement Concrete, PCC). With a proper design and construction, the foundation upon which the material is laid does not degrade. The maintenance of the road, as well as its rehabilitation, is also economically strategic. Economic factors, mixed with it being replaceable within a day, make its choice of being the most used clear. Moreover, with the construction industry heavily basing its decisions on economic factors, the effects keep getting compounded. Governmental agencies have been picking up the pace in this aspect by funding research into greener approaches to building pavements and compensating companies that currently use these methods.

Depending on the mix design, asphalt binders can make up between 4 to 6 percent of the total mixture weight. Serving as the glue that holds the granular materials (aggregate) together, its importance cannot be overstated. However, with the decline of crude oil and its environmental impacts, the demand for alternatives has never been higher, prompting researchers and engineers alike to set out to work.

1.2 Life Cycle Assessment (LCA)

Over the last few decades, there has been an increasing number of agencies, companies, and organizations across all sectors of commerce that are pushing for and embracing sustainable practices in conducting their day-to-day operations. These practices try to bring in environmental factors into these firms' already existing criteria towards decision-making in their operations. The Federal Highway Administration (FHWA) defines sustainable development as any "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (2014). This approach means that apart from economic factors, environmental factors will play a significant role in making decisions.

Life-Cycle Assessment (LCA) is an ever-growing analysis technique that all industries across the world are gradually coming to use that enables these sectors to run on a greener and more economical level for production. LCA is a technique used to analyze and quantify the environmental impacts of a product, system, or process. At the same time, it is providing a comprehensive evaluation of the environmental impacts of a product over its life cycle from its production to end of service (a cradle to grave approach as it is commonly called). This helps to find areas where the most significant impacts are and how best to mitigate them. The pavement industry, over the last four decades, has been steadily developing its LCA practices. This industry, alongside the construction sector, has always struggled to mitigate their environmental impact arising from their practices. LCA provides one of the most efficient ways to quantify the impacts from these practices and account for their burden and strain on the resources.

With these impacts on the environment, there has been an enormous call for developing new materials to serve as a modifier or, in some cases, substitutes for the binders to mitigate their effects. Some of the materials that are used include reclaimed asphalt pavement (RAP), ground tire rubber (GTR), fly ash, and bio-oil from food waste. These materials act as substitutes or rejuvenators for asphalt binders. The question then becomes what the perfect combination is between what works and how much help it does to the environment.

1.3 Problem Statement

The United States currently produces over 500 million tons of asphalt pavement per year (NAPA 2013). Asphalt is a bituminous, petroleum-based material used as the binding material in flexible pavements. Due to its source, it has adverse effects on the environment. This, coupled with limited petroleum reserves, there is a need to find alternative sources for this material. This has given rise to several materials being substituted at various levels for this purpose. The research towards finding the perfect combination of modified binder that will serve its purpose as a binding material for pavement as well as reducing environmental impact has proven itself to be tricky, and this makes it an ever going one. One of the approaches within a couple of decades has been to use the LCA approach to tackle this problem.

The earliest application of LCA to pavements was in the 1990s. LCA is now widely used in Europe in the construction industry, especially in France, Germany, and the Netherlands. These countries include LCA in green construction regulations that govern pavements and other structures. In contrast, LCA has only surfaced within the last ten years and has begun to be considered a decision support tool in North America, Canada, and the United States. The development of an environmentally friendly Life Cycle Assessment guideline has proven to be more difficult than usual. Apart from a "systematic and comprehensive summary of the outcome" of a study, there is a need for a completely "transparent presentation of the data, methods, results, and limitations" realized from such study (FHWA 2014).

1.4 Scope of Research and Research Objectives

The most important part of an LCA analysis is to have a system boundary. The system boundary is broadly defined as a line that divides the system that is to be studied from other constraints. In LCA, system boundaries are defined as the boundaries in which processes in the products life cycle are included in the analysis. There are two main system boundaries that can be used for pavement LCA and they are cradle-to-grave and cradle-to-gate. The cradle-to-grave approach takes all six stages of pavement life cycle into account while the cradle-to-gate approach considers only a set target.

This project looks at developing a guideline to produce asphalt mixtures. An asphalt mixture can simply be defined as a produced composite material consisting of aggregates (coarse and fine) and liquid binder. Often, this mixture has some form of modifiers which can be in the form of recycled materials or additives. With many materials forming the pavements, there are multiple avenues to go to study for the reduction of the adverse effects of this material. This project focuses on studying asphalt binders and their substitutes and their impact on the environment.

The study starts by exploring the literature which sets the precedence for the need for LCA and from that the goals for the project were set.

The goals of this project were to:

1. Define asphalt binder substitutes and use available information to evaluate the effects of using recycled materials in asphalt mixtures.
2. Define a system boundary for the analysis of asphalt mixtures.
3. Recommend a modified approach to LCA.

1.5 Thesis Layout

The thesis was structured to be broken down into five main sections: Introduction, literature review, methodology, results, and conclusion. A further breakdown of the sections is explained below.

Chapter 1 of introduces the subject matter and gives an insight to the scope of research. The problem statement is presented, and the research objective are expressed in this section. There is also an introduction into Life Cycle Assessment (LCA).

Chapter 2 gives detailed information about the background of the problem, current industry practices, and state of research into the subject matter. The sections in this chapter also introduce environmental LCA, pavement lifecycle stages, and choosing binder substitutes. This is where the raw materials used in the study were also introduced, as well as the software that will be used in this study, openLCA.

Chapter 3 focuses on the methodology and approach used for analysis. It further explains topics involving openLCA. The main information here is the data acquisition method and their sources. The study also talks about the data analysis method, as well as the impact analysis method by using TRACI.

In chapter 4, the focus was set on results on discussion. By implementing the data from the previous chapter and introducing a mix design guide, the chapter focuses on interpreting the life cycle impact categories. The chapter also touches on analyzing the results and factors that can influence the impact categories. There is also a section for the summary of data and results in the chapter.

Chapter 5, being the final chapter, presents the conclusions of this thesis and provides recommendations that can be applied to future work. The limitations that were experienced in the course of the research period was also highlighted, as well as ways to mitigate them.

CH 2 BACKGROUND AND LITERATURE REVIEW

This review looks at Life-Cycle Assessment with a significant concentration on studies that relate to asphalt binders. Looking at earlier work in this area revealed variations in ways that researchers have approached this topic, with most of the earlier work done on the pavement life cycle. The literature review also suggested a strong need for the development and standardization of an LCA approach for pavements.

2.1 Environmental LCA

The guidelines and parameters for LCA can be traced back to the 1960s, and the intention was to analyze impacts on air, land, and water emissions from solid wastes (Harvey et al. 2016). This set the foundation upon which all other research is based. In 2004, the International Organization for Standardization (ISO) set out to develop guidelines, and they set LCA parameters in the "ISO 14000 family of standards" (FHWA 2016). The two main ISO guidelines that all research focuses on are ISO 14040 and 14044 because they define a widely accepted standard for LCA, and this is needed because there are different software programs and applications in the market for LCA. With the production of binders, one of the highest influencers in the impact assessment, the study looks at how they are produced. The table below shows how the binders evaluated by A.I. were extracted both by conventional and unconventional methods.

Table 2-1: Crude oil extraction method of A.I. asphalt binder

Category of Extraction Technology	Percentage by mass (%)
Crude from oil sands	44
Primary Extraction	22
Secondary Extraction	16
Tertiary extraction, steam injection	15
Tertiary extraction, CO2 injection 1%	1
Tertiary extraction, nitrogen injection	1
Tertiary extraction, natural gas injection	1
Other (refinery products)	Less than 1

Adopted from Asphalt Institute 2019

With the asphalt binder being the major factor to look at in this thesis, there is a need to understand its contribution factor of its environmental impact. Extracting the crude oil itself drives the impacts from the binder the most. Table 2-1 highlights an average of the current technology that are used for extraction in the United States and how much each step contributes to the impact factor. This production is modelled in form of electricity and energy allocated to its production. This helps in the methodology phase while inputting it in the Life Cycle Inventory. The average for this is an industry average in the North American region.

2.2 Industry Practices and Pavement Lifecycle

The flexible pavement construction industry is one of the most recycle-friendly industries in the country. With a yearly reclamation of asphalt mix of over 100 million tons, it has over 95 percent of reuse, constituting over 95 million tons of RAP. There is currently high interest in focusing on pavement LCA amongst both researchers and practitioners (Harvey et al. 2016 and Osmani et al., 2017). The complexities of getting accurate and reliable data, however, limit their ability to use this approach. This is where standardizing the guidelines plays a massive role by setting what constitutes a transparent and precise data review.

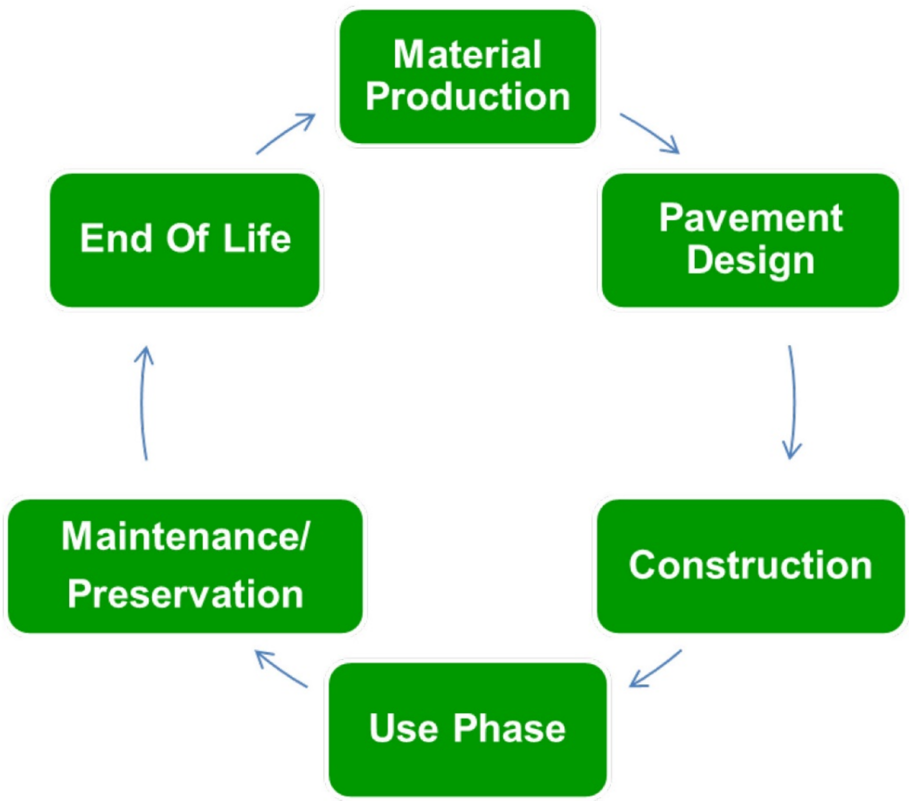


Figure 2-1: Pavement life-cycle stages.

Source: FHWA 2014

The pavement life cycle currently consists of six (6) primary areas:

- Material Production - This involves all the processes used in getting and processing (I.e., refining, manufacturing, and mixing) pavement materials.

- Design Phase – This is the process of finding structural and functional conditions of the pavement (I.e., subbase, traffic expectations, climate, drainage conditions). Sometimes, this phase is categorized as part of the construction stage.
- Construction Stage - This includes all processes and equipment associated with the initial construction of the pavement.
- Use Phase - This is also commonly referred to as the service life of the pavement. This refers to the period when the pavement is in service while being in a functional condition.
- Maintenance/Preservation - This refers to all the activities applied at various times on the pavement to support its serviceability. It also encompasses rehabilitative measures that may be applied at any time during service life.
- End of Life - This refers to the final disposition and later reusing, processing, and recycling of the pavement materials after it has reached the end of its service life. This is one of the trickiest aspects of the pavement life cycle because it can involve processes within the same materials used to build the pavement as is the case of RAP, but sometimes it goes to other sectors like the use of Fly Ash, which is a by-product of the coal industry.

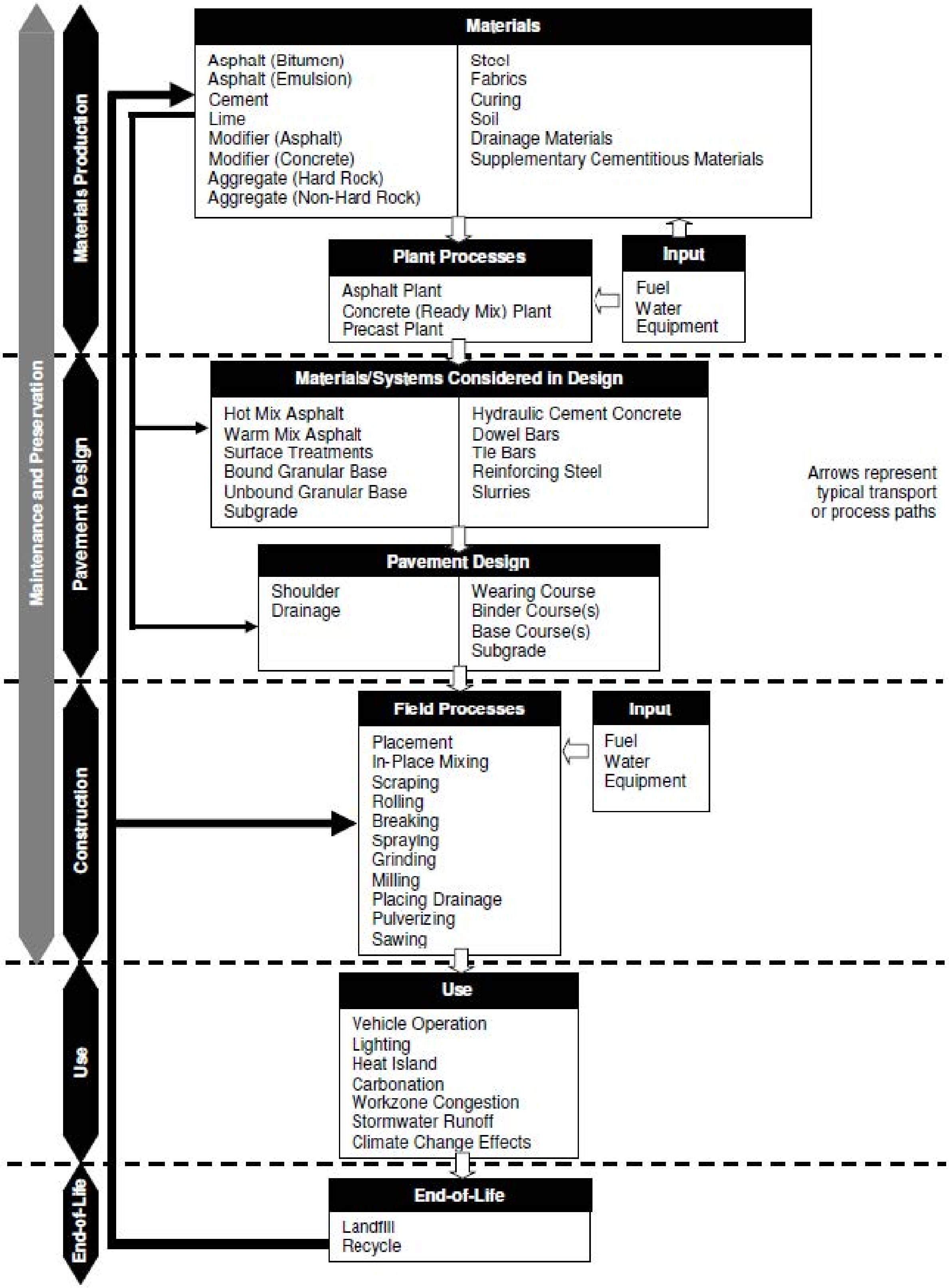


Figure 2-2: Comprehensive look at pavement life cycle. (Harvey et al.2016)

The two main system boundaries for pavement LCA and they are the cradle-to-grave and cradle-to-gate approaches. The cradle-to-grave approach takes all six stages of the pavement life cycle into account, while the cradle-to-gate approach considers only a set target. For this study, the system boundary will be categorized by a cradle-to-gate approach, and only the first three stages will be considered (material production, design, and construction). Of these three stages, on average, material production contributes about 70 percent of the total potential impacts on the environment across the categories.

2.3 Choosing Binder substitutes

This study focuses on three asphalt substitutes: Reclaimed Asphalt Pavement (RAP), Fly Ash, and Bio-oil from food waste. The literature on the subject matter suggests that the most common substitute is RAP, with a yearly use of 95 million tons. It is also the most studied material for the use of substitution amongst researchers. Fly Ash is a newer technology gotten as a "waste" from the coal industry. It serves as a mineral filler in asphalt paving applications. Bio-oil, on the other hand, does not serve as a filler but as a rejuvenator for the binder.

2.3.1 Reclaimed Asphalt Pavement (RAP)

Reclaimed asphalt pavement (RAP) is a reprocessed pavement containing asphalt and aggregates, and this means that it involves the excavation of an already laid pavement and processing it (excavation, crushing, screening, stockpiling, and testing) for the eventual use in an asphalt mix design. As with any material, RAP has varying mechanical properties that heavily depend on "the original asphalt pavement type, the method(s) utilized to recover the material, and the degree of processing necessary to prepare the RAP for a particular application" (FHWA 2014). The first question that comes with using

RAP is how much can be incorporated into a mix (of asphalt concrete) and how significant it will be in terms of the overall performance of the pavement. In fact, this question continues to give contractors and government agencies a battleground.

Figure 2-3: Stockpile of RAP

With a potential of about 18 billion tons of RAP and a yearly use of 100 million tons, there is considerable room for more use of this material, and yet the question remains, "Why don't we use more RAP in our mix?". The answer is during the design phase of a mix, the contractors and engineers must adhere to, and the highest usage rate by weight is currently maximized at less than 30 percent, with more than 20 states in the country capping at about 10 percent of total weight. This study compares data for using a RAP content from 15 percent substitution to 35 percent substitution. Also, for the purpose of this research, RAP is looked at as waste material from the initial construction of the pavement, and its usage of resources during production will not be considered.

2.3.2 Fly Ash

Fly ash is a by-product of the coal industry resulting from the combustion of coal and is used as a mineral filler in the pavement industry. It is currently used in a meager percentage of about 5 percent of mixture weight. Apart from its fine nature, making it a perfect void filler, fly ash also has a hydrophobic nature that makes it very treasured for reducing moisture susceptibility and stripping in asphalt pavements. There are different classes of fly ash with comparable properties, but the commonest currently used in pavement engineering are Classes C and F. With a yearly production of over 75 million tons, there is also enough room to accommodate more users. On an annual basis, less than 200,000 tons of fly ash is currently used in asphalt pavements. This study explores the potential of using the current industry standard of about 3 percent to 15 percent of mixture weight.

Figure 2-4: A fly ash silo at the plant

With the different classes of fly ash having specific functions, it is important to know which one will be used. The two most common classes are class C and class F, and the main difference between them is that Class F fly ash is pozzolanic and it has little to no binder properties, while Class C fly ash has self-binding properties as well as pozzolanic properties. This makes class C feasibly serve as a form of a binder, while class F fly ash will be reserved as a mineral filler. Another difference between them will be their sources. Class F fly ash is gotten from burning anthracite or bituminous coal, while class C is gotten from burning lignite or sub-bituminous coal (FHWA 2016). For the purpose of this research, fly ash is looked at as a waste product, and its usage of resources during production will not be considered.

2.3.3 Bio-Oil

Just like fly ash, bio-oil is a by-product from another material, in this project, organic matter and specifically plant-based (e.g., coffee). These oils are obtained by distillation of coffee beans and filtering them to give them consistent chemistry. Although serious work is currently being done in labs across the world to substitute bio-oils for binders, for the purpose of this project, bio-oils are considered as rejuvenators for RAP, serving as a modifier for the binder. Rejuvenating agents are used to improve the mechanical properties of asphalt mixtures, especially with high RAP content. Regarding the severe aging and different chemical composition of RAP, "the reconstituting of the chemical composition of RAP binder is essential to balance stiffening effect" (Haghshenas et al. 2016). Hence, softening agents and rejuvenators have been conventionally used to moderate the stiffness of the RAP binders. The role of these softening agents is mainly to decrease the viscosity of the aged asphalt, and this means a better level of stiffness, and this helps in better mixing and consequently better compaction of the mix.

2.4 Mechanical Performance of Modified Asphalt Binder

No amount of LCA calculations and impact analysis can justify using a modified binder if the binder cannot pass rheological properties tests. This study focuses on using two recycled materials to formulate new polymers of asphalt binders that will be more eco-friendly. The two materials that were studied are Reclaimed Asphalt Pavement (RAP) and Fly Ash. This study's analyses were based on proven levels of RAP and Fly Ash levels. After the intended levels were established, the binder's performance was now explored. The process of mixing a binder with modifiers is usually referred to as mastic production. The results on testing these mastics were then explored for mechanical performances on established criteria. The bio-oils were mainly used to rejuvenate/de-age the RAP's effective binder. The amount that can be used is also heavily debated as well as even the idea to use it at all. Since fly ash is the more modern technology, its properties are more debated than that of RAP's. There are at least eight classes of fly ash on the market, with each one having a slightly different chemical composition than the other. The standard way to characterize the performance of fly ash-mastic is by measuring its carbonyl and sulfoxide indices by using Fourier-Transform Infrared Spectroscopy (FTIR).

2.5 Data Quality Management

This requirement is also spelled out in the ISO 14000 family of standards. It requires data used inflows to calculate impact analysis to be sufficient to meet the study goals and should be easy to interpret. ISO 14044 defines data quality as "characteristics of data that relate to their ability to satisfy stated requirements" (Harvey et al., 2016). This makes its requirements dependent on the goals of the study and should be documented according to the LCA study. This study focuses on using data guidelines set by the Asphalt Institute (A.I.) and the National Asphalt Pavement Association (NAPA). The A.I. supplied data on binders from the refinery to factories, while NAPA supplied data used in the mix design and construction phase.

2.6 openLCA

openLCA is open-source and free software that is used for Sustainability Analysis and Life Cycle Assessment (LCA). It was developed by GreenDelta, a sustainability consulting firm, in 2006. It offers a reliable calculation for the following.

- LCA
- Life Cycle Costing (LCC)
- Social Life Cycle Assessment (S-LCA)
- Carbon & water footprints
- Environmental Product Declaration (EPD)

This study will focus on the LCA aspect of the software. Using the EPA guidelines and available parameters, the process schema was coordinated by the ILCD data quality system, while the impact assessment was done by the guidelines set by TRACI 2.1. More information on TRACI will be provided in the Methodology section. Although TRACI was used as the impact assessment method, LCA provided other information on things like health factors, and those will be briefly looked at in this study.

CH 3 METHODOLOGY

3.1 LCA Inventory

This section focuses on describing the inputs, outputs, and processes involved in making the asphalt mixture and will be categorizing them as primary and secondary data. Due to the inability to collect data firsthand, this study focuses on using the industry average as collected by the Asphalt Institute (A.I.) across 12 refineries and 11 terminals in the U.S and Canada. The primary data analysis will focus on data that are clearly defined for the purpose of LCA, while secondary data are those that were outside the system boundaries but still needed for the study.

3.1.1 Time Coverage

The A.I. conducted their research during a period of 12 consecutive months during the 2015 and 2016 calendar years (A.I. 2019).

3.1.2 Geography Coverage

Just like the A.I. guidelines, this study focuses on defining its data within the North American region, particularly the United States and Canada. This is because of the specificity of the data gathered based on the region they are gotten.

3.1.3 Primary data

This section focuses mainly on data directly related to the production of asphalt mixtures. Most of the data are based on the industry average that has been gotten by the Asphalt Institute.

1. Asphalt binder produced at the refinery, reported in kg.
    a. Refinery data provided information from the cradle stage.

    b. Binder used in production, reported in kg.
    c. This study also considers the amount of binder used in the mixture process at the plant, also reported in kg.
2. Electricity and energy
    a. Wind power, in M.J.
    b. Hydropower reservoir, in M.J.
    c. Geothermal energy, in M.J.
3. Factory energy for mixture stage
    a. Diesel fuel, in gallons (us fl)
    b. Natural gas, in M.J.
4. Transportation
    a. Rail transport was represented by coal energy in M.J.
    b. Truck transportation, diesel fuel, in gallons (us fl)
5. Natural aggregate used during the production of the mixture, in tons.
6. Water used in gallons (us fl)
7. Energy for converting RAP, in M.J./ton
8. RAP and fly ash used in production, in tons.

Since LCA works in terms of using the information provided on both input and output, and the study treats this analysis as one single process from drilling for asphalt to the mixture production, the energy and materials used here were defined as the input data. The output was defined as the total emissions to air, land, and water and the actual mixture as the outputs.

3.1.4 Secondary Data

As said earlier, these are all the data that were used in arriving at the output in the system processes. These include data on impacts from refining and extracting raw materials, especially asphalt binders. Also, the data on transportation of both the binders using rail as well as truck are classified under secondary data.

3.2 Data Importation and Implementation of openLCA

The goals of this project required gathering, creating, importing, converting, and interpreting datasets and forming a database for them.

The LCA model was created using the openLCA for life cycle engineering, developed by GreenDelta. The openLCA database provides the main life cycle inventory data for the background system (raw materials, fuels, transportation). The database containing flows and impact methods was imported from Asphalt Institute and imported into openLCA using the ILCD format. The International Reference Life Cycle Data System (ILCD) is an initiative developed by JRC and DG ENV in 2005, with the aim to provide guidance and standards for greater consistency and quality assurance in applying LCA (Aymard and Botta-Genoulaz 2016).

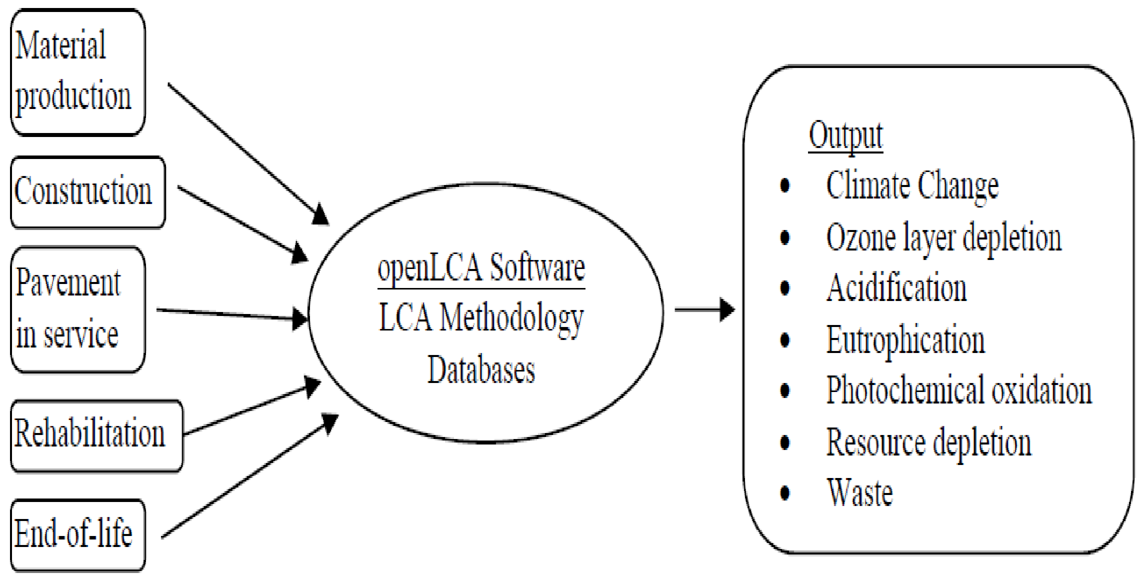


Figure 3-1: Illustration of LCA Method

Adopted from Osmani et al. 2017.

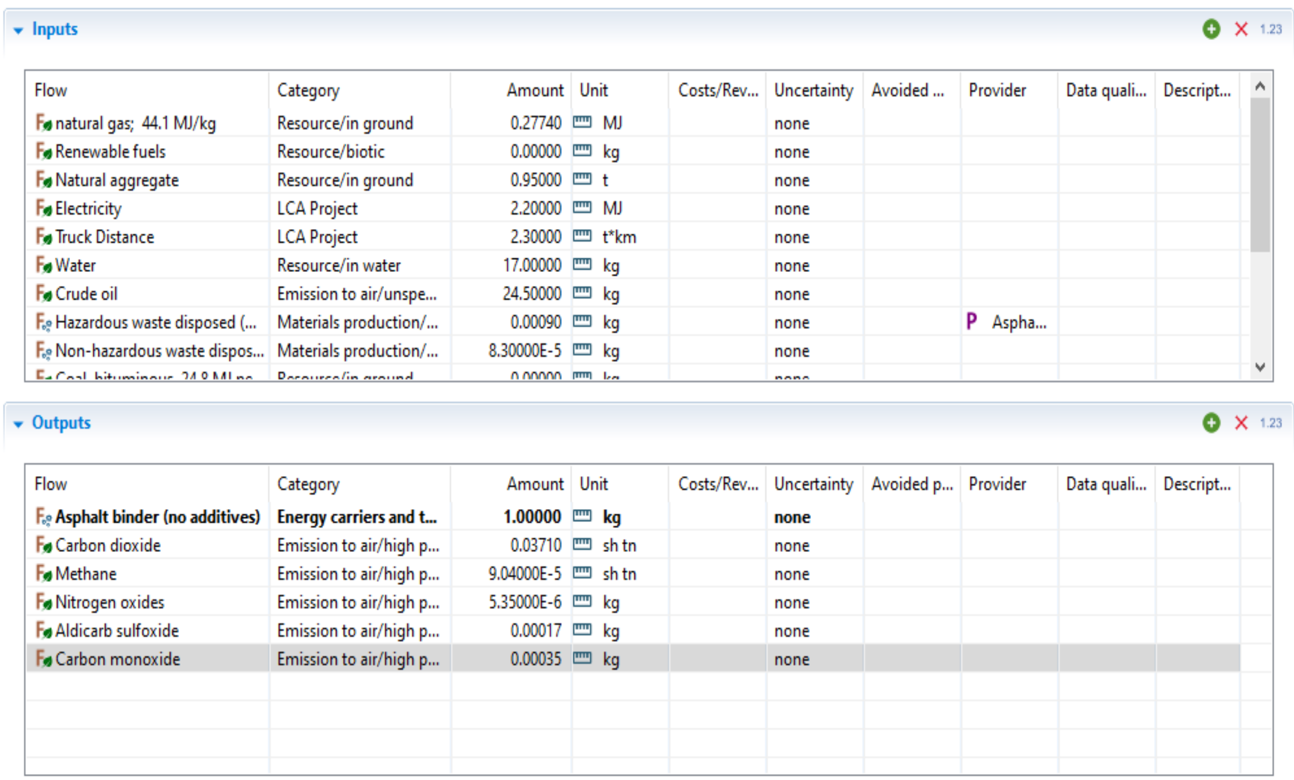
3.3 openLCA Database Analysis

3.3.1 Flows

Flows are essential components of raw data used for life cycle assessment (LCA). It serves as the functional unit of the whole LCA process. The raw materials needed for the analysis were also defined in the flows. Flows are used to represent the resources in the processes used for assessment. In this study, these flows also represent emissions of pollutants and wastes into the environment (land, air, and water). Every input and output that is defined in the process is also referred to as a flow. The ISO 14044 defines flows as "materials, energy, or space that are taken directly from the environment or released directly back into the environment." These flows usually are made up of three (3) components:

- Name of the resource (e.g., Groundwater, crude oil)

- Flow context – describes the environmental conditions of the flow origin or destination (e.g., resource or emission)
- Flow unit and property – characterizes physical conditions associated with the flow (e.g., kg, L, M.J. etc.) and can also include conversion factors (e.g., kg to lbs., L to m^3).



Inputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided ...	Provider	Data quali...	Descript...
natural gas; 44.1 MJ/kg	Resource/in ground	0.27740	MJ		none				
Renewable fuels	Resource/biotic	0.00000	kg		none				
Natural aggregate	Resource/in ground	0.95000	t		none				
Electricity	LCA Project	2.20000	MJ		none				
Truck Distance	LCA Project	2.30000	t*km		none				
Water	Resource/in water	17.00000	kg		none				
Crude oil	Emission to air/unspe...	24.50000	kg		none				
Hazardous waste disposed (...	Materials production/...	0.00090	kg		none		P Aspha...		
Non-hazardous waste dispos...	Materials production/...	8.30000E-5	kg		none				

Outputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided p...	Provider	Data quali...	Descript...
Asphalt binder (no additives)	**Energy carriers and t...**	**1.00000**	**kg**		**none**				
Carbon dioxide	Emission to air/high p...	0.03710	sh tn		none				
Methane	Emission to air/high p...	9.04000E-5	sh tn		none				
Nitrogen oxides	Emission to air/high p...	5.35000E-6	kg		none				
Aldicarb sulfoxide	Emission to air/high p...	0.00017	kg		none				
Carbon monoxide	Emission to air/high p...	0.00035	kg		none				

Figure 3-2: Flows depicting input and output for a system.

3.3.2 Processes

A process is an activity that transforms an input into an output. It can either be a "unit process" or a "system process." The simplest form of a process in openLCA is a unit process, and this is the type of process that this study defines its data. A unit process is the smallest unit analysis for which input and output data can be quantified, while a system process is a unit for which input and output data are aggregated. A system process is often used in a Life Cycle Inventory analysis. With more comprehensive data that looks into the crude refinery, asphalt production factory, quarries from which aggregates are gotten, the different energy sources (renewable and non-renewable) amongst other data sources, a system process would be needed because of the intertwining nature of these sources.

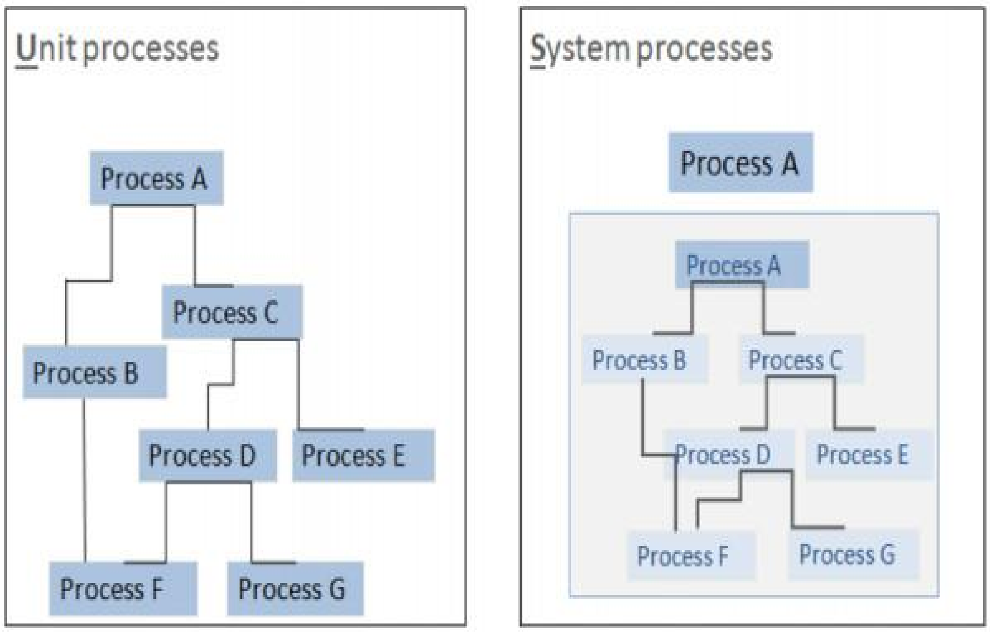


Figure 3-3: Difference between Unit process and system process

Adopted from openLCA openLCA manual(2020)

For processes, the data quality entry must be clearly defined in a general information section. This is the section where tasks like changing names of a process, adding descriptions, setting quantitative references, and adding geography and technology can be done. The process that is set is also where the input and output functions are defined.

3.3.3 Product Systems

The ISO defines a product system as a "collection of materially and energetically connected unit processes, which perform one or more defined functions" (2010). It is the system of consecutive and interlinked processes that serve as the life cycle model of any product. There are several ways to create, edit, and complete product systems, and this all depends on the type of database and user preferences.

3.4 Analysis and Interpretation

3.4.1 Data Analysis

openLCA provides several impact assessment categories and metrics that can be looked at for different assessments, but this project focuses on those established by TRACI 2.1. The United States Environmental Protection Agency (EPA) established this as an "impact assessment methodology framework that incorporates U.S. average conditions to establish characterization factors" (EPA 2012). The results gotten from the impact assessment were then reported based on the CML methodology. CML is an impact assessment method that restricts quantitative modeling to the initial stages in the cause-effect chain to limit uncertainties which then groups results in midpoint categories (Gabi^{TM}). This is done so that the results will conform with the standards that have been established according to the National Asphalt Pavement Association (NAPA) EPD program.

The characterization of a product is done in the form of calculating indicator results by converting inventory results to common units and putting these results in the form of impact categories. While there are many impact categories and characterization models that can be used for these analyses, pre-existing impact assessment methodologies are often used in practice (Harvey et al., 2016). One of the main reasons to use these pre-existing methodologies is that they apply consistent methods across impact categories. One of the major methodologies that are currently in use is the EPA-developed TRACI.

3.4.2 TRACI

The impact analysis refers to the impact categories that relate to the inputs (resources) and outputs (pollutants and emissions). openLCA uses the Environmental Footprint (Mid-point Indicator) to run analysis and calculate impact categories. This methodology was developed by the EPA and is currently the only LCIA methodology that is explicitly developed for use in the United States. The midpoint indicator method is a characterization method that provides indicators for comparison of environmental interventions at a level of cause-effect chain between emissions/resource consumption and the endpoint level (Benini et al., 2014). The EPA currently uses an impact assessment tool known as the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI). TRACI is used to provide sustainability metrics and Life Cycle Impact Assessment by quantifying the potential impact of inputs and emissions on the environment. TRACI defines specific parameters to base the impact categories on, and this study focuses on six (6) of them. TRACI uses a methodology known as a midpoint approach which "draws simple cause-effect chains to show the point at which each impact category is characterized" (Gabi™).

- Acidification Potential
- Eutrophication Potential
- Global Warming Potential
- Ozone Depletion

- Photochemical Ozone Formation
- Resource Depletion

The table below describes the impact categories talked about in this study, their sub-categories, and the impact indicator unit as set by the TRACI methodology.

Table 3-1: TRACI 2.1 Impact categories (EPA and Bare 2012)

Impact Category	Sub-category	Indicator Unit
Acidification	Air	kg SO_2 eq
Eutrophication	Air and water	kg N eq
Global Warming	Air	kg CO_2 eq
Ozone Depletion	Air	kg CFC-11 eq
Photochemical Ozone Formation	Air	kg O_3 eq

3.4.2.1 Acidification Potential (A.P.)

This is a measure of pollutants that cause acidifying effects on the environment. These pollutants are typically air pollutants (such as sulfur dioxide, SO_2) that are deposited on the earth's surface. Acid rain is the most common form of deposition of acidifying pollution. The acidification potential measures the capacity of increasing hydrogen ions (H^+) concentrations in an environment, especially water which then reduces its pH value (A.I. 2019 and Harvey et al., 2016). Apart from the pollution of air, land, and water, acidification can damage ecosystems and human-made systems, such as buildings and structures. These emissions show up in pavement LCA, where fuels are combusted

(Harvey et al. 2016). These effects are most heavily felt in marine life as well as in the forest, where it can lead to quicker deforestation with lands being contaminated. This potential is calculated as an equivalent of mass (e.g., kg SO_2 equivalent).

3.4.2.2 Eutrophication Potential (E.P.)

Eutrophication refers to the excessive infusion of nutrients in a body of water, which can then cause a dense growth of plant life and the death of animal life from lack of oxygen. The primary sources of these nutrients include nitrogen and phosphorus fertilizers (NPK fertilizers). This type of occurrence then causes a shift in species composition and elevates biomass production in aquatic and terrestrial ecosystems (A.I. 2019). This is because it causes a decrease in the levels of dissolved oxygen in water bodies (FHWA 2014). This potential is also calculated as an equivalent of mass (e.g., kg N equivalent).

3.4.2.3 Global Warming Potential

The EPA's description of global warming is that it is "the recent and ongoing rise in global average temperature near Earth's surface. It is caused mostly by increasing concentrations of Greenhouse Gases (GHGs) in the atmosphere" (2014). This process is what is causing climate patterns to change. These G.W. impacts can range from climate change, including sea-level rise, increased incidence and intensity of extreme weather events (like tornadoes and flooding), and changes to natural habitats, agriculture, and human health. GHG emissions are primarily associated with the combustion of fuels (e.g., the combustion of gasoline by traffic during use) but can also occur during some production processes.

3.4.2.4 Ozone Depletion

The earth's ozone layer serves as its primary source of protection against ultraviolet radiation. This is one of the most widely known impacts of degradation of the environment as it is widely known that an excessive passage of ultraviolet radiation can lead to skin cancers in humans as well as causing damaging effects on plants and livestock. The ozone depletion potential is a measure of air emissions that directly contribute to depleting the stratospheric ozone layer.

3.4.2.5 Photochemical Ozone Formation

POF refers to the measure of reaction that contributes to tropospheric ozone depletion. This is produced by the reaction between Volatile Organic Compounds (VOCs) and Carbon Monoxide (CO.) or Nitrogen Oxides (NO_X) in the presence of sunlight, especially UV light. Excess exposure to this ground-level ozone may be harmful to human health and ecosystems and damage crops. It damages living tissues in humans, animals, and plants, and can cause damage to human lungs, and reduce plant productivity (FHWA 2014). Emissions from traffic during use are the most relevant contribution to ozone and smog formation.

3.4.2.6 Resource Depletion

This encompasses the reduction in the availability of all non-renewable resources as well as reusable ones like land and water. The impacts of land use, water use, and mineral resource depletion usually vary due to local conditions but also usually have a typical tone in the reduction of raw materials availability. Pavement LCA relates to resource depletion, especially when fuels, oil, energy, or metals are used.

3.4.3 Impact Analysis

The impact analysis is the method used for translating inventory data from a life cycle assessment into a set of potential impacts. This then enables people to understand better the damage caused by resource use and emissions to the environment (air, land, and water). While analyzing with TRACI, it is important to know how the numbers that will be gotten can be translated. The impact analysis is then sub-divided into three (3).

3.4.3.1 Inventory Result

This refers to the actual result (in stated unit) that shows the impact arising from the compilation and quantification of inputs and outputs of a product throughout its life cycle. It is developed because of defining a system boundary, collecting relevant data, and inputting the data. It also shows the category, sub-category, and amount of each contributing material. The category gives information on whether a material is a resource or an emission, while the sub-category gives information about the impact location of material, i.e., to or from air, land, or water. The amount is a measurement of the magnitude of the potential impact on the environment.

3.4.3.2 Impact Factor

This is a way to show the actual effects of each input and output to the environment arising from a product, system, or process. The factors are a way to standardize the characterization of the potential impacts on the environment based on each impact category.

3.4.3.3 Impact Result

This is a standardized method of calculating the impact of a product on the environment. It is expressed as a converted inventory analysis as it has been multiplied by the impact factor. So, this value shows the impact of each material on each impact category. This is the most widely reported form of result that is used for impact analysis.

CH 4 RESULTS AND DISCUSSION

The study established five (5) different mix designs and used the variations found below as the asphalt binder composition.

Table 4-1: Mix Design for Analysis

Mix	Variation in Binder Composition (by mixture weight)
1	Plain mix with no RAP or Fly Ash with 5% virgin binder
2	15 % RAP, no fly ash and 4.0 % virgin binder
3	15 % RAP, 5% fly ash and 4.2 % virgin binder
4	20 % RAP, no fly ash and 4.0 % virgin binder
5	35% RAP, no fly ash and 3% virgin binder

These variations served as the basis for asphalt binder in the mixture, and the total input for the raw materials for the asphalt mixture can be found in the Appendix. As stated earlier, openLCA was used for the LCA with TRACI 2.1 used as the impact assessment method. The following assumptions were made in order to create a proper mix design.

- Each design was based on a mixture weight of 1 ton.
- The air void weight in the mixture was neglected.
- The effective binder level is set at 5 percent.

4.1 Life Cycle Impact Categories

Using TRACI 2.1 impact assessment method, the following data were obtained for the impact categories for the various asphalt mix designs. As is the way of LCA analysis, the results are a measure of impact potentials, i.e., they are relative results based on approximation of impacts that could occur for the stated approach.

Table 4-2: Impact Categories per ton of asphalt mix

Impact Category	Reference Unit	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Acidification Potential	kg SO_2eq	0..00113	0.00102	0.001	0.00091	0.00079
Eutrophication Potential	kg Neq	0.00126	0.00128	0.00127	0.00096	0.00086
Global Warming Potential	kg CO_2eq	0.65425	0.5478	0.4923	0.4015	0.4236
Ozone Depletion	kg CFC-11eq	1.37 E-10	1.28 E-10	1.23E-10	1.30 E-10	8.91 E-9
Photochemical Ozone Deformation	kg O_3eq	0.0192	0.0232	0.0228	0.0198	0.0137

The impact analysis, for the most part, behaved as expected. Since asphalt binders are the heaviest contributors to these impacts, it is expected that reducing the amount of the binder used in the mixture should lessen the burden formed on the environment.

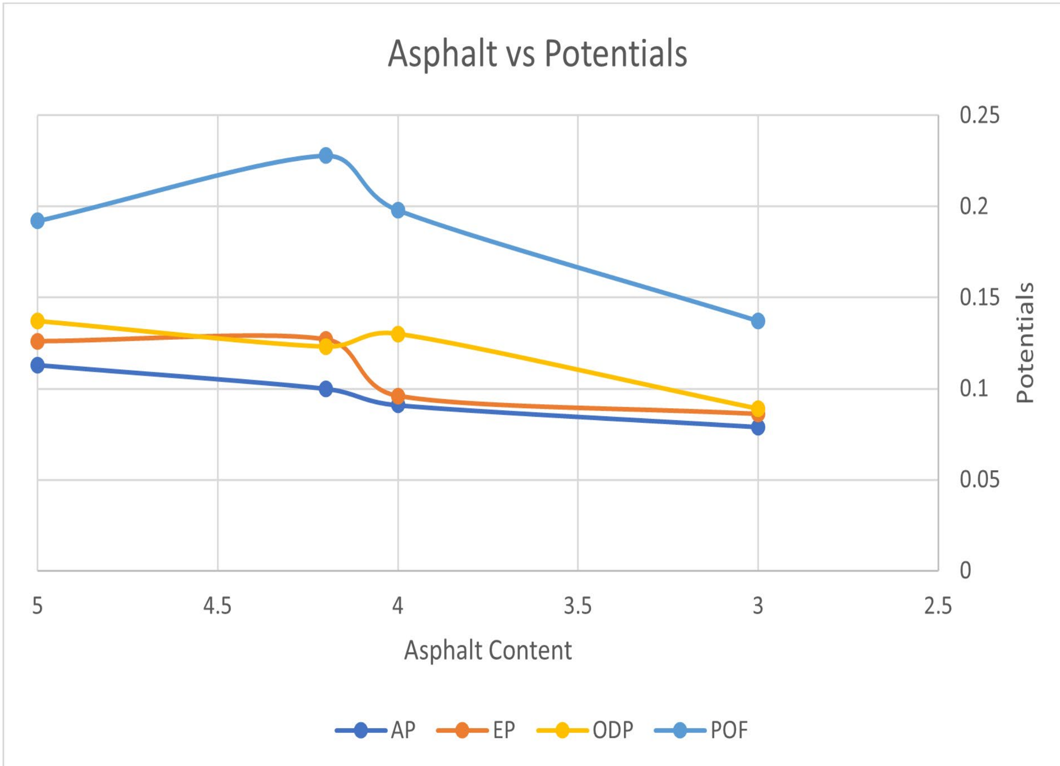


Figure 4-1: Asphalt Content vs Impact Categories

4.2 Analysis

4.2.1 Change in RAP Size

With the focus of the study on substituting recycled materials to replace virgin binders, there is a need to see how sensitive these materials are to the environmental impact. Increasing the RAP content shows a linear reduction in the acidification potential impact on the environment.

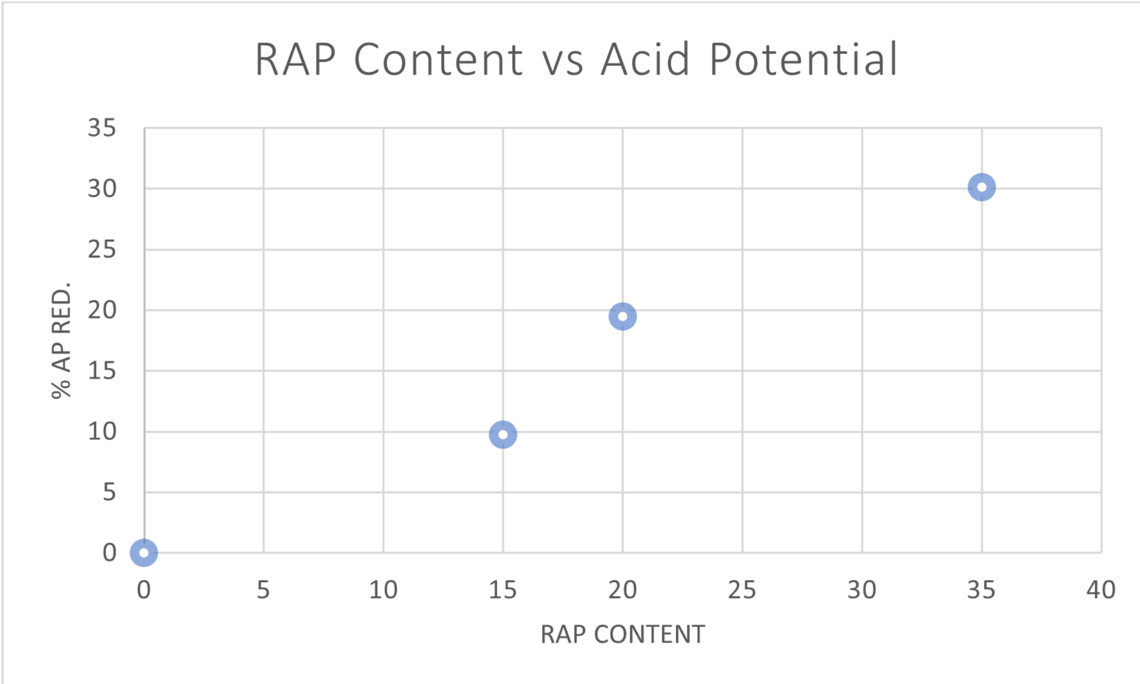


Figure 4-2: RAP content vs acidification potential reduction (in %)

From the graph above, there is a linear relationship between the amount of RAP content used and the reduction experienced in the potential impact that is considered.

4.2.2 Addition of Fly Ash

With fly ash being a relatively newer technology, there is a need to characterize its effects on the impact potential from a mixture. The table below explores these impacts between mixes 2 and 3, with the addition of just 5% of fly ash being the difference between the binder makeup.

Table 4-3: Influence of fly ash on impact categories

Impact Category	Reference Unit	Mix 2	Mix 3	% Difference
Acidification Potential	kg SO_2eq	0.00102	0.001	-2
Eutrophication Potential	kg Neq	0.00128	0.00127	-0.78
Global Warming Potential	kg CO_2eq	0.4236	0.4015	-5.22
Ozone Depletion	kg CFC-11eq	1.26 E-10	1.23E-10	-3.91
Photochemical Ozone Formation	kg O_3eq	0.0232	0.0228	-1.72

Even with the low levels of fly ash infusion, there is a decrease across all impact categories. It is noteworthy that there is a 0.2% increase in the binder content of mix three than that of mix 2. However, even with this increase in binder content, the overall potential impact went down with the addition of fly ash into the mixture.

4.2.3 Change in Binder Replacement Quantity

It is important to know that effective binder content is a culmination of the fresh binder added to the mix plus the binder gotten from the recycled substitutes, i.e., RAP and fly ash. With the increase in the part size of these substitutes, the binder replacement quantity increases. This is important to check because asphalt binders have the biggest impact on the environment amongst all the materials needed to produce pavements.

To analyze the effects of binder reduction, it is important to check for these impact potentials. The table below shows global warming potential reduction as a factor of replacing the virgin binder used by percentage.

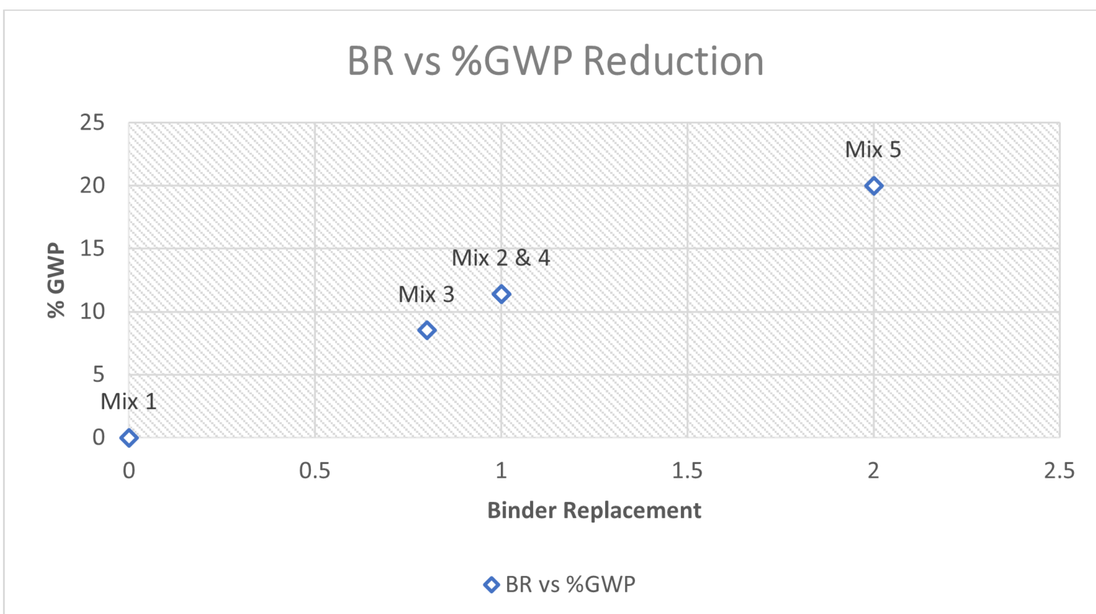


Figure 4-3: Binder replacement vs GWP reduction (in %)

As expected, the relationship between them is a linear one. With binder replacement levels reaching 2 percent, the GWP reduces by about 20 percent in a linear progressive manner.

4.2.4 Cost Analysis

Since the contractors are usually more moved with economic factors rather than environmental factors, especially when not mandated, this study looked into the cost of using asphalt substitutes.

Table 4-4: Simple Cost Analysis for Mix Designs 1, 2, and 3 (per ton):

Variation of Mix				
Components	Cost ($/ton)	Mix 1 ($/ton)	Mix 2 ($/ton)	Mix 3 ($/ton)
FRAP	8	0	1.2	1.2
5/8" Chip	10	1.6	1.6	1.5
3/8" Chip	10	1.7	1.3	1.1
Manufactured Sand	14	2.8	2.24	2.1
Natural Sand	6	2.52	2.16	2.1
AC (PG58-28)	550	27.5	22	23.1
FA-Class C	25	0	0	1.25
Total		36.12	30.5	32.35
%Savings			15.56	10.44

Table 4-5: Simple Cost Analysis for Mix Designs 1, 4, and 5 (per ton)

Variation of Mix				
Component	Cost ($/ton)	Mix 1 ($/ton)	Mix 4 ($/ton)	Mix 5 ($/ton)
FRAP	8	0	1.6	2.8
5/8" Chip	10	1.6	1.7	1.1
3/8" Chip	10	1.7	1.4	1.6
Manufactured Sand	14	2.8	2.1	1.4
Natural Sand	6	2.52	1.8	1.5
AC (PG58-28)	550	27.5	22	16.5
FA-Class C	25	0	0	0
Total		36.12	30.6	24.9
%Savings			15.28	31.1

The cost analysis shows a steady decline in cost and an upward motion of savings up to about 30% of the initial cost. For example, using mix five and saving about 11 dollars per ton can translate to a savings of about 45000 dollars per lane-mile for a 15 ft wide lane and 4-inch-deep pavement construction. Factors like the mechanical performance of the pavement will need to be considered, but from a cost assessment, the savings from substituting asphalt with recycled material cannot be overstated.

4.3 Summary

This study described a framework for developing an environmental LCA methodology using a cradle-to-gate approach. The results for the different impact categories determined by openLCA software for the three design alternatives are listed in Table 5-1. The results for each impact category are the sum of impact categories for each of the first three phases of the pavement life cycle. As expected, for each impact category, the values are mostly influenced by the asphalt binder's contribution. The study provides a detailed analysis of the impact categories by using data acquired from governing bodies on asphalts. The study can be summarized with the following statements.

- The system boundary used in this study is described as a cradle-to-gate approach. This is because it picks a specific position to analyze. The positions analyze are the material production stage, design phase, and construction stage. This includes the extraction, refining and transporting of the raw materials needed to make the asphalt mix as well as the electricity and energy required at the plants and factories that mix the materials.
- This study used openLCA software to import its acquired data and run its analysis. The data for raw materials were obtained from Asphalt Institute and National Asphalt Pavement Association, and the electricity and energy data were generated by datasets provided by the Non-Renewable Energy Laboratory. The data were analyzed with guidelines set by the EPA through TRACI 2.1, and this was by using a midpoint approach to get the impact categories.
- The mix design for this study was devised to account for the variations needed to accommodate the goals of the study. There were four variations in the binder

composition, with the first being the control (a virgin binder composition). The effective binder is set at 5 percent with variations of up to 2 percent of mixture weight. The RAP content is the major variable in this study, and there was an account of using up to 35 percent by mixture weight. There is also the infusion of fly ash of up to 5 percent by mixture weight. This served as the independent component of the pavement mix while other materials were tweaked to accommodate the variations in the binder composition.

- The mix designs adopted in this study was heavily influenced by guidelines set by NAPA. This was needed for the reproducibility requirement of the study. Following a federally mandated guideline also helps in creating a transparent result.
- The reproducibility nature of this study means that it can be used for different applications in pavement LCA by just defining the wanted parameters.
- The impact categories that were focused on in this study are acidification potential, eutrophication potential, global warming potential, ozone depletion potential, and photochemical formation potential. The results that were obtained in this study were mainly expected across the different variations of mix designs.
- As shown in Figure 4-2, the RAP content in the mixture has a linear relationship with the acidification potential reduction. For an application of 35 percent of RAP content, the acidification potential can be reduced by up to 30 percent, and this is not only applicable to the acidification potential. All the other categories also see a decline in the impact on them as the RAP content increased steadily.

- The effects of the addition of fly ash can be seen in Table 4-2. Even with an increase in the asphalt content, the overall impact saw a decline in their values, albeit minimal across all the impact categories.
- With asphalt binder substitution being the scope of this research, there is a need to look at the values across all categories. The results, for the most part, help up as expected. It was expected that as the amount of binder used in the mixture reduced, there would be a linear reduction in the potential impacts. With a 2 percent reduction in binder weight, the GWP reduced by about 20 percent. This relationship also translated across the other impact categories. There was a noticeable decline in the potential impacts across all the categories.
- The last analysis was done on the cost of the asphalt mixture per ton. The relationship was also linear, with a decrease in the cost per ton as the amount of binder used to decrease. This is especially important when convincing the contractors to incorporate the use of the recycled materials. The reduction in cost is attributed to both the high cost of asphalt binders as well as the very cheap cost of the substitute materials.

CH 5 CONCLUSION, LIMITATIONS AND RECOMMENDATION

5.1 Conclusion

The pavement structures serve a very important role in the community. They provide a source of mobility to move from one place to another. However, with this importance, it poses a severe risk on the environment, and there is a need to characterize these impacts caused by the components of the asphalt mixtures. This study focused on stating the importance of developing a methodology to study the environmental impacts of asphalt binders using Life Cycle Assessment (LCA). The scope of research was to focus on the North American region in terms of data acquisition. The datasets used in this study were sourced from an existing database from Asphalt Institute (AI) and National Asphalt Pavement Association (NAPA) and interpreted using the openLCA software.

Previous literature reviewed showed that the mechanical performance of substituting some recycled material up to a certain extent is acceptable. This study focused on the environmental impacts of using these materials and explore beyond levels of current usage. This study presented the results for the following three asphalt binder composition: without additives, with RAP, and with Fly Ash.

This thesis presented software-generated results for the first three phases of the pavement life cycle by using the openLCA software. With the reproducibility of the results, the data can be translated to fit with a different magnitude. This study was guided by guidelines set by both the ISO and EPA to develop an LCA methodology and check for the feasibility of pavement analysis. From previous literature and available data, asphalt binder was established as the major contributing factor on the impact categories, and this made it the independent variable. Through the results, trends in the impact analysis and categories were shown, and they aligned with the expected results of linear relationships. Linearity in the relationships from the infusion of the substituted materials (RAP and fly ash) is explained because of the decline in the amount of the virgin binder used.

Pavement LCA is a growing technology, and this thesis study takes into account of using the first three stages of a pavement's life cycle by defining a system boundary and using the cradle-to-gate approach. The promising results from this study plus continued efforts into studying the environmental impacts of materials will lead to the standardization of protocols involved in decision making for designing pavements.

5.2 Limitations

The largest obstacle in this study came in the manner of data acquisition and interpretation. There is currently a limited database to get relevant data from, and even with the few ones, there is a need to interpret them before importing them to software. This is where a solid previously set system boundary helps a little bit. By setting a system boundary, the focus of a study has been established, and the relevant data will because clearer. The data used in this report were obtained from an outside source (Asphalt Institute).

Due to the limited time constraint for the completion of the thesis, the mix design had to be hypothesized to work without a lab backing. The mix design was also formed heavily dependent on data from NAPA.

Running analysis of the data is where another limitation comes into focus. TRACI 2.1 is currently the only impact assessment method approved in the United States. This can bring up problems for lack of comparison in the software.

5.3 Recommendations

The main goal of this thesis is to serve as a framework for the development of a methodology for which further work on pavement analysis can be done. The first recommendation to aid in this goal will be to start from the limitations of this thesis. Since the major limitation was in the form of the availability of data, government agencies should work with the major players in the pavement industry to create a more comprehensive database that will be open source. This will enable independent researchers to have access to these datasets, and they can then work on them to create more literature on the subject.

Developing a different approach to pavement LCA will be the next phase to check. Checking for the impact analysis by using the cradle-to-grave approach will give a more comprehensive analysis of the pavement life cycle. Reaching this level can only be achieved by the provision and availability of a more comprehensive database. Although the reproducibility of a study is an important factor in LCA, using a different dataset with varying contribution factors will most likely present two different results. Thus, it is important to know that LCA results are more of relative expressions rather than actual impact results that depend on a clearly defined impact pathway.

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APPENDIX

Appendix A
Raw Data for Analysis (Input Inventory)

Table A-1: Input Inventory (for 1 ton of asphalt mixture)

Material	Unit	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Asphalt binder (no additives)	tn	0.05	0.034	0.0344	0.034	0.0272
Carbon dioxide	sh tn	1.63E-04	1.00E-04	9.71E-05	1.05E-04	8.48E-05
Coal, bituminous, 24.8 MJ per kg	sh tn	7.84E-03	6.00E-03	4.69E-03	5.08E-03	4.09E-03
Crude oil	sh tn	0.0311	0.0262	0.0248	0.0262	0.0181
crude oil; 42.3 MJ/kg	MJ	7.40E-05	6.04E-05	6.07E-05	6.04E-05	4.76E-05
Diesel	gal (US fl)	0.22	6.92E-02	0.0343	0.0741	0.03154
Electricity	kWh	6.14	2.78E+00	2.33	3.05	4.13
Fly Ash	t	0	0	0.08	0	0
Energy, kinetic (in wind), converted	MJ	1.14	0.65	0.68	0.738	0.594
Energy, potential (in hydropower reservoir), converted	MJ	3.14	1.8	1.87	2.03	1.63
Energy, primary, unused, from geothermal	MJ	0.184	0.11	0.109	0.119	0.0953
Hazardous waste disposed (HWD); Beware: limited use only	sh tn	2.13E-03	1.42E-03	1.47E-03	1.57E-03	1.17E-03

Lignite, 11 MJ per kg	sh tn	6.74E-04		3.99E-04	4.32E-04	3.48E-04
Natural aggregate	t	0.95	0.762	0.75	0.659	0.6
natural gas; 44.1 MJ/kg	MJ	9.00E+00	9	9	9	9
Non-hazardous waste disposed (NHWD); Beware: limited use only	kg	1.93E-05	1.20E-05	1.15E-05	1.24E-05	1.00E-05
RAP	t	0	0.25	0.25	0.33	0.304
Truck Distance	t*mi	1.58	2.8	3	11.7	46
Water	kg	0.1817	2.87	17.0343	3.29	0.24454

Table A-2: Cost Analysis for the five mixes

Components	Mix 1	Mix 2	Mix 3	mix 4	Mix 5
FRAP	0	15%	15%	20%	35%
5/8" Chip	16%	16%	15%	17%	11%
3/8" Chip	17%	13%	11%	14%	16%
Manufactured Sand	20%	16%	15%	15%	10%
Natural Sand	42%	36%	35%	30%	25%
AC (PG58-28)	5%	4%	4.20%	4%	3%
FA-Class C	0%	0	5%	0	0%
Total	1.00	1.00	1.00	1.00	1.00

Appendix B
Data Quality System

	Very good	Good	Fair	Poor	Very poor
Technological representativeness	Technology aspects have been modelled exactly as described in the title and metadata, without any significant need for improvement	Technology aspects are very similar to what described in the title and metadata with need for limited improvements. For example: use of generic technologies' data instead of modelling all the single plants.	Technology aspects are similar to what described in the title and metadata but merits improvements. Some of the relevant processes are not modelled with specific data but using proxies.	Technology aspects are different from what described in the title and metadata. Requires major improvements.	Technology aspects are completely different from what described in the title and metadata. Substantial improvement is necessary
Time representativeness	The data (collection date) can be maximum 2 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 4 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 6 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 8 years old with respect to the "reference year" of the dataset.	The data (collection date) is older than 8 years with respect to the "reference year" of the dataset.
Geographical representativeness	The processes included in the dataset are fully representative for the geography stated in the "location" indicated in the metadata	The processes included in the dataset are well representative for the geography stated in the "location" indicated in the metadata	The processes included in the dataset are sufficiently representative for the geography stated in the ""location" indicated in the metadata. E.g. the represented country differs but has a very similar electricity grid mix profile.	The processes included in the dataset are only partly representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs and has a substantially different electricity grid mix profile	The processes included in the dataset are not representative for the geography stated in the ""location" indicated in the metadata.
Completeness	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods

Fig B: ILCA Grading System Scale

Precision	Measured/calculated and verified. Very low uncertainty (< 7%)	Measured/calculated/ literature and plausibility checked by reviewer	Measured/calculated/ literature and plausibility not checked by reviewer OR Qualified estimate based on calculations plausibility checked by reviewer	Qualified estimate based on calculations, plausibility not checked by reviewer	Rough estimate with known deficits
Methodological appropriateness and consistency	Meets the criterium to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a still sufficient degree, while having the need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an	Does not at all meet the criterium, having the need for very substantial improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
Overall quality	Meets the criterium to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a still sufficient degree, while having the need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an	Does not at all meet the criterium, having the need for very substantial improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.

OK Cancel

Fig B: ILCA Grading System Scale (cont.d)