DEVELOPMENT OF LIFE CYCLE ASSESSMENT TOOL FOR

PAVEMENT SUSTAINABILITY ANALYSIS

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ABSTRACT OF THE THESIS

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Motivated by the emerging importance of sustainability in transportation infrastructure, this study aims at developing a Life Cycle Assessment (LCA) tool to quantify the energy and environmental impacts of pavements. The general LCA framework is incorporated into a highly customizable Excel-based software tool that can be used to facilitate environmental assessment of pavements at the project-level. The impact assessment focuses on the cumulative energy demand (CED) and greenhouse gas (GHG) emission in the material, construction, and maintenance phases of pavement life-cycle. LCA results are highly dependent on the quality and appropriateness of data in the life cycle inventory. Therefore, different inventory database from major pertinent studies were reviewed and summarized. To implement the LCA framework, case studies regarding runway pavement rehabilitation/reconstruction at the John F. Kennedy (JFK) airport and new runway pavement designs conducted using the Federal Aviation Administration (FAA) pavement design methodology were conducted. Life-cycle inventory data were compiled from literature and field surveys from contractors. The data variations in the material-related energy and emission rates were considered for sensitivity analysis. Both direct energy consumption and GHG emission and their corresponding upstream components related to process fuels were considered in the impact assessment. The results indicate that the expected pavement service life and maintenance treatments significantly affect the comparison between hot-mix asphalt (HMA) and Portland cement concrete (PCC) pavements. The consideration of energy and emissions associated with the production of process fuels and electricity in the upstream process cannot be neglected in the LCA. The analysis findings suggest that there are no general conclusions on pavement type selection for sustainability and the project-level analysis need be conducted for selecting the most appropriate design alternatives.

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Chapter 1 Introduction

Transportation infrastructure plays a vital role in the social and economic wellbeing of any country. Pavements contribute to a huge proportion of transportation infrastructure and their construction and maintenance requires the consumption of large amount of non-renewable materials and creates significant energy and environmental impacts. The IEA (International Energy Agency) has estimated that almost 25% CO_2 emissions can be attributed to the transportation sector (Cazzola et al., 2009). With the increasing importance of environmental sustainability, agencies and contractors are benchmarking the need to adopt sustainable products, processes and technologies associated with design, construction, and maintenance of transportation infrastructure.

A sustainable pavement consists of interrelated characteristics like durability, cost effectiveness, eco-efficiency and high performance. Many sustainable practice initiatives have been implemented in pavements by incorporating and increasing the use of recycled materials and industrial by-products (e.g. reclaimed asphalt pavement [RAP], recycled asphalt shingle [RAS], fly ash, steel slag), using innovative design, construction and production techniques that are energy intensive and efficient (e.g. warm mix asphalt, etc.) and finally evaluating sustainability using qualitative and quantitative assessment methods (e.g. life cycle assessment, sustainability rating tool).

1.1 Background

Life Cycle Assessment (LCA) is a technique to assess environmental effects associated with a product's life cycle. This technique starts with the beginning of a product/process and finishes with the end of the product/process. It includes raw material extraction, material production, processing, manufacturing, distribution, transportation, maintenance, and disposal/recycle (ISO 1997). There are three major types of LCA models which depends on the source of information used in the LCA process.

The first is Economic Input-Output model (EIO), known as EIO-LCA, which is developed by Carnegie Mellon University. The Economic Input-Output Life Cycle Assessment (EIO-LCA) method is used to estimate the materials and energy resources required activities and the environmental emissions resulting from, activities in our economy. . This method can be applied to any transactions between industries related to the economy of the sectors.

The second is process-based LCA which is based on the methodology set by International Standards Organization (ISO) 14040 and 14044 for LCA and known as ISO-LCA too. The process bases LCA looks at material and energy inputs and environmental outputs to each process in the life cycle system. This includes processes related to manufacturing, assembling, maintaining, using and disposing of the product. In process based LCA, specific process data and a computational tool or matrix analysis is used to form a model for the assessment of the process.

The third method is called Hybrid LCA in which an EIO model is integrated with process based data to produce more comprehensive representations for environmental effects of the processes (Greenroads Manual v1.5).

The formal structure of LCA was framed by International Standards Organization (ISO). It shows three basic stages: Goal and scope definition, inventory analysis, impact analysis as shown in Figure 2.1.

Goal Definition and Scope

The first and basic step in LCA is definition of goal and scope of the process. In any process for LCA consideration, the goal is to quantify and characterize the flow of all the materials involved in the process which helps in identifying the environmental impact of the material and find an alternative approach to reduce the impact. LCA has emerged as a widely practiced process to reduce the harmful environmental effects and it has given many beneficial results. Defining the goal of any process is considered to be the most critical step in beginning a LCA evaluation. Goal is to define the questions that are to be answered followed by choosing the evaluation's scope. Scope includes defining what and how the whole process will be portrayed, what alternatives need to be defined. The assessment of the resources should also be done which can also be applied to analysis. This step involves defining the system boundaries, assumptions and limitations of the system.

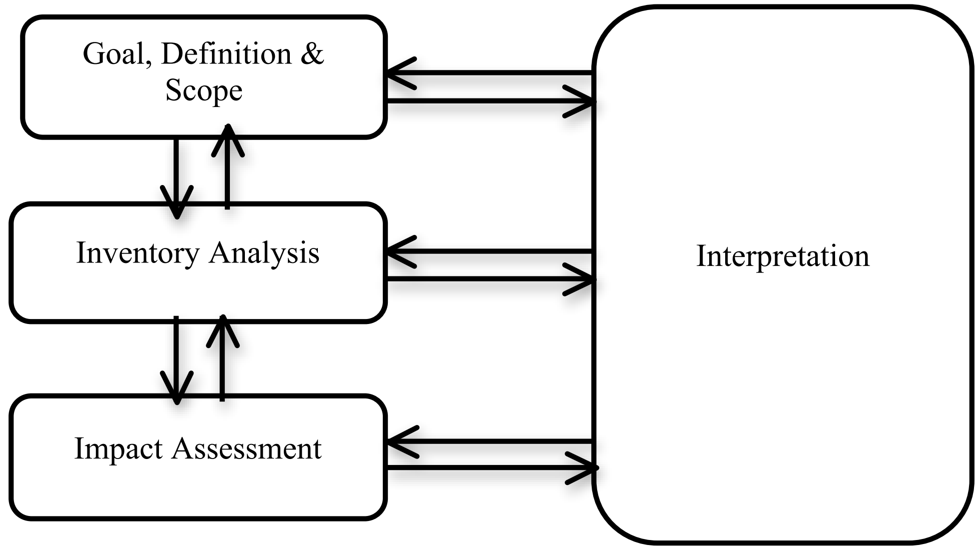


Figure 1.1 Life Cycle Assessment Framework (Adapted from ISO 14040)

Inventory Analysis

The next stage following goal and scope definition is inventory analysis, sometimes also known as life cycle inventory (LCI). Inventory analysis is analyzing an inventory flow for a product or process from cradle stage to end stage. It includes inputs from water, energy and raw materials to air water and soil. Inventory model is constructed as a flow chart and it includes input and output data about the system being considered, a flow model is made using the data of the technical system. These data are collected according to the technical system boundaries. Data consists of products initial form as raw material to the end of life/recycle stage. Data is directly related to the goal defined for the LCA.

Impact Assessment

LCA's impact assessment constitutes of influences of the activities conducted by LCA inventory analysis on specific environmental properties and relative seriousness of the changes in the affected environmental properties. Assessing environmental impact of process is a complicated; but it can be performed by employing relationships between environment and elements affecting the environment, which are the items listed in the inventory analysis that have potential to produce harmful effects to the environment. The relationships between stressors (element producing stress to a system) and environment can be developed by combining LCA inventory results with its effects.

As the name 'impact' suggests, this step assesses the impact of any product and process on environment and human health. The assessment categories include global warming potential, acidification, eutrophication; criteria air pollutants, photochemical smog and etc. Among these burdens, energy consumption and Greenhouse Gas (GHG) emission are considered as major contributors to environmental impacts that affect all ecosystems.

The consumption of fossil fuels over the years has caused the consumption of non-renewable energy. This also leads to the increase of concentration of GHG significantly in our atmosphere. These greenhouse gases are any gases in the atmosphere, which absorb and re-emit heat and thereby keep the planet's atmosphere warmer than it would be otherwise. Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. CO_2, CH_4, and N_2O are continuously emitted to and removed from the atmosphere by processes on Earth. However, human activities can cause additional quantities of these and other greenhouse gases to be emitted, thereby changing their global average atmospheric concentrations

The GWP of a greenhouse gas is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas (IPCC 2001). The reference gas used is CO_2, and therefore GWP weighted emissions are measured in kilograms of CO_2 equivalent (kg CO2 Eq.). The relationship between grams of a gas and kg CO_2 eq. can be expressed as shown in Equation 1.1. Table 1 represents the GWP values as published in the Fourth Assessment Report (2007) of Intergovernmental Panel on Climate Change (IPCC).

$$g\ CO2\ Eq. = (g\ of\ gas)\times(GWP) \tag{1.1}$$

where,

g CO_2 Eq. = grams of CO_2 equivalent; and

GWP = Global Warming Potential.

Table 1.1 GWP of greenhouse gases

Emission type	GWP
CO_2	1

CH_4	25
N_2O	298

1.2 Problem Statement

Efforts have been brought into assessing and reducing GHG emission in order to alleviate the undesirable environmental burden generated by pavement construction and usage. Life cycle assessment (LCA) is one of these approaches. Life cycle assessment is a well-developed and widely used method to measure an object's environmental impact through its entire life. When it is utilized in road construction projects, it can take all the GHG emission generated from construction to end of life into consideration and quantifies the environmental impact within a defined system boundary. Traditionally, a life cycle assessment includes material, construction, usage, maintenance and rehabilitation, and end of life. Lots of research and studies have been conducted on each component. However, most of the work focuses on one or two aspects (such as material and construction, or maintenance alone), and there is little research trying to incorporate all the components by building a complete framework. What's more, the previous studies only concentrate on carbon dioxide (CO_2), while the other emission factors like methane (CH_4) and nitrous (N_2O) are not addressed, which turn out to have a great impact on climate change.

With the continuous increase of air traffic volumes and the development of heavy wide-body aircraft, airfield pavements require frequent maintenance and rehabilitation activities in order to provide sufficient structure capacity and satisfactory surface characteristics. Asphalt pavement and Portland cement concrete (PCC) pavement are commonly used in airfield pavements and overlays. The factors affecting the selection of pavement type and rehabilitation strategy may include agency experience, the long-term performance of alternatives, the impact on airport operations, construction and maintenance costs, and environmental and sustainability considerations (Hallin et al.). The life-cycle cost analysis (LCCA) has been mandated by the Federal Aviation Administration (FAA) Advisory Circular to be the part of the pavement type or treatment selection process. The LCCA is mostly used to aid airport planners in identifying the most cost-effective pavement construction and rehabilitation strategies. Construction and rehabilitation of airfield pavements produce significant impacts on energy conservation and environmental pollution resulting from the consumption of large amounts of construction material and the operation of construction equipment. Most of the pavement LCA studies are focused on highway roads but a very few studies focus on airport runways. Airport authorities are interested in selecting the preferred pavement design and rehabilitation strategy considering economic and environmental factors along with performance requirements. Therefore, an assessment methodology to properly quantify environmental sustainability in airport pavement design, construction, maintenance, and rehabilitation processes is needed for airport authorities.

There are currently a number of gaps in measurement and quantification of the on-going sustainable practices that make it difficult to include sustainability as an integrated part in the decision making process for public and private agencies. Also, a user friendly LCA tool that can quantify environmental impacts of pavement system focused for airport runways is missing and required. This tool is intended to assist decision-makers, planners and researchers to achieve a more environmentally conscious decision. The study results can be used for decision making among different runway pavement design and rehabilitation alternatives.

1.3 Objective

The objectives of this study are:

1. To summarize life cycle inventory for pavement processes related to raw materials, plant production, transportation and construction. The inventory environmental impact values were extracted from relevant studies including energy consumption and GHG emissions (CO_2, CH_4 and N_2O).

2. To present the development of a project-level LCA tool which can be used for comparing the design, construction and maintenance options of pavement projects for airports and highways. Both direct energy consumption and GHG emission and their corresponding upstream components related to process fuels were considered in the impact assessment.

3. To conduct case studies on comparing asphalt and concrete airport runway pavements using LCA. The design alternatives include runway

rehabilitation/reconstruction designs considered in the constructability study at the JFK airport and new runway pavement designs conducted using the FAA pavement design method.

1.4 Thesis Outline

The thesis report is divided into six chapters. The first chapter presents the introduction, background, problem of statement, and objective. The second chapter summarizes the literature review of pertinent LCA studies on comparing different pavement types, LCI studies on pavement materials, LCA studies on pavements with recycled material or industrial by-products, and available LCA tools. The third chapter summarizes the life cycle inventory for the pavement processes related to raw materials, plant production, transportation and construction. The fourth chapter presents the LCA framework and tool development methodology. The fifth chapter presents case studies comparing design alternatives for pavement rehabilitation and new pavement design at John F Kennedy airport, New York. The sixth chapter summarizes the findings and future research recommendations.

Chapter 2 Literature Review

2.1 LCA Studies on Comparing Different Pavement Types

The pavement LCA studies have often compared rigid and flexible pavements. It is noteworthy that every study uses different methodology to conduct LCA and the desired outputs also vary. The factors like system boundaries, life cycle phases analyzed, life cycle inventory, and the regional location of the study may affect the comparison of different types of pavement. However, majority of the studies reviewed in this chapter compare rigid and flexible pavements based on the environmental impacts of energy and emissions.

Hakkinen and Makela (1996) performed a study based on motorway pavement structure in Finland that compared stone-mastic asphalt (SMA) and jointed plain reinforced cement concrete (JPCP). Process-based LCA is used in the study and its scope includes each phase of the pavement life cycle except the end of life phase. The two pavement structures were evaluated using 18 different environmental criteria including CO_2 emissions, energy consumption, air pollutants and heavy metal releases. The environmental burdens for the material phase are quantified by the upstream supply chain of each material in both pavement structures. The construction phase includes fuel consumption and onsite paving equipment and does not consider traffic delays as it assumes completely new pavement construction. The results concluded that the concrete pavement produced 40-60% more CO_2 emission as compared to the asphalt pavement. When feedstock energy of bitumen was included, they estimated that the asphalt pavement consumes almost twice the amount of energy as compared to concrete pavement.

Horvath and Hendrickson (1998) performed a study using EIO-LCA(Economic Input- Output Life Cycle Assessment) model developed by Carnegie Melon University to assess a hot-mix asphalt (HMA) and a continuously reinforced concrete pavement (CRCP) in United States. The environmental outputs include consumption of various fuel types, electricity demand, air water and land emissions. This study focused on extraction and production of different surface materials and qualitative analysis of construction phase and end of life. It did not consider feedstock energy of asphalt and concluded that the asphalt pavement consumes 40% more energy than the concrete pavement. However, the results also showed that most of the other environmental outputs are higher for the concrete pavement.

Roudebush (1999) compared the life cycle of concrete and asphalt pavement structures by a unit called *emergy*. The unit *emergy* is described as the summation method for life cycle energy consumption that accounts for the quality and source of energy. The pavement section dimensions for the analysis were 24 ft width and 3281 ft. length, and the analysis period was 50 years. The system boundaries included materials, construction, maintenance and end-of-life phases. They concluded that the asphalt pavement consumes 90.8% more *emergy* than the concrete pavement. The feedstock energy of bitumen was not included.

Berthiaume and Bouchard (1999) compared asphalt and concrete pavements by a form of energy called *exergy*. *Exergy* is a measurement of the work and accounts for differences in energy quality. The system boundary only included the material production phase. It was concluded that concrete has higher *exergy* consumption for the three traffic levels -residential, urban and highways when compared to asphalt. The feedstock energy in bitumen is not considered due to the properties of *exergy*.

Stripple (2001) presented an extensive life-cycle inventory study including electricity generation, emissions from transportation and construction equipment, pavement material production and other minor roadway facilities based in Sweden. All LCA phases, except for the use phase, were covered in the study. Stripple's study showed that the total energy for construction, operation and maintenance of a 1 km long road during its 40 year life varied for JPCP and two asphalt pavements using hot and cold production techniques. This study concluded that asphalt pavements were more environmentally friendly than JPCP pavements in terms of CO_2 emission and energy consumption by 17% and 34% respectively. The results also reported that for asphalt production the feedstock energy of cold production method is higher in comparison to hot production method due to bituminous-based emulsion additive.

Nisbet et al., (2001) is an LCI study that compares an asphalt pavement and doweled JPCP pavement by energy consumption and air emissions of CO_2, SO_2, NO_x, VOC, CO and CH_4. Each phase of the pavement life cycle is included except for the use phase. They concluded that concrete pavements require less overall material and have a lower embodied primary energy, and thus produce lower air emissions. However, CO_2 and NO_x emission is lower for asphalt pavement. Feedstock of bitumen was included for the analysis.

Treloar et al (2004) performed a hybrid LCA analysis to compare energy consumption on Continuously Reinforced Concrete (CRCP), an undoweled jointed plain concrete(JPCP), full depth asphalt, composite, deep strength asphalt on bounded sub base, and asphaltic concrete on bounded sub base. Hybrid LCA approach is used for the life cycle phases of materials, construction, use, maintenance and rehabilitation phases. The study excludes end of life phase. They concluded that the undoweled JPCP had the lowest energy input, while the full depth asphalt had the highest energy input.

Zapata and Gambatese (2005) performed a life cycle analysis for energy consumption of a Continuously Reinforced Concrete Pavement (CRCP) and an asphalt pavement. Process based LCA approach is used and the system boundaries included material extraction, manufacturing, and construction. This study concluded that the CRCP consumed more energy in comparison to asphalt pavement. The study also concluded that bitumen extraction and production requires less energy than cement manufacturing. Energy consumption for asphalt pavement was affected majorly by mixing and drying of aggregates whereas for CRCP pavement the energy consumption was most affected by cement manufacturing.

Hoang et al. (2005) studied asphalt pavement and CRCP for energy use, emission of CO_2, and use of natural aggregates and bitumen. Analysis period is 30 years and the results show that CRCP consumes around 40% more energy than asphalt pavement and produces three times more CO_2 emission. The differences in energy consumption and CO_2 emission were mainly induced at the construction phase.

The Athena Institute (2006) compared life cycle of HMA and Portland cement concrete (PCC) pavements in terms of energy consumption and global warming potential (GWP) in Canada. The study uses process based LCA for six pavement case studies comparing asphalt pavements with jointed plain concrete(JPCP) pavements for an analysis period of 50 years. All pavement designs were developed using the Mechanistic Empirical Design Guide (MEPDG) model and the environmental data was collected from United States and Canada sources. The study did not include traffic operational considerations. In case of asphalt, comparison between virgin mix and a mix containing 20% reclaimed asphalt pavement (RAP) was done. Feedstock energy was considered separately in the analysis for asphalt. Results show that the asphalt pavement consumes greater energy than the concrete pavement. The feedstock energy was found to have the highest contribution to the total energy for asphalt pavements. The GHG emissions are in higher values (11% higher) for concrete alternatives than asphalt alternatives.

Chan (2007) developed an LCA model to investigated environmental aspects along with the economic aspects of LCCA for asphalt and concrete alternatives for thirteen Michigan DOT projects. The system boundary included Material production and waste treatment; material transportation; and construction and maintenance phases. They concluded that concrete alternatives had higher GHG emissions than asphalt alternatives. The primary energy consumption of asphalt pavements is higher than concrete pavements and also the reconstruction process has yielded more GHG emissions than the rehabilitation process.

Zhang, Keoleian & Lepech (2008) developed an integrated LCA and LCCA model to provide sustainability indicators for pavement overlay systems. The primary energy consumption, GHG emission and Life Cycle Cost for concrete, Engineered Cementitious Composites (ECC) and Hot mix asphalt (HMA) overlays was conducted. They concluded that ECC overlay system reduces total life cycle energy by 15% and 72% GHG emissions by 32% and 37% and costs by 40% and 58% compared to concrete overlay systems and HMA overlay systems, respectively.

Weiland and Muench (2010) developed a LCA approach to compare the energy and emissions for three different rehabilitation alternatives: (i.) remove the existing PCC pavement and replace it with new PCC pavement; (ii) remove the existing PCC pavement and replace it with a new hot-mix asphalt (HMA) pavement; (iii) crack and seat the existing PCC pavement and then overlay it with HMA. The system boundaries included material production, construction and maintenance. The analysis concluded that energy consumption is highest in the HMA option while the global warming impact is highest in the PCC option.

Cass and Mukherjee (2011) developed a hybrid LCA approach to calculate GHG emissions by using observed construction data. Two hybrid LCA models were developed where Model-1 used tools like (i) EIO-lCA for material acquisition, (ii) SimaPro for material acquisition and production, and fuel production, and (iii) e-Clac for construction equipment use and transportation impacts; whereas Model-2 used tools like (i) EIO-ICA to estimate equipment manufacturing impact, material acquisition and production, fuel production and (ii) the emission calculator tool for construction equipment use, transportation impacts. They concluded that total CO2 emissions for Model-1 were lower compared to Model-2. They also conclude that the production of materials, equipment and fuel used to construct project account for 90% and 94% of the total CO2 emission for Model-1 and Model -2, respectively. The equipment use and transportation impacts together only represent 6-10% of the total emission through the construction phase.

Milachowski et al. (2012) studied the environmental impact of concrete and asphalt pavement for motorway construction and maintenance. A usage period of 30 years was considered for the pavements with normal traffic conditions. Two maintenance conditions were taken into account (minimum and maximum maintenance scenarios). By comparing all the impact categories it is deduced that that the maintenance measures applied on both pavements for rehabilitation show much less environmental impact for the concrete pavement than for the asphalt pavement. The largest potential impact reduction lies in lowering fuel consumption since the impact is mainly due to the combustion of fossil fuel. Both concrete and asphalt pavements show similar environmental impacts on GWP. They concluded that the potential environmental impact due to traffic is 100 times more than construction and maintenance together.

Al-Qadi et al. (2013) uses LCA to quantify environmental improvements for current (2013) and past (2000) pavement reconstruction and rehabilitation projects. The system boundaries included material, construction and maintenance phases. Pavement ICT LCA 0.95 tool was used to evaluate sustainability performance index (SPI), global warming potential (GWP), and cumulative energy demand (CED). They concluded that the SPI/GWP/CED of the 2013 project improved by 28%/16%/26% for concrete pavement, 17%,/12%/13% for full-depth pavement and 28%/14%/26% for composite pavement when compared with material baseline.

2.2 Life Cycle Inventory Studies

Hakkinen and Makela (1996) performed a LCA study comparing stone-mastic asphalt (SMA) and jointed plain reinforced cement concrete (JPCP) based in Finland. They used a process-based LCA considering each phase of the life cycle of pavement excluding end of life module. As a process LCA, environmental burdens for the material phase are quantified by tracing and calculating the upstream supply chain for each constituent in both the structures. The data comes from variety of Nordic sources making this LCA relatively specific to the explored case study. Both types of pavements were evaluated using 18 different environmental criteria including CO_2 emissions, energy consumption and air pollutants.

Stripple (2001) presented an extensive life-cycle inventory study including electricity generation, emissions from transportation and construction equipment, pavement material production and other minor roadway facilities. All LCA phases, except for the use phase, were covered in the study. The study considers a large group of environmental metrics, including energy consumption, water and air pollutants, waste generation and resource consumption.

The Athena Institute (2006) compared the 50 year life cycle of HMA and Portland cement concrete (PCC) pavements in terms of energy consumption and global warming potential (GWP) in Canada. The design alternatives include pavement structures respectively using a 200-mm concrete slab and a 175-mm asphalt layer. All pavement designs were developed using the AASHTO 1993 design method and Cement Association of Canada design method. The study did not include traffic operational considerations. In case of asphalt, comparison between virgin mix and a mix containing 20% reclaimed asphalt pavement (RAP) was done. Feedstock energy was considered separately in the analysis for asphalt. Results show that the asphalt pavement consumes greater energy than the concrete pavement. The feedstock energy was found to have the highest contribution to the total energy for asphalt pavements. The GHG emissions are in higher values for concrete alternatives than asphalt alternatives.

PCA (2007) conducted a LCI study on Portland cement concrete (PCC). The system boundaries included the raw material manufacturing stage, the transportation of raw materials to the plant, and the PCC mixing stage. The energy use and emission from aggregate production were estimated using the data from the U.S. Census Bureau and EPA AP-42 emission factors. The energy and emission information for cement was retrieved from PCA's 2006 cement LCI report. The plant energy was calculated from confidential LCI surveys of ready-mix concrete plants.

Eurobitumine (2011) conducted the LCI of asphalt binder. In this study, mass allocation was used for crude oil extraction and oil transport, while economic allocation was used for the oil refinery process. Inventory analysis was divided into four stages: crude oil extraction, oil transport, oil refining, and storage. The primary sources of CO_2 were flaring and fuel burning for extraction. In the oil transport stage, depending on the geographic location, the method of transport differed. In the refining process, 98.3% of the energy used for crude oil refining is produced using refinery gas (79.2%) and heavy fuel oil (19.1%) while the remaining 1.7% is assumed to be electricity. The study also includes inventory analyses for polymer modified bitumen and bitumen emulsion.

Yang (2014) developed a regional LCI database for asphalt binder considering that crude oil sources and refinery fuel consumption vary among different regions in the US. In this study, the commercial Ecoinvent-v2.2 database was used to simulate the unit process for asphalt binder production. The system boundaries include crude oil extraction and flaring, crude oil transportation, refining, refined product transportation, blending, and storage. The U.S. Energy Information Administration (EIA) reports for Petroleum Administration for Defense Districts (PADDs) and Petroleum Supply Annual (PSA) were used for analysis of crude oil distribution and refining process. The study also includes LCA case study of a full pavement based on the regionalized LCA framework for an Illinois highway project. They concluded that with regards to energy and GWP, the use phase contributed the highest followed by material phase, construction phase and finally end-of life phase.

As a part of NCHRP 9-47A project, energy usage and stack emission were collected from three asphalt plants in Michigan, Indiana, and New York. The collected energy data vary depending on the fuel type used in the heating, burner tuning, casing loss, and the aggregate moisture content in the stockpile. Fuel usage was obtained from the direct site measurements and analysis of two-year averages at the same plants. Reported stack emissions included carbon dioxide to assess greenhouse gas production and other air pollutants.

Table 2.1 summarizes major pavement related LCI studies.

Table 2.1 Summary of LCI releated pavement LCA

Author Year	Title	Location	Outputs	LCA Phase
Hakkinen and Makela (1996)	Environmental adaption of concrete: Environmental impact of concrete and asphalt pavements	Finland	Energy, air emissions	Material, Construction
Stripple (2001)	Life cycle assessment of road: a pilot study for inventory analysis	Sweden	Energy, air emissions	Material, Construction, Use, Maintenance
Athena (2006)	A life cycle perspective on concrete and asphalt roadways: embodied primary energy and global warming potential	Canada	Energy, GHG emissions	Material, maintenance
PCA (2007)	Life cycle inventory of Portland Cement concrete	USA	Energy, air emissions	Material
Eurobitume	Life cycle inventory:	Belgium	Energy,	Material

(2011)	bitumen		emissions to soil, water and air	
Yang (2014)	Development of a pavement life cycle assessment tool utilizing regional data and introducing an asphalt binder	USA	Energy, air emissions	Material, Construction, Use, Maintenance
NCHRP 9-47A (2014)	Effects of WMA on Plant Energy and Emissions and Worker Exposures to Respirable Fumes	USA	Energy, air emissions	Material, Use

2.3 LCA Studies on Pavements with Recycled Material or Industrial By-Products

LCA was initially used in 1990s to analyze and compare different pavement types. Over the years of development of LCA studies the focus shifted from comparing asphalt and concrete pavements, to developing life cycle inventories and accounting for issues such as feedstock energy, albedo, concrete carbonation etc. Sustainable pavement strategies like the used of warm-mix asphalt, recycled asphalt pavement, blast furnace slag, fly ash etc. have been promoted over the past years. However, LCA of pavements with recycled materials or industrial by products have been addressed in a very few studies.

Mroueh et al. (2001) examined the environmental burdens of using coal ash, crushed concrete waste, and blast furnace slag as substitutes for virgin materials based on several case studies. The environmental burdens include energy consumption, air emissions, raw materials, leaching water use and noise effect. This study considered material, construction and maintenance phases, excluding use and end of life phases. This allowed combining all environmental burdens together into a single score. The conclusion acknowledges that variation in transportation and construction methods can affect the results. However, no general conclusion was drawn based on the results.

Jullien et al. (2006) investigated impacts for asphalt mixes with different RAP content (0%, 10%, 20%, and 30%) during road construction. The focus of the study was to determine the airborne emissions, odors and pollutant release by asphalt laying operation. The study considered the reclaimed old bitumen from RAP along with additional bitumen and a combination of new aggregate along with reclaimed asphalt pavement aggregate for asphalt plant production. The results concluded an increase in gas emissions and decrease in odor as the percentage of RAP increased.

Athena Institute (2006), examined the environmental impact of using 20% RAP mix compared to virgin material mix for a asphalt pavement highway in Canada. Process based LCA was used and the analysis period was 50 years. The study presumes that RAP consists of same components in the same proportions as the asphalt concrete that its replacing. It is also assumed that no additional energy and GHG emissions are associated with processing RAP at the asphalt plant.The results recommended 7.5 % reduction in energy and 13 % reduction in GWP when asphalt mix with 20% RAP was used instead of asphalt mix with virgin material.

Huang et al. (2009) performed case studies to compare the environmental impacts of using RAP and incinerator bottom ash in asphalt pavement. The paper discusses performance issues, reprocessing costs, and environmental burdens for each material. They found that using 25 % RAP and 10% incinerator bottom ash reduced the total energy and CO_2 emissions by 4 % in material production and construction phases.

Santisteve et al. (2013) examined the environmental impacts of asphalt pavement case study using HMA with 0 % RAP, HMA with 15 % RAP, WMA with 0% RAP and WMA with 15% RAP. Process based LCA was used for all the pavement life cycle phases. The results showed a 13-14% decrease in all endpoint impacts in addition to climate change, fossil depletion, and total cumulative energy demand over the pavement's life cycle by adding 15% RAP. However, comparing HMA with zeolite based WMA resulted in similar impacts. The reduction in the impacts of WMA due to lowering the manufacturing temperature is offset by greater impacts of the material used.

Aurangzeb et al. (2013) investigated environmental impacts of using high RAP content (30%, 40% and 50%) in asphalt mix for the phases of material production and construction. A hybrid LCA approach was used for the pavement life cycle phases of material, construction, and maintenance and rehabilitation. Use phase was not considered in the study and for end of life; cut-off approach was used. The analysis concluded reduction of up to 28% in energy consumption and GHG emissions when RAP was introduced in the mixture. A reduction of 26%, 33%, and 41% in feedstock energy was observed for the mixtures with 30%, 40%, and 50% RAP, respectively

Liu, Cui & Schwartz (2013) developed a LCA methodology to quantify expected GHG emissions and performed a case study for 20 rehabilitation and expansion projects for PCC, HMA, Warm Mix Asphalt (WMA) and Foam Stabilized Base (FSB). The system boundary includes site preparation, material production, equipment usage, traffic delay, use phase and end-of-life. They concluded that FSB for base rehabilitation prevented approximately 50% GHG emissions compared to HMA and WMA for surface treatment could result in 40% emission savings as compared to HMA.

Booz,Allen & Hamilton (2013) analyzed the environmental impacts of using seven asphalt mixes with various percentages of reclaimed asphalt (RAP) and recycled shingles (RAS) to a baseline of virgin asphalt for the material production phase. The binder replacement and virgin aggregate replacement are considered for the RAP content used. The environmental impacts include energy consumption, GHG emission and resource depletion. The study reported that using 20% RAP and 7 % RAS in asphalt mixture causes highest reduction in GHG emissions compared to default case. Furthermore, the use of WMA with 20% RAP resulted in a 12 % reduction in energy used at asphalt plant compared to the 20% RAP in HMA case. The authors also recommended that larger reductions in impacts are seen when RAP is included over solely using RAS.

2.4 Life Cycle Assessment Models and Tools

Pavement LCA is typically used to quantify the environmental impacts of different activities that occur during the life cycle of pavement. The protocols specified by International Organization for Standardization (ISO) for the assessment of life cycle emissions, are used as reference for current estimation models/tools. Some of the popular tools developed over the years are discussed below

PaLATE

The Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is one of the first pavement LCA software developed by University of California, Berkley in 2004. It is an open source spreadsheet- based tool that can estimate emissions, energy consumption and water consumption in the LCA phases of material, construction, maintenance, and end-of-life. The tool follows a hybrid LCA approach by using both economic input-output LCA and process based LCA. However, due to outdated database and lack of use phase, a new version of PaLATE was launched in 2011 by University of Washington. The main modifications were removal of life cycle cost analysis and the outputs were limited to energy use.

<u>asPECT</u>

The asphalt Pavement Embodied Carbon Tool (asPECT) was first released in 2010 by the Transportation Research Laboratory. The asPECT tool uses a process based LCA approach to calculate GHG emissions for the phases of life cycle dealing with asphalt related material processing like raw material acquisition, transportation, processing, construction, maintenance and end of life. The tool however doesn't consider the use phase.

<u>PE-2</u>

Project Emissions Estimator (PE-2) is a web based tool developed by Mukherjee and Cass(2012). The tool accounts for GHG emissions for material, construction, use, maintenance, and end-of-life phases of a pavement. The tool uses process based approach and the LCA model was based on data collected from 14 Michigan DOT projects and emission factors were collected from the literature and other databases. This tool allows users to compare GHGs between various pavements and construction practices.

<u>Athena IE for Highways</u>

Athena Impact Estimator (IE) for Highways software was released by Athena in 2013, which is one of the most developed and accessible pavement LCA tool (*Athena, 2013*). The life cycle stages include: materials manufacturing, roadway construction and maintenance. It allows custom roadway design, or users can draw from a library of over 150 existing roadway designs. The software includes large equipment and materials database and the flexibility to specify unique pavement systems – sub-base and base granular materials as well as hot and warm mix asphalt and a host of user-specified concrete mix designs. Users can also input use-phase operating energy and apply built-in pavement vehicle interaction algorithms, if desired, to be included in the final LCA results. The tool reports the following environmental impacts: global warming potential, acidification potential, human health respiratory effects potential, ozone depletion potential, smog potential, and eutrophication potential.

Santos et al. (2014) developed a customizable LCA project level tool. The system boundaries included extraction of raw material and production, construction, maintenance and rehabilitation, transportation of materials, work-zone traffic management, and usage and end-of life. The tool was developed using Visual Basic.net (VB.NET) and SQL programming language. The results are split into emissions related to the process energy combustion and emissions related to the upstream energy requirement.

Chapter 3 Life Cycle Inventory

This chapter summarized the life cycle inventory from published literature and compared their differences due to system boundaries and regional limitations.

3.1 Raw Material

When it comes to pavement materials, it is divided into two categories, which are raw materials and production of asphalt and cement concrete. According to pavement structure, the raw material includes the material used in subbase/base, asphalt layer and concrete.

Asphalt concrete is the surface layer for asphalt pavement, which located right on the base course. Asphalt pavement is commonly used in typical highways, parking lots and airports. It generally consists of granular materials bound together with asphalt binder. Cement concrete can be also used as the surface layer. It is a mix of cement, aggregate, and water. Steel is used in dowel bar and tie bar at the joint and in steel reinforcement for the reinforced concrete pavement.

Subbase/base is the layer that laid on the subgrade of the pavement structure, and it is often the main load-bearing layer of the pavement. Subbase/base layer is the combination of aggregate materials, and the materials can be divided into two categories based on the use of cement: unbound granular and cement-bound. Unbound granular mainly refers to crushed stone or sand/gravel, while cement bound-material is mainly used when extra load is expected and cement is usually added in the mix to increase strength.

3.1.1 Asphalt Binder

Asphalt binder, a constituent of petroleum, is a sticky, black and highly viscous liquid that is used for asphalt mixtures. While there is only 5–6% of asphalt binder by weight in asphalt mixture, it contributes significantly to energy and GHG impacts due to raw material production.

The typical process of producing asphalt binder is divided into four stages: crude oil extraction, transport, production, and storage. Table 3.1 shows comparisons of energy consumptions and GHG emissions for asphalt binder that were obtained from published sources. The observed differences originate from the inconsistencies in the system boundary and the inherent regional differences in fuel use and processes.

Table 3.1 Energy and Emission Data for Asphalt Binder

Source	VTT (1996)	IVL (2001)	Athena (2006)	Eurobitume (2012)
Energy (MJ/t)	6000	3634	5812	3980
CO_2 (kg/t)	330	173	377	244
CH_4 (g/t)	-	0.0227	107	719
N_2O (g/t)	-	0.0680	0.20	-

Table 3.2 lists the system boundaries used in different studies. The Athena and VTT studies did not include refined transportation or blending storage; while the IVL and Eurobitume study covered the complete process of bitumen production, from raw material extraction and ending with a bitumen product ready for delivery to customers. In addition, physical or non-physical parameter for allocation at the refinery-level can be used. Physical parameters may include mass, volume or energy content, while an example of a non-physical parameter is economic or market value. The Eurobitume study used an economic-based allocation in refining, while the IVL and Athena used mass-based allocation. Thus, it is important to recognize the effect of system boundary on significant differences in LCI.

Table 3.2 System Boundaries for Asphalt Binder

Source	System Boundaries			
	Crude Oil Extraction	Crude Transportation	Refining (Production)	Blending & Storage
VTT (1996)	x	x	x	
IVL (2001)	x	x	x	x
Athena (2001)	x	x	x	
Eurobitume (2012)	x	x	x	x

VTT (1996)

The data is retrieved from one company and all calculations and assumptions are specific to Finland. The system boundaries include pre-combustion or indirect fuel processes, but no processes beyond refining are considered.

IVL (2001)

The crude oil source in this study is from Venezuela and is transported by tanker boat to Sweden, where it is refined. A mass allocation is used in the refinery process to attribute 40% of the energy and emissions to processing asphalt binder. After refining, it is assumed that the asphalt binder is transported by tanker boat to a depot where it is stored for end-users. The production of transportation fuels and generation of electricity is included, but production of natural gas is excluded.

Athena (2007)

The crude production is based on US processes, but estimates for Canada are also covered. The refinery operations are examined at the process-level for energy allocation. For emissions, mass allocation is done at the refinery-level due to lack of data. Fuel upstream processes are included along with energy and emissions needed for electricity generation. The LCI from Athena contains the most comprehensive list of emissions when compared to the other reports.

Eurobitume (2012)

This report utilized local questionnaires to collect regional information. Local sources of data were used when possible and data from Ecoinvent were supplementary.

The crude oil distribution is specific to the European context, with crude coming from the Former Soviet Union, Middle East, South America, and Europe. The allocation method used in refinery processes is based on market value at the process-level. It is assumed that the refined material is transferred to the storage depot via pipeline and that various blending or milling processes are present, depending on the final binder product.

Although the LCI data are available for asphalt binder from different sources, it has been found that the environment impacts of petroleum products are highly susceptible to regional factors, especially crude oil sources (NETL 2009). Recently, a regional LCI database was developed for asphalt binder considering that crude oil sources and refinery fuel consumption vary among different regions in the US (Yang 2014). In this study, the commercial Ecoinvent-v2.2 database was used to simulate the unit process for asphalt binder production. The system boundaries include crude oil extraction and flaring, crude oil transportation, refining, refined product transportation, blending, and storage. The U.S. Energy Information Administration (EIA) reports for Petroleum Administration for Defense Districts (PADDs) and Petroleum Supply Annual (PSA) were used for analysis of crude oil distribution and refining process.

Table 3.3 lists the energy and GHG impacts of asphalt binder derived from the work by Yang (2014). In this study, the data corresponding to PADD1 (east coast) is used. It is noted that PADD1 has the highest energy consumption and GHG emission for asphalt binder compared to other regions and the national average. This is mostly due to flaring and foreign crude transportation processes.

Table 3.3 Energy and emission data for asphalt binder at different regions (After Yang 2014)

	PADD1 (East Coast)	PADD2 (Mid-West)	PADD3 (Gulf Coast)	PADD4 (Rockies)	PADD5 (West Coast)	US (National)
Energy (MJ/ton)	5810	4630	4990	4430	5190	5440
Eq.CO_2 (kg/ton)	462	294	343	227.3	326	363

On the other hand, feedstock energy is another consideration in binder production in addition to process energy. Feedstock energy is defined as the "heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value" (ISO 14044:2006). The inclusion of feedstock energy for asphalt binder is not considered here because it is not commonly used as a fuel in any applications. The feedstock energy of asphalt binder (36,469 MJ/ton) has been reported and it can be added separately if needed. (Garg et al., 2006)

3.1.2 Modified Asphalt Binder

Asphalt pavement is sensitive to extreme temperature condition: it will be brittle and easy to have cracks when exposed in cold conditions, while it will soften at higher temperatures, which will cause rutting and surface deformation. In order to solve this problem, polymer modified binder (PMB) is used for better pavement performance. Polymer is added into asphalt to make the product more durable under extreme weather conditions.

Two types of polymer are generally used to modify bitumen for pavement: elastomers and plastomers. Elastomers exhibit a low modulus of elasticity, which permits the polymer matrix to expand without failure when stretched, so it will improve the elastic behavior of the bitumen. Styrene-Butadiene-Styrene (SBS) is most commonly used elastomer, and other elastomers, like natural and synthetic rubbers, crumb rubber modifiers (CRM) are also used.

Unlike the elastomers, plastomers attain high strength at a rapid rate, but are brittle and resistant to deformation once set, so they can increase the viscosity and stiffness of asphalt binder. The common plastomer examples are Ethene-Vinyl-Acetate (EVA) and Polyethylene (PE). Typical values for Polyethylene are 85,000 MJ/ton for energy and 1100 kg/ton for CO_2 (Stripple 2001). However, these values could vary depending on the manufacturing process of polymer.

One commonly used modified binder is crumb rubber modified (CRM) asphalt that is produced from end-of-life tires. The production of crumb rubber includes grinding, crushing, and mechanical pulverizing of scrap tire at a plant (Corti and Lombari 2004). The crumb rubber can be added into asphalt binder in two ways: dry or wet process. In the wet process, crumb rubber is added to asphalt binder and mixed at temperatures usually higher than 180°C to produce a modified high-viscosity binder. The percentage of crumb rubber can be up to 20% of asphalt binder. The wet procress is usually used for producing the gap-graded or open-graded asphalt mixture that allows the use of relatively higher binder content. In the dry process, crumb rubber is used to substitute part of aggregates. The percentage of crumb rubber is usually between 1% and 3% of the weight of total aggregates in the mix (FHWA, *User Guidelines for Waste and Byproduct Material in Pavement Construction*). In this case, rubber particles may absorb a part of asphalt binder and thus the optimal binder content is often slightly higher compared to non-modified asphalt mixtures. The LCI data for production of crumb rubber is not available in most literature. An Italian study reported that one ton of crumb rubber can be produced from 1.45 tons of end-of-life tires in typical production and it comes with 384 kWh of electric power, 2.99 liters of diesel oil, and variable quantities of auxiliary materials (Ecopneus 2013). The resulted energy consumption and GHG emission from crumb rubber production are estimated to be 5,200 MJ/ton and 307 kg CO_2 eq/ton, respectively. The main contribution (70% of total values) comes from electric power used for shredding operations. However, if recycling of co-products (steel and textiles) is considered, the overall environmental impact of crumb rubber production is significantly reduced. The total GHG emission reduction is around 41.6 kg CO_2 eq/ton that mainly derives from the reduction of steel production. The energy saving effect is also obtained that is equal to 3,220 MJ/ton (Farina et al. 2014).

Another frequently used asphalt product is emulsion, which is used for tack coating, prime coating and recycling. Modified Emulsions are used in micro surfacing and slurry seal. Emulsion consists of modified binder and emulsifier-added water. The environmental impact is varying since the ratio of binder and emulsifier-added water can be different under certain conditions. Emulsifiers are added to make asphalt binder mixed with liquid water at the room temperature. Table 3.4 shows the energy consumption and emission values for SBS polymer additive, emulsifier additive, and crumb rubber.

Table 3.4 Energy Consumption and Emissions for asphalt binder additives

Source	**Polymer Additive (IVL,2000)**	**Polymer Additive (CEREA,2010)**	**SBS-Polymer Additive (Eurobitume ,2012)**	**Emulsifier Additive (Eurobitume ,2012)**	**Crumb Rubber (Farina et al. 2014)**	
Energy (MJ/t)	85,730	71,710	76,742	27,937	5200	
CO_2 (kg/t)	1100	1837	3363	1534	**GHG emission ($kg.CO_2eq.$)**	307
CH_4 (g/t)			14,085	2566		
N_2O (g/t)			-	-		

It is noted that in the Eurobitumen study the system boundary for polymer additive include SBS production and transportation and PMB milling, and the system boundary for emulsion additive include emulsifier production, transportation, and milling.

3.1.4 Recycled Asphalt Material

Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) are often used in asphalt pavement given their environmentally friendly attributes. RAP is often used as a partial aggregate and binder replacement in flexible pavements, while RAS is used as a partial binder replacement. RAP or RAS are the recycled materials from old pavements or waste shingles. It is reasonable to assume that the environmental impacts associated with the original material will be fully attributed to the original material and none to the recycled materials. It is noted that the energy and emission related to milling and transporting RAP to recycling facility are attributed to the end-of-life stage of the pavement being recycled. Similarly, the relevant process in RAS production from post-consumer waste shingles or "tear-off" roof shingles were accounted as part of the end-of-life activities.

The environmental indicators here represent the energy consumption and emission generated during the post-processing production (such as crushing and screening for RAP, grinding and removing metal piece for RAS), transportation, and storage processes for new applications. Table 3.5 lists the LCI data reported by different researchers for different RAP processing techniques with and without upstream values.

Table 3.5 Energy and Emission Data for RAP Processing

	RAP with upstream values (Proust 2014)	RAP without upstream values (Proust 2014)	Yang et al (2014)
Energy (MJ/ton)	47.4	18.9	17

CO_2eq (kg/ton)	2.6	1.5	1.3

In the study by Yang (2014), the environmental burdens were based on a survey and further modeled in SimaPro. The system boundaries for RAP include crushing and screening of the RAP onsite. The milling of RAP from the previous pavement and transportation of RAP to the processing site were considered as end-of-life activities from previous pavement and a cut-off strategy was used.

3.1.5 Portland Cement

The manufacturing process of Portland cement mainly include four steps: 1) quarry and crush that includes extracting raw material from the earth, crushing to small pieces, and conveying and stockpiling;2) raw meal preparation that includes recovering materials from stockpiles, proportioning to the correct chemical composition, and grinding and blending; 3) pyroprocess that includes processing raw meal to remove water, calcining limestone and causing the mix components to react to form clinker, cooling and storing the clinker; and 4) finishing grind that includes reclaiming the clinker from storage, adding gypsum and grinding to a fine powder, conveying to storage, and shipping in bulk or in bags .

The system boundary of cement production is shown Figure 3.7 .The system boundaries activities included are blasting, wet drilling in un-fragmented rock, product loading in open truck, unloading, primary crushing, secondary crushing, screening, conveyor transfer, and storage piles.

Table 3.6 shows a comparison of energy consumption and GHG emissions for Portland cement from published sources. Different from the LCI data for asphalt binder, the LCI data for Portland cement are quite consistent with small variations. Table 3 lists the system boundaries used in different studies.

Table 3.6 Energy and Emission Data for Cement Material

Source	VTT (1996)	IVL (2001)	Athena (2001)	PCA (2007)
Energy (MJ/t)	5350	4776	5232	4340
CO_2 (kg/t)	799	806	670	927
CH_4 (g/t)	750	0.0546	12	39.5
N_2O (g/t)	0.0021	0.164	0.0504	-

Table 3.7 System Boundaries for Cement Material

Source	System Boundaries				
	Quarry & Crush	Raw meal Preparation	Pyroprocess	Finish Grind	Transportation to Cement Plant
VTT	x	x	x	x	x
IVL	x	x	x	x	
Athena	x	x	x	x	x
PCA	x	x	x	x	x

<u>VTT (1996)</u>

The data is retrieved from one (Finncement-Stefan Lindfors) company and all calculations and assumptions are specific to Finland. The system boundaries include extraction and transportation of raw materials, production of raw meal, burning of clinker and grinding of cement.

IVL (2001)

The cement inventory data from Swedish average production (Cementa AB) has been used in this study. The system boundary includes data from the working to the final product at the factory gates.

Athena (2007)

The Canadian weighted averages were than calculated, based on cement production in the four regions under consideration (West Coast, Prairie, Central and East). All results are based on the most recent information about the Canadian cement plants' production capacities and equipment used, provided by the CAC (2004/05 data).

PCA (2012)

The Portland Cement Association conducted collection, analysis, and dissemination of LCI data for Portland cement. The system boundary of cement includes the four main steps in manufacturing Portland cement: (1) quarrying and crushing, (2) raw meal preparation, (3) pyroprocessing, and (4) finish grinding.

3.1.6 Aggregate

Aggregates can be classified into two categories: crushed and natural. Crushed aggregate are those that undergo additional, mechanical breaking after acquisition or quarrying; while natural aggregates are often done by dredging. The energy and emission data for aggregates are extracted from different sources as shown in Table 3.8. The wide range of values indicates the difference between sand/gravel and coarse aggregate from crushed stone. Table 3.9 and Table 3.10 compare the system boundaries used in different studies.

Table 3.8 Energy and Emission Data for Aggregate (Sand Gravel and Coarse Aggregate from Crushed Stone)

Source	VTT (1990)	IVL (2001)	Athena	PCA (2007)
Energy (MJ/t)	24-52	6-38	68.6	21-32
CO_2 (kg/t)	1.7-2.0	0.073-1.42	6	0.073-1.42
CH_4 (g/t)	1.7-4.3	0.000376-0.00382	3.6	-
N_2O (g/t)	-	0.00230-0.0361	0.03	-

Table 3.9 System Boundaries for Fine aggregate (Sand-Gravel)

Source (year)	System Boundaries					
	Product Loading	Material Transfer and Conveying	Screening	Pile Formation with a stacker	Storage piles	Bulk Loading
VTT (1996)	x	x	x	x		
IVL (2001)		x	x	x	x	x
Athena (2006)	x	x	x	x	x	x

PCA (2007)	x	x	x	x	x	x

Table 3.10 System Boundaries for Coarse Aggregate

Source (year)	System Boundaries					
	Blasting	Wet Drilling	Loading & Unloading	Crushing (Primary & Secondary)	Screening	Conveyor Transfer	Storage Piles
VTT (1996)	x	x	x	x	x	x	
IVL (2001)	x		x	x	x	x	
Athena (2006)	x	x	x	x	x	x	
PCA (2007)	x	x	x	x	x	x	x

VTT (1996)

The calculations and assumptions are specific to Finland. The system boundaries include quarry and breaking, transportation of bread rock, crushing and transportation of crushed materials.

IVL (2001)

The life cycle inventory of crushed aggregates is based on a production of crushed aggregates from rock mass. The material in the analysis is based on real total values for energy consumption for a whole factory (Sabema) including all energy consumption for the site. The system boundary included blasting, Transporting, Crushing, Sieving. The extraction of natural gravel and sand has in the analysis been assumed to take place from a pit where the gravel/sand is dug out and further transported, screened and piled.

Athena (2007)

It is assumed that both coarse and fine aggregates require the same extraction energy input; the processing (crushing, grinding) energy of the fine aggregate is higher than that of coarse aggregates.

PCA (2007)

PCA adapts the energy values of producing sand and gravel and coarse aggregate from crushed stone from U.S. Census Bureau data and the U.S. Geological Survey. The activities included in the production of sand and gravel are product loading in open truck, material transfer and conveying, screening, pile formation with a stacker, storage piles, and bulk loading. The activities included in the production of coarse aggregate from crushed stone are blasting, wet drilling in unfragmented rocks, product loading in open truck, unloading, primary crushing, secondary crushing, screening, conveyor transfer, and storage piles.

3.1.7 Steel

Steel is mainly used in the jointed reinforced concrete pavement. The joint spacing can be increased when steel reinforcement is used to hold together intermediate cracks in concrete slab. Steel is also used in the form of dowels for Jointed Plain Concrete Pavement (JPCP) or Jointed Reinforced Concrete Pavements (JRCP). The energy and emission data from published sources are summarized in Table 3.11. The Vehicle Cycle Model in GREET were also run to calculate the energy and emission values for virgin steel, recycled steel and stainless steel. It is assumed that the recovery rate of steel is 70% (SRI, 2012) and the recycled content is 35% (Ram et al., 2012).

Table 3.11 Energy and Emission Data for Steel

Source	IVL (2001)	Athena (2006)	GREET (Virgin Steel)	GREET (Recycled Steel)
Energy (MJ/t)	218300	11300	51830	21500
CO_2 (kg/t)	2220	565	4314	1496
CH_4 (g/t)	9170	9000	7558	2965
N_2O (g/t)	30.6	20	46.1	27

IVL (2001)

Data for steel and hot dip galvanized steel are from Swiss Federal Institute of Technology, Zurich, Switzerland, 1994. The consumption of zinc in the galvanizing process has been calculated to be 0.5 % of the weight of the steel used. Data represents new, not recycled, material.

Athena (2007)

The Steel energy, greenhouse gas emissions have been derived from an updated (2002) Athena Institute report, using the data for reinforcing bar (rebar). The system boundary encompasses scrap metal transportation and preparation, rebar production and transportation to the road construction site.

GREET Vehicle Cycle Model

The GREET Vehicle Cycle Model (2013) Spreadsheet is downloaded from the Argonne National Laboratory's Website (https://greet.es.anl.gov/greet_2_series). The processes included for steel production are ore recovery, ore pelletizing & sintering, coke production, blast furnace, basic O_2 processing, electric arc furnace, sheet production & rolling and stamping.

3.1.8 Supplementary Cementitious Material

The commonly used supplementary cementitious materials include slag cement and fly ash. Slag is a by-product produced during iron production. The molten slag remained in the blast furnace can either become waste or recovered as aggregate. If the molten slag is rapidly quenched with water in a controlled process and then ground into fine powder, it becomes hydraulic cement, known as slag cement (or ground granulated blast furnace slag). Slag cement substitution rates for Portland cement ranges from 25 and 80% depending on applications. The manufacture of slag cement includes the following processes: 1) quenching and granulation, 2) dewatering and/or drying, 3) crushing, 4) grinding, 5) storage, and 6) shipping.

Fly ash is the unburnt particulate (mainly siliceous components) released in exhaust gas when coal is burnt in coal power plants. Fly ash is obtained from the exhaust gases of coal power plants and then dried and stocked. The system boundaries for this material included drying and stocking of fly ash and also transportation from coal production plant to treatment plant.

A study was conducted by CTL in 2003 to obtain the life cycle inventory of slag cement manufacturing process. In their study, data were collected from members of the Slag Cement Association. The responders reported the materials, energy, and emissions to air, water, and land for each stage in the manufacture of slag cement. The system boundary for the LCI was selected to start at the point where slag is quenched with water and end with slag cement ready for shipment, which does not include upstream values.

An allocation study was conducted by Chen et al. (2010) to quantify the environmental burdens for granulated blast furnace slag (GBFS) and coal combustion fly ash. Their analysis considered both primary process (the process that produces the main product and the by-product) and secondary process (Process aiming at treating the by-product or waste to produce a by-product suitable for its further use as cement concrete component). The secondary process is considered as it is and the primary process is multiplied by an allocation coefficient. The environmental impacts of slag cement are shown in Table 3.12.

Table 3.12 Energy and Emission Data for Slag Cement

	Blast Furnace Slag (Marceau et al. 2003)
Energy (MJ/t)	444
CO_2 (kg/t)	770
CH_4(g/t)	0.01088

3.2 Asphalt Mixture and Concrete Production

3.2.1 Asphalt Mixture Production

Asphalt production is mainly the mixing of asphalt binder, aggregate and other additives, and energy consumption and emission are mainly generated from heating and mixing. Typically, aggregates are accurately measured out through the cold feed bins, and then these aggregates are dried and heated in the drying drum before mixing with the asphalt binder. After the mixing, hot mix asphalt (HMA) are stored in the storage silo before loading onto trucks for paving jobs. The system boundaries included natural gas for the dryer/drums and heater, diesel for in-plant loaders, and electricity for plant components such as exhaust fans and conveyors.

The typical energy and emission data for HMA production from different published sources are shown in Table 3.13. The values form the recent NCHRP 9-47A report were taken as the average values of the survey data obtained from Michigan, Indiana, and New York. The value from Athena (2006) includes 0-20% RAP material. It is noted that the values are typical inventory data for asphalt production at different regions but the exact values may vary at each asphalt plant.

Table 3.13 Energy and Emission Data for Production of Asphalt Mixture

Source	IVL (2001)	Athena (2006)	NHCRP 9-47A (2014)	EPA AP42 (2010)
Energy (MJ/ton)	485	432	266	N/A
CO_2(kg/ ton)	34.4	21	16.4	15
CH_4(g/ ton)	10.7	74.42	N/A	5.45
N_2O (g/ ton)	0.51	N/A	N/A	N/A

IVL (2001)

The hot mixed asphalt plant, bitumen and stone materials are mixed according to the hot method. The energy consumption for HMA is based on Operation data for a plant.

Athena (2007)

The method of calculating the energy and emissions per cubic meter of asphalt involved four steps: basic asphalt production at the refinery, aggregate production, transportation, and asphalt concrete production at the asphalt plant. Calculations of energy consumption and greenhouse gas emissions are based on the composition of the asphalt concrete and the relevant energy use data by fuel type and associated emission factor.

NCHRP 9-47A

A part of NCHRP 9-47A project, energy usage and stack emission were collected from three asphalt plants in MI, IN, and NY. The collected energy data vary depending on the fuel type used in the heating, burner tuning, casing loss, and the aggregate moisture content in the stockpile. Fuel usage was obtained from the direct site measurements and analysis of two-year averages at the same plants. Reported stack emissions included carbon dioxide to assess greenhouse gas production and other air pollutants (volatile organic compounds and oxides of nitrogen, carbon monoxide, sulfur dioxide, condensed particulates (component of PM-10) and formaldehyde emissions).

EPA AP-42

EPA AP 42 study reports production related fugitive emissions and emissions from ducted production sources for batch mix asphalt plants and drum mix plants. The emission factors for CO, CO_2, NO_x, and SO_2, Total organic compounds, CH_4 and VOC for batch mix plant and drum mix plant are reported.

3.2.3 Asphalt Mixture Production at Specific Plant

Fuel usage depends on a number of factors including, but not limited to: aggregate (and recycled materials, if used) moisture content, production rate, mix temperature, and excess air (damper setting). It is hard to quantify the energy and emissions in asphalt production since it is the function of material mix, percentage of moisture in aggregate and temperature. However, in this tool, the users can define their own asphalt production process.

Heating is an essential part of asphalt production, and the energy (Q) required to heat materials is the product of specific heat value (c), the mass of the material (m) in pounds, and the temperature difference (ΔT) in degrees Fahrenheit. The formulation for calculating the heating energy is shown in Equation 3.1.

$$Q = c \times m \times \Delta\mathrm{T} \tag{3.1}$$

Where,

$Q = Energy\ required\ to\ heat\ material$;

$c = Specific\ Heat;$

$m = Mass\ of\ material;\ and$

$\Delta T = Temperature\ Difference.$

The following specific heat values are typically used in this model: 1.00 Btu/lb for water, 0.5 Btu/lb for steam, 0.22 Btu/lb for aggregate and 0.468 Btu/lb for asphalt binder.

According to the equation above, the heating energy used in asphalt production is the sum of heating energy for water (which is the moisture in aggregate), steam, aggregate and binder. Additionally, when water turns into steam, it requires additional energy, which should also be considered in this process. The latent heat required to evaporate water is 970 Btu/lb (Hanson et al. 2012). Based on the heating energy, the emissions were calculated for the HMA plant production process. The GREET 2013, Fuel cycle model developed by Argonne National Laboratory was used to get the emissions(CO_2, CH_4 and N_2O) from combustion of process fuels like Natural Gas, Distillate Fuel oil, Gasoline, Residual Oil, Liquefied Petroleum Gas (LPG) etc. as shown in Table 3.14. The energy usage profile for production process in HMA plant was assumed 80% fuel natural gas and 20% fuel oil (EPA AP-42).

It is noted that heating energy is just one part of the energy used in asphalt production, and other sorts of energy, like mixing, should not be neglected. However, this kind of energy is hard to quantify.

Table 3.14 Emissions from Combustion of Process Fuels (After GREET Fuel Cycle Model)

Emission (g/MMBtu)	Coal	Natural Gas	Distillate Fuel Oil	Gasoline	Diesel	LPG	Residual Oil	Petroleum Coke

CO_2	99,844	59,379	78167	75,645	88,169	68,024	85,045	104,622
CH_4	1.2	1.1	0.18	5.193	3.9	1.08	3.24	4
N_2O	1.06	1.11	0.39	2.4	2	4.86	0.36	1

3.2.4 Asphalt Mixture Production with RAP at Specific Plant

RAP is used more frequently because of its environmentally friendly impact. One of the challenges of using RAP in HMA plants is the difficulty in drying RAP since RAP usually contains more moisture compared with virgin aggregates. If RAP is directly heated, the binder coating may burn off and evaporate that will produce additional emissions. If the residual of burned binder is left on the aggregate surface of RAP material, the performance of HMA mixes will be affected. In the HMA plant, RAP is added at the mid-term, and it is dried by the "superheated" virgin aggregate. In previous studies, RAP is regarded to reduce energy consumption and emission since it can substitute certain amount of virgin asphalt and aggregate and thus saves energy in raw materials, such as the extraction of crude oil for virgin binder and the crushing of stone for virgin aggregate. However, the extra energy required to superheat the virgin aggregate may offset the saved energy from raw material acquisition.

Overheating the virgin aggregates before introducing the RAP to the drum is a common practice followed to avoid direct heating of RAP materials. It can cause extra fuel and energy use, which offsets the economic benefits of using RAP. More specifically, when using RAP, the discharging temperature needs to be increased in order to achieve the "superheated" status. Actually, the increased temperature is the function of RAP content, moisture content in RAP, and HMA discharge temperature. An equation provided by Wen et al. (2012) can be used to estimate the increased temperature for aggregate superheating.

Based on field data in the literature, Wen et al. (2012) developed an equation for quantifying the energy to heat RAP and virgin aggregate. The energy to heat RAP was based on the energy required to superheat virgin aggregate to an elevated temperature, moisture content and discharge temperature. The equation to quantify the energy consumption to heat RAP (ΔH_{RAP}) is shown in Equation 3.2. The energy to heat virgin aggregates was based on the energy required to heat moisture, evaporate water remove vapor, and heat aggregate to the discharge temperature. The equation to quantify the energy consumption to heat virgin aggregate (ΔH_{Agg}) is shown in Equation 3.3.

$$\Delta H_{RAP} = M_{RAP} c_{agg} (100 - P_{RAP})/P_{RAP} [(-0.0234 + 0.0079 P_{moi} + 0.000345 T_{dis}) P_{RAP}^2 + (1.05 + 0.1029 P_{moi} + 0.00179 T_{dis}) P_{RAP} + 1.5 P_{moi} + 1.067 T_{dis} - 124.102] \tag{3.2}$$

$$\Delta H_{Agg} = M_{agg} P_{moi} (100 - T_{amb}) c_{water}/100 + M_{agg} P_{moi} (LH/100) + M_{agg} P_{moi} (T_{dis} - 100) c_{vapor}/100 + M_{agg} P_{moi} (T_{dis} - T_{amb}) c_{agg} \tag{3.3}$$

Where,

$\Delta H_{RAP} = Energy\ to\ heat\ RAP$

$\Delta H_{Agg} = Energy\ to\ heat\ virgin\ aggregate$

$P_{moi} = Moisture\ content\ of\ RAP, \%$;

$T_{dis} = Discharge\ Temperature, °C$;

$T_{amb} = Ambient\ \ Temperature, °C$;

$P_{RAP} = RAP\ content, \%$;

$M_{RAP} = Mass\ of\ RAP, kg$;

$M_{agg} = Mass\ of\ aggregate, kg$;

LH = $Latent\ heat\ to\ evaporate\ water$,MJ/kg

$c_{agg} = Specific\ Heat\ of\ aggregate$,MJ/kg/$°C$

$c_{vapor} = Specific\ Heat\ of\ vapor$, MJ/kg/$°C$

$c_{water} = Specific\ Heat\ of\ water$, MJ/kg/$°C$

3.2.5 Concrete Production

Concrete is produced by mixing cement with fine aggregate (sand), coarse aggregate (gravel or crushed stone), and water. A small amount of chemicals are usually added to the concrete mix to control setting time and plasticity (Choate 2003), which is not considered here. Only the concrete plant operations are considered here for emissions and energy consumption. Compared with asphalt production, concrete production is much easier.

Table 3.15 Energy and Emission Data for Production of Cement Concrete

Source	IVL (2001)	DOE (2003)	Athena (2006)	PCA (2007)
Energy (MJ/ t)	40	56	110	18
CO_2 (kg/ t)	1.66	9.54	7.463	0.72
CH_4 (g/ t)	0.002	0	9.4	0
N_2O (g/ t)	0.036	0	0.0037	0

IVL (2001)

The production of concrete has been assumed to take place according to a fixed general recipe for road concrete of Sweden. The system boundary includes the transport of crushed aggregates and gravel/sand to the mixing plant or the transportation of cement from the cement plant to the mixing plant.

DOE (2003)

The concrete production in plant assumes a typical concrete mix based on National Ready Mix Concrete Association. The energy consumption and emission for ready mixed concrete production are based on the operations of quarrying, mixing and blending and transporting the concrete mix to work site.

Athena (2006)

Athena uses the weighted average design mix for Concrete Mix design among several regions. The model developed by Athena Institute was used for energy and emission values of all cement and structural concrete products. The system boundary ends at concrete plant gate.

PCA (2007)

The Portland Cement Association conducted collection, analysis, and dissemination of LCI data for Portland cement, ready mixed concrete, concrete masonry, and precast concrete. The survey was distributed to a sample of 47 member-plants of the National Ready Mixed Concrete Association. The raw data were used to calculate inputs and emissions on a production-weighted basis per unit volume of concrete.

3.3 Transportation

There are three transport stages in the pavement life-cycle: 1) transportation of raw materials from extraction site to processing facility, such as transport of crude oil to refinery; 2) transportation of processed material to manufacturing plant, such as transport of asphalt from refinery to the hot-mix asphalt plant, 3) transportation of manufactured material from production site to construction site. The transportation stages can be considered separately or with the stage in which transportation activities occur.

Truck transportation was usually assumed as the mode of transporting manufactured material from production site to construction site. The environmental impacts resulting from the transportation of materials are influenced by the following primary characteristics: vehicle type, fuel type, engine capacity (HP rating), payload capacity of the transportation mode, transportation distance, transportation speed, and the mass of materials being transported.

3.4 Construction

In the construction phase, the environmental burdens are due to the combustion-related emissions from construction equipment usage. The equipment session includes the equipment used in construction and maintenance and rehabilitation. Most studies capture these data from NONROAD. NONROAD 2008 model is developed by EPA, which provides emission data (i.e., fuel consumption and CO_2) for off-road equipment by its function, horsepower, and fuel type. NONROAD itself can provide national or state level average data for different equipment, and it can also estimate county level emission data if certain background are provided by user. The NONROAD model first estimates zero-hour steady-state criteria pollutant emissions and fuel consumption. Zero-hour emissions are not adjusted for normal deterioration of engine performance over its useful life. Steady-state refers to running an engine under a constant load under laboratory conditions without a load adjustment to correct for variations in load during normal use. NONROAD estimates deterioration factors (DF) and transient adjustment factors (TAF) to correct for the zero-hour state and the steady state emissions, respectively (Noland & Hanson, 2011).

In the construction phase, the environmental burdens are due to the combustion-related emissions from construction equipment usage. The NONROAD (nonroad engines, equipment, and vehicles) 2008 model developed by Environment Protection Agency

(EPA) was used to calculate CO_2 emission for off-road equipment by its function, horsepower, and fuel type. Based on the work by Weiland and Muench (2010), seventeen equipment types are commonly used for pavement construction activities. Table 3.16 lists the CO_2 emission rates that were obtained from NONROAD based on equipment type and horse power.

Table 3.16 NONROAD construction equipment CO_2 emission

Construction Activity	NONROAD Equipment Type	Equipment HP Range	CO_2 Emission (kg/hour) Range
Grading	Graders	50-750	16.96-237.31
Compaction	Rollers	6-600	1.90-133.03
Breakdown Rolling			
Finish Rolling			
Site Utility Work	Excavators	6-3000	2.10-743.12
Slipform Paving	Pavers	25-600	7.68-122.41
Texture/Cure Paving			
Spraying	Sprayers	25-600	7.90-113.27
Saw Cutting	Concrete/Industrial Saws	11-300	3.50-76.38
Placing/Spreading	Surfacing Equipment	11-2000	2.34-487.84
Milling			
Tack Coating	Surfacing Equipment	11-2000	2.34-487.84
Seal Coating			
Grooving			

PCC Cracking	Crushing/Proc. Equipment	11-1000	7.93-209.65
Articulated dump truck	Off-Highway Truck	175-3000	50.78-766.63
Cement Mixing	Cement & Mortar Mixers	6-600	1.51-91.69
Joint Sealing	Welder	11-75	1.51-91.69
Dowel Bar	Bore/Drill Rigs	11-100	2.02-21.54

3.5 End of Life

At the end of pavement service life, pavement can meet one of three fates: 1) demolished and landfilled; 2) demolished and recycled; 3) remaining on site and serve as support for a subsequent structure (Figure 3.1). Option one takes lots of money and consumes lots of energy, so landfill is basically not an option given its great cost. Option two is to treat the old pavement as RAP material and the energy consumption and emission is mainly generated during the demolishing and transporting processes of RAP to a recycling facility. Option three is to mill the old pavement or conduct in-place recycling. The in-place recycling process is not considered as an EOL treatment but considered as maintenance and repair activities.

Two different approaches can be used to consider the EOL phase: (1) the cut-off approach and (2) the substitution variant of the system expansion approach. (Nicholson, A.L. et al. 2009) The cut-off approach, commonly applied in LCA of open recycling systems, follows the principle that each product is assigned only the burdens directly associated with it. On the other hand, the substitution approach, also called ‘avoided burden approach’ or ‘crediting approach’, consists of expanding the boundaries of the current pavement system to account for the environmental burdens that would be generated within the next pavement system to deliver a new pavement structure that incorporates either the recycled materials or the remaining pavement structure. The avoided environmental burdens are later 'credited' or subtracted from those produced during the pavement system under analysis.

In most studies, cut-off approach is used for the EOL phase. Thus, the existing pavement does not receive any environmental benefit for its potential to produce recycled materials. This is a common approach used in pavement materials because the pavement materials may not retain their inherent properties when recycled, as opposed to a material such as recycled steel (Huang et al. 2012; Link et al. 2009).

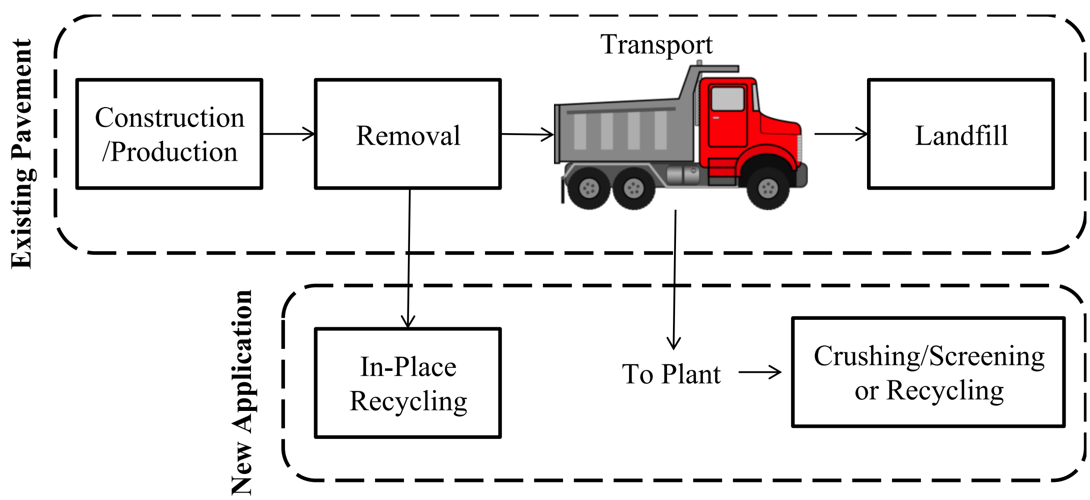


Figure 3.1 Illustration of end-of-life options

3.6 Upstream Values

The U.S. Energy Information Administration (EIA) defines direct emission as the combustion emissions from both stationary and mobile sources (U.S. EPA, 2008). Direct energy refers to the energy obtained during fuel combustion or electricity. For example, direct emissions are generated in plant process operations such as cement production, aggregate crushing, HMA production, and others. Direct emissions also resulted from operating mobile sources (transportation and construction equipment) such as dump trucks and pavers.

The overall environmental impact of a process depends on both the combustion (direct) energy and emissions for operating equipment and vehicles, and the upstream energy requirements for producing and delivering the energy source. The upstream (indirect) emissions are generated from processing fuel consumed during various processes from material extraction to construction. Energy is required to produce fuels and electricity used in the downstream processes. Therefore, in addition to the energy use and emission of direct use of fuels and electricity, the energy and emissions associated with the production of these fuels and electricity should be considered in the analysis.

To incorporate the upstream (indirect) values, the GREET 2013 model developed by Argonne National Laboratory was used. GREET is an open spreadsheet-based software used to evaluate the impact of fuel use. The GREET model includes all fuel production processes from oil exploration to fuel use (from well to wheels). A five-stage life-cycle approach is used in GREET to address emissions for fuels consumed in vehicles, including emissions from combustion of process fuels, related feedstock, and fugitive or flared emissions. The five stages include:

- Feedstock extraction and raw material acquisition;
- Feedstock transportation, storage, and distribution and raw material transport;
- Refining and fuel production;
- Transportation, storage, and distribution to the delivery system and transport of fuels to refueling station; and
- Consumption and operation.

The energy consumption and emission values for the upstream and combustion of process fuel are listed in Table 3.19, respectively for coal, natural gas, conventional gasoline, conventional diesel, and liquefied petroleum gas (LPG).

Table 3.19 Upstream Energy and Emissions of Process Fuels

	Coal	Natural Gas	Distillate Fuel Oil	Gasoline	Diesel	LPG	Residual Oil	Petroleum Coke
Total Energy (Btu/MMBtu)	22,974	199,510	309,634	309,840	230,070	164,524	133,514	314,688
CO_2 (g/MMBtu)	1,836	12,701	15,993	16,010	18,727	11,766	11,105	22,809
CH_4 (g/MMBtu)	148	224	118	118	118	183	104.333	136.396
N_2O (g/MMBtu)	0.037	0.354	3.950	3.950	0.314	0.268	0.184	0.501

Energy and emissions from electricity are the sum of emissions from the fuels used to generate power. Energy sources for electricity production are taken from the GREET Fuel Cycle Model. Table 3.20 represents the mix of energy sources for electricity generation among U.S Mix, Northeast Power Coordinating Council-NPCC mix (including NY) and Reliability First Corporation-RFC mix (including NJ). The total energy consumption and emission values for electricity production are shown in Table 3.21. Transmission and distribution loss is an input in the GREET Fuel cycle model which users can change in the simulations. Currently the default value is used which is set as 6.5% in the GREET.

Table 3.20 Energy Matrix for Electricity Generation

	U.S. mix	NPCC mix (NY)	RFC mix (NJ)
Residual Oil	0.9%	1.1%	0.3%
Natural Gas	22.7%	41.0%	9.6%
Coal	46.0%	10.3%	59.6%
Nuclear Power	20.3%	30.5%	28.0%
Biomass	0.3%	1.4%	0.1%
Other (Hydro Electric, Wind, and Geothermal Energy)	9.8%	15.7%	15.7%

Table 3.21 Energy and Emission for Electricity Generation

	U.S. (Mix)	NPCC mix(NY)	RFC mix (NJ)
Total Energy (Btu/MMBtu)	2,313,860	1,886,435	2,395,024
CO_2(g/MMBtu)	175,991	93,592	197,106
CH_4(g/MMBtu)	2.630	3.610	2.359
N_2O(g/MMBtu)	2.390	0.942	2.866

Chapter 4 Development of LCA Tool

This chapter is to delineate the development of the LCA tool. This discussion includes the framework of LCA tool and, the worksheet categories from the LCA tool are discussed.

4.1 Goal and Scope

The goal of developing the LCA tool is to carry out quantitative assessment of environmental impacts for the LCA stages in the pavement life cycle- raw material extraction, plant production, construction and maintenance. An excel based tool, Pavement Project Energy and Emission Calculator (PPEEC) has been developed to facilitate the quantification of energy consumption and GHG emission of pavement project life cycle based on the user input. Furthermore, the tool reports a database of life cycle inventory values from pertinent studies.

The tool presented in this paper is intended to give airport agencies a highly customizable tool to assist them in quantitatively assessing the total environmental footprint of their procedures, strategies and decisions regarding the construction and maintenance airfield pavements at project level.

The tool enables the user to assess the environmental impacts and resources consumption of alternative solutions for pavement design and maintenance throughout the different phases of life cycle.

The system boundaries of the proposed pavement LCA model entails six pavement life cycle phases, modeled through individual but interconnected modules. The LCA phases included are: (1) extraction of materials and production, consisting of the acquisition and processing of raw materials and the mixing process of HMA mixtures in plants; (2) construction and M&R, including all construction and M&R procedures and related construction equipment usage; (3) transportation of materials, accounting for the transportation of materials to and from the construction site and between intermediate facilities (e.g. transportation of aggregates from the quarries to HMA mixing plants).

The pavement system only considers the pavement structure including the subbase, base, wearing course and surface course. The pavement system does not consider draining, lighting, and tack coats.

The pavement system evaluated included upstream (indirect) processes along with combustion (direct) processes. Figure 4.1 summarizes the system boundaries for the study.

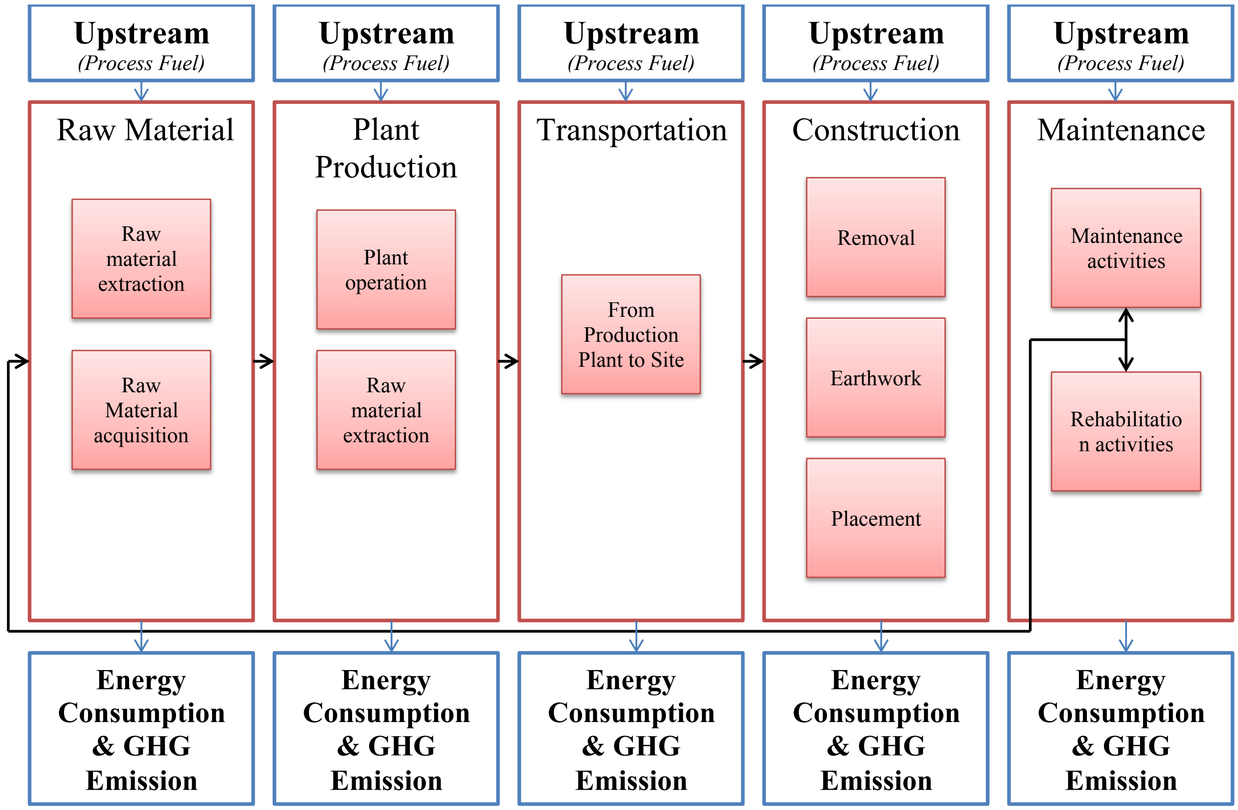


Figure 4.1 System Boundaries for the study

4.2 Framework of LCA Tool

The proposed Pavement Project Energy and Emission Calculator (PPEEC) was developed on Microsoft Excel platform consisting of multiple excel worksheets following the LCA framework. The worksheets have an allocated input area for the user to create an easy to use interactive interface primarily designed for agency decision-makers to benchmark and estimate the energy consumption and emissions. The PPEEC tool also reports all relevant material production energy consumption and emission values as inventory database and its variation. The following section describes the overall framework and architecture of the PPEEC.

The framework for PPEEC tool follows three main life cycle stages relevant to pavements: materials, construction and maintenance. The PPEEC Tool is a collection of spreadsheets and allows for different inputs at a project level, including geometry of the pavement, frequency of maintenance activities, mix design for material, equipment operating rate for construction tasks.

The user first inputs basic geometric information (length, width and thickness) and general life cycle characteristics (construction year, structure, maintenance activities) of the pavement project in the *General Project Information* worksheet. These geometries and characteristics are used throughout the PPEEC to calculate the volume related quantities. The series of worksheets guide the user through the stages of LCA. Each pavement life cycle phase has its own inputs and outputs.

The inputs for PPEEC tool are split into *Primary Inputs* and *Secondary Inputs* that the user can specify; however, they are interrelated. The *Primary Inputs* is the desired inputs at a project level, including geometry of the pavement, frequency of maintenance activities, mix design for material, equipment operating rate for construction tasks. The *Secondary Input* is the advanced input for analyzing the energy consumption and emission value variation among the inventory database from relevant publication sources. It also provides an alternative for the input of user defined unit energy consumption and emission values.

The combustion (direct) and upstream (indirect) CED and GWP results of the pavement LCA are displayed in the Results worksheet and Summary Report worksheet which has numerical and graphical representation.

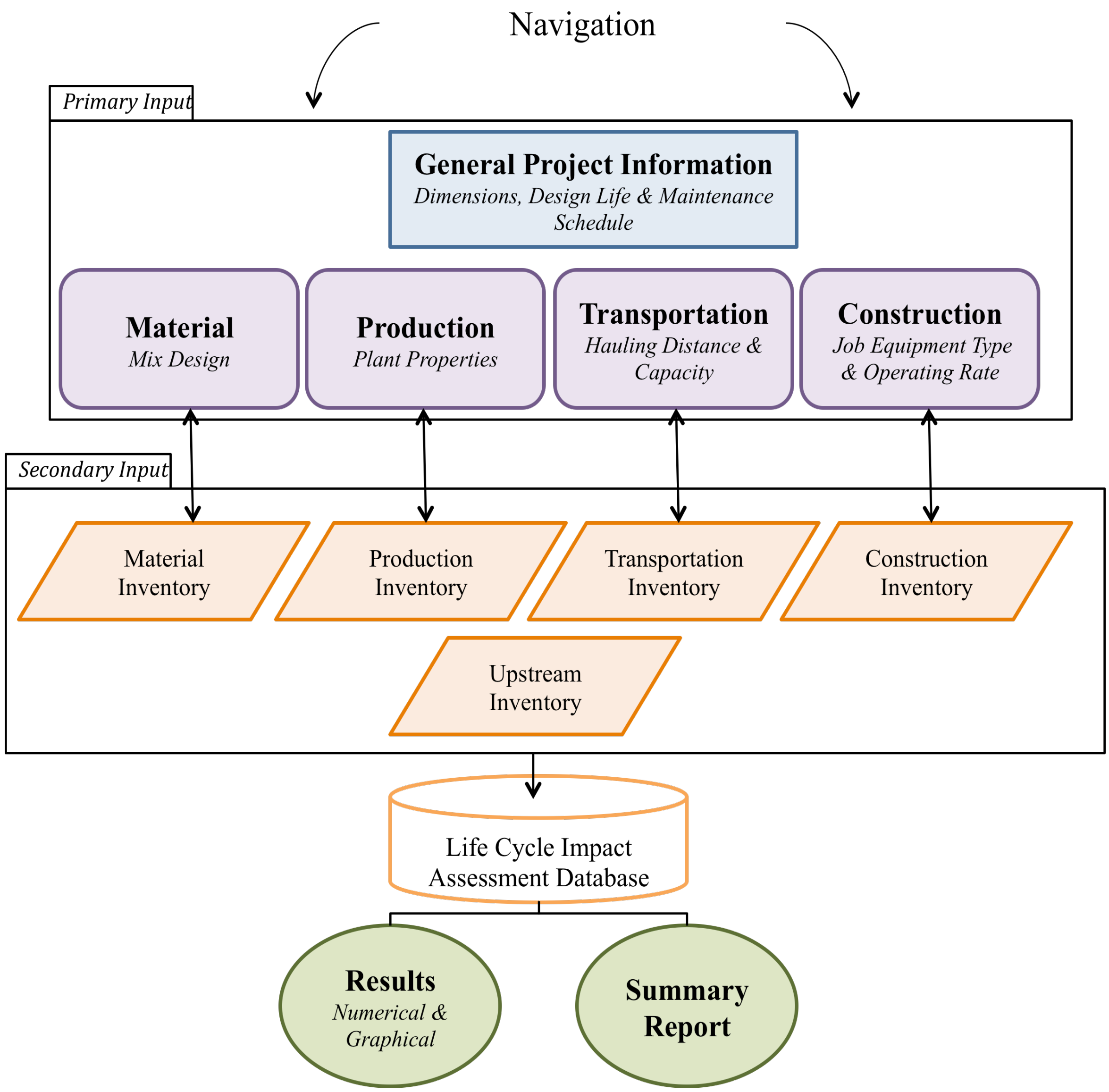


Figure 4.2 System Architecture

4.3 Worksheet Categories

The PPEEC consist of thirteen worksheets as shown in Table 4.1. The input parts of the worksheets are interactive to the user, and other supporting parts of the worksheet are ready-only for the user.

Table 4.1 Worksheet categories for the PPEEC tool

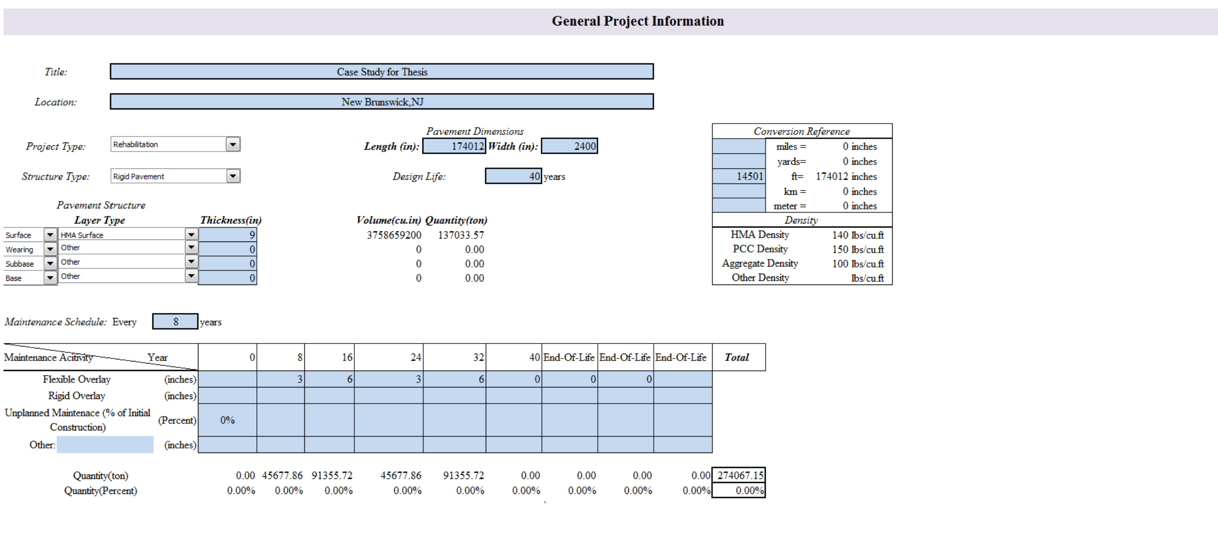
Worksheet	**Primary Input**	**Secondary Input**
General Project Information	Project Title, Location, Project Type, Design Life, Pavement Structure Dimensions, Maintenance Schedule and Activity	
Material	Mix Design	
Production	Plant Production Type	Plant Properties: Ambient Temperature, Heating Temperature, % Moisture Content
Transportation	Capacity of Truck, Distance to & From site, Operating Speed of Truck	
Construction	Equipment type based on HP, Operating Quantity, Operating Rate	
Results	-	-
Reports	-	-
Material Inventory		Select Relevant Publication Source from Inventory Database, User Defined unit energy consumption

		and emission values
Production Inventory		Select Relevant Publication Source from Inventory Database, User Defined unit energy consumption and emission values
Transportation Inventory	-	-
Construction Inventory	-	-
Upstream Inventory		Energy Matrix for Materials and Plant Production

The PPEEC Tool desires inputs at a project level, including geometry of the pavement, frequency of maintenance activities, mix design for material, equipment operating rate for construction tasks etc. which are termed as *Primary Inputs.* These Primary Inputs correspond to the following worksheets:

General Info Worksheet

The *General Project Information* worksheet (Figure) functions as the main input for the tool and the user can enter basic geometric information and general life cycle characteristics of the pavement project. These inputs include the title and location, project type, pavement dimensions, layer type and thickness, maintenance schedule and activities. The maintenance activities only consider flexible overlay, rigid Overlay and unplanned maintenance (% impact of initial construction). These geometries and characteristics are used throughout the tool to calculate the volume-related quantities.



General Project Information

Title: Case Study for Thesis

Location: New Brunswick,NJ

Project Type: Rehabilitation

Structure Type: Rigid Pavement

Pavement Dimensions

Length (in): 174012 **Width (in):** 2400

Design Life: 40 years

Conversion Reference		
	miles =	0 inches
	yards=	0 inches
14501	ft=	174012 inches
	km =	0 inches
	meter =	0 inches

Density	
HMA Density	140 lbs/cu.ft
PCC Density	150 lbs/cu.ft
Aggregate Density	100 lbs/cu.ft
Other Density	lbs/cu.ft

Pavement Structure

	Layer Type	Thickness(in)	Volume(cu.in)	Quantity(ton)
Surface	HMA Surface	9	3758659200	137033.57
Wearing	Other	0	0	0.00
Subbase	Other	0	0	0.00
Base	Other	0	0	0.00

Maintenance Schedule: Every 8 years

Maintenance Acitivity / Year		0	8	16	24	32	40	End-Of-Life	End-Of-Life	End-Of-Life	*Total*
Flexible Overlay	(inches)		3	6	3	6	0	0	0		
Rigid Overlay	(inches)										
Unplanned Maintenace (% of Initial Construction)	(Percent)	0%									
Other:	(inches)										
Quantity(ton)		0.00	45677.86	91355.72	45677.86	91355.72	0.00	0.00	0.00	0.00	274067.15
Quantity(Percent)		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Figure 4.3 General Info Worksheet

Materials Worksheet

The *Materials* worksheet (Figure) is associated with raw material extraction phase. For each layer in the pavement structure, the user can specify the mix design (percentage by weight or tonnage) for the respective material type. Raw materials included in the worksheet are asphalt bitumen, polymer additive, emulsion additive, cement, slag, steel, sealant, fine aggregate, coarse aggregate and recycled asphalt pavement (RAP). The user defined input helps analyze the effect of using different mix designs for material selection in projects. This allows users to quantify the impacts of sustainable practices like using RAP and slag cement. The *Materials* worksheet has separate mix design inputs for initial construction and maintenance.

Material Energy consumption and Emission

Summary

Initial Construction

Energy (MJ)			GHG(t CO2 eq.)		Total GHG(t CO2 eq.)
Upstream	Combustion	Total Energy(MJ)	Upstream	Combustion	
1.60E+07	4.41E+07	6.01E+07	1022.74	3309.14	4331.88

Maintenance

Energy (MJ)			GHG(t CO2 eq.)		Total GHG(t CO2 eq.)
Upstream	Combustion	Total Energy(MJ)	Upstream	Combustion	
2.20E+07	6.24E+07	8.44E+07	1426.01	4725.81	6151.82

Initial Construction

1.)

Surface

Energy (MJ)			GHG(t CO2 eq.)		
Upstream	Combustion	Total Energy(MJ)	Upstream	Combustion	GHG(t CO2 eq.)
1.60E+07	4.41E+07	6.01E+07	1022.74	3309.14	4331.88

HMA Surface

Material Mix Design			*Energy Consumption and Emission*					
Material	Mix Design (% by weight)	Quantity (ton)	Energy (MJ)		Total Energy(MJ)	GHG(t CO2 eq.)		Total GHG(t CO2 eq.)
			Upstream	Combustion		Upstream	Combustion	
Asphalt Bitumen	5.10%	6988.71	1.24E+07	4.06E+07	5.30E+07	868.44	3228.79	4097.23
Polymer Additive	0.00%	0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Emulsion Additive	0.00%	0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Cement	0.00%	0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Slag	0.00%	0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Steel		0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Sealant		0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Fine Aggregate	56.50%	77423.97	1.99E+06	1.80E+06	3.79E+06	84.70	5.64	90.34
Coarse Aggregate	38.40%	52620.89	1.59E+06	1.68E+06	3.27E+06	69.59	74.72	144.31
RAP		0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Total	100.00%	137033.57	1.60E+07	4.41E+07	6.01E+07	1022.74	3309.14	4331.88

2.)

Wearing

Energy (MJ)			GHG(t CO2 eq.)		
Upstream	Combustion	Total Energy(MJ)	Upstream	Combustion	GHG(t CO2 eq.)
0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00

Other

Material Mix Design			*Energy Consumption and Emission*					
Material	Mix Design (% by weight)	Quantity (ton)	Energy (MJ)		Total Energy(MJ)	GHG(t CO2 eq.)		Total GHG(t CO2 eq.)
			Upstream	Combustion		Upstream	Combustion	
Asphalt Bitumen	4.90%	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Polymer Additive	3.70%	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Emulsion Additive		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cement		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Slag		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Steel		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sealant		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fine Aggregate	56.30%	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Coarse Aggregate	38.40%	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RAP		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	1.033	0	0	0	0	0	0	0

Figure 4.4 Materials Worksheet

Production Worksheet

The *Production worksheet* (Figure) lets the user select plant production operations like hot-mix asphalt, cement concrete, user defined HMA/WMA, and user defined HMA with RAP. If the user-defined alternatives are chosen, the user has to input plant parameters like ambient temperature, heating temperature, and moisture content. The *Production* worksheet is also split into initial construction and maintenance.

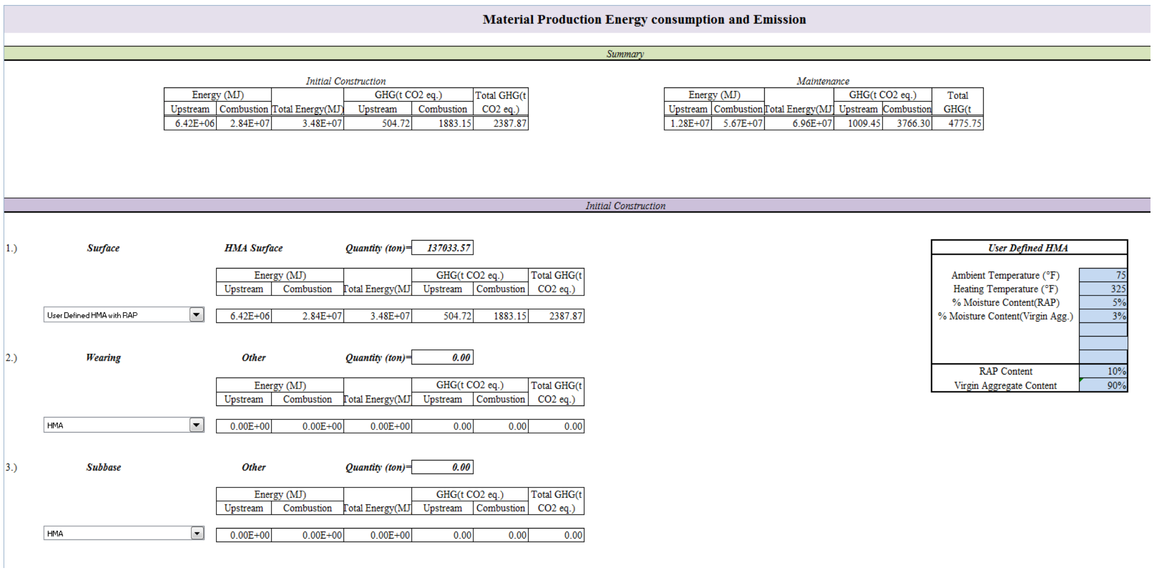


Figure 4.5 Production Worksheet

Transportation Worksheet

The Transportation Worksheet (Figure) relates to the transportation of paving material from the plant to the job site. For each layer, the user has to input properties like capacity of truck, distance to and from site and operating speed of truck.

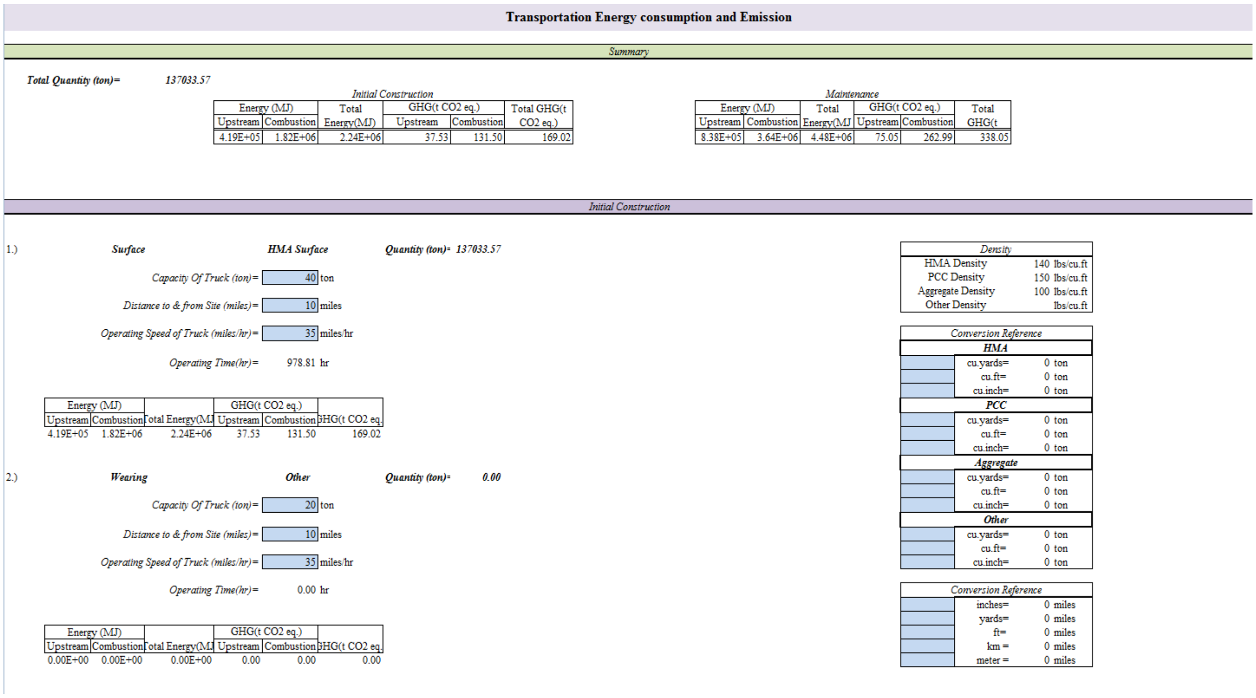


Figure 4.6 Transportation Worksheet

Construction Worksheet

The *Construction Worksheet* (Figure) corresponds to the construction activity for initial construction and maintenance. For each construction activity (e.g. paving, milling, rolling, grooving etc.), the user has to select the equipment type based on horse power (HP), specify the operating quantity for a selected unit (e.g. ton, sq. ft, cu. ft etc.) and the operating rate for the selected unit per hour (e.g. ton/hr, sq. ft/hr, cu. ft/hr etc.).

Material Inventory Worksheet

The *material inventory* worksheet reports inventory database for energy consumption and emission values collected from relevant published sources. Raw materials included are asphalt bitumen, polymer additive, emulsion additive, cement, slag, steel, joint sealant, fine aggregate, and coarse aggregate. By default setting the recommended values (sources with an asterisk (*) mark) are selected. However, the user is allowed to choose any energy consumption and emission value from the inventory database source for any corresponding material. The user can also enter 'user defined' unit energy consumption and emission values from any relevant source outside the database.

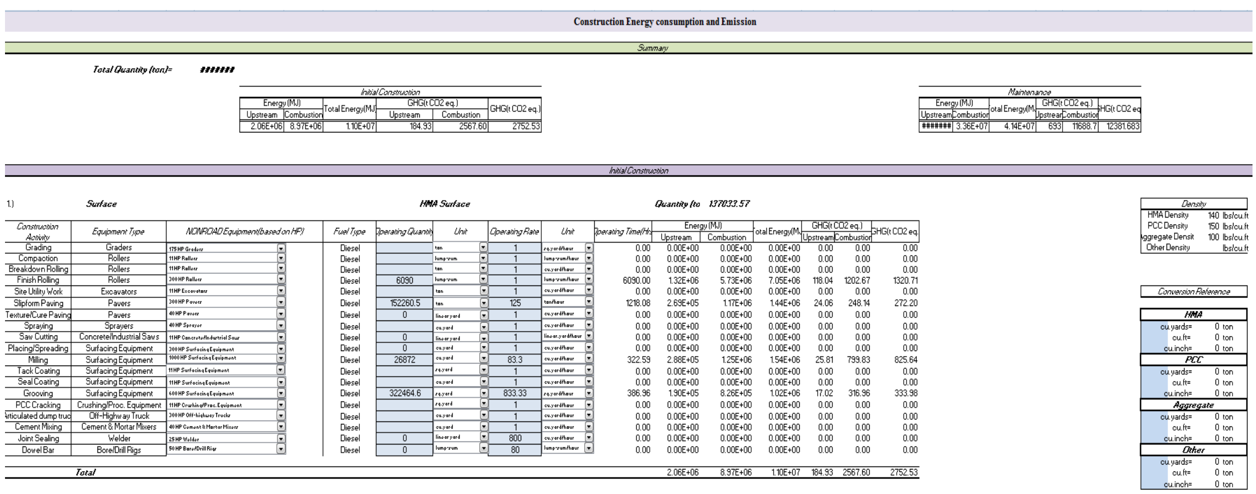


Figure 4.7 Construction Worksheet

Production Inventory Worksheet

The *production inventory* worksheet reports inventory database for energy consumption values and emission values collected from relevant published sources. Production plant includes HMA plant and cement concrete plant. By default setting the recommended values (sources with an asterisk (*) mark) are selected. However, the user is allowed to choose any energy consumption and emission value from the inventory database source for any corresponding production plant. The user can also enter 'user defined' unit energy consumption and emission values from any relevant source outside the database.

Transportation Inventory Worksheet

The *transportation inventory* worksheet reports inventory database for energy consumption values and emission values for truck transportation based on NONROAD model as discussed in section 5.3.2

Construction Inventory Worksheet

The *construction inventory* worksheet reports inventory database for energy consumption values and emission values for seventeen different construction equipments (Table 3.16) obtained from NONROAD model based on equipment type and horse power as discussed in section 5.3.2

Upstream Worksheet

The *upstream inventory* worksheet reports inventory database for energy consumption values and emission values for all phases of material, production transportation and construction. The upstream energy and emissions of process fuel and electricity (Table 3.19, 3.20) are extracted from GREET. The energy usage profile for raw material and plant production process of PCC and HMA (Table 5.3) from various sources are listed, which can be changed by the user.

Results Worksheet

Calculations are performed in hidden formulas across the tool but the Results worksheet summarizes the energy consumption and GHG emissions across the life cycle phases. Furthermore, it also variation among different inventory database values for the material and production stages. Based on the user input the impacts are linked to the unit process from the inventory database and then, using the tool, the impacts are consequently summed at different phases and levels.

Reports Worksheet

The reports worksheet provides the user with a printable format of the results. This worksheet is intended for agencies and decision makers to summarize the results at various phases of LCA at the pavement project level. The benefits of report worksheet are that it provides an overview of the LCA for the pavement projects; the generated reports for different structures, materials, and construction and maintenance options can be easily compared and benchmarked.

4.4 Inventory Values and Impact Assessment

Available literature includes various sets of data sources for the various materials, representing different geographic conditions, procedures, technologies and system boundaries. Ideally, these data should be checked for representativeness (technological, geographical and time related), completeness (regarding impact category coverage in the inventory), precision/uncertainty (of the collected remodeled inventory data), and methodological appropriateness and consistency. However, the literature sources do not always describe all the processes accounted for in the cradle-to-gate LCI of some materials. This introduces difficulties in assessing whether the system boundaries associated with available data fully match the goal and scope.

The environmental indicators are used in the tool: energy consumption and GHG emissions (GWP from greenhouse gases: Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O)). Most of the data are from existing up-to-dated studies, and certain indicators are calculated according to proper methodology. One advantage of this tool is the use of different environmental indicators for various relevant sources. The LCI data available from various relevant sources helps the user access the variation in environmental impact of pavement projects for the phases of material production and plant processing. Because of the highly customizable nature throughout the various modules of the tool, the user is not constrained to predefined conditions and assumptions. The tool allows the user to choose from different materials, structures, construction techniques and maintenance plans. Further, the user has an option to input ‘user defined’ inventory values or choose from the listed inventory data sources, which makes the life cycle analysis more relevant to the goal and scope of the respective pavement project.

Chapter 5 Case Studies on Pavement Design Alternatives

The energy consumption and GHG emission for airport pavement design alternatives were performed using the PPEEC Tool with the LCI database as discussed in the previous chapters.

5.1 Background

Runway 13R-31L at John F. Kennedy (JFK) International Airport was originally constructed during the 1940s. The current runway is 14,511-feet long and 150 feet wide. It is the second-longest commercial runway in North America. The original pavement section was 12-inch Portland cement concrete (PCC) on 6-inch crushed stone screenings. During the 1970s, the runway was overlaid with hot-mix asphalt (HMA). Over the years, the runway has been overlaid number of times and as a result, there was 16-inch HMA on top of the original PCC surface.

The aim of reconstruction/rehabilitation project at JFK airport was primarily to increase the airport capacity to accommodate new large aircrafts in Group VI in general and the A-380 specifically. Based on the studies conducted by the Port Authority of New York and New Jersey (PANYNJ) and discussions with the FAA, a number of required airfield modifications were identified including widening Runway 13R-31L from 150 feet to 200 feet. Another development that would impact the project scope was the significant growth in air traffic operations at JFK airport starting in 2005, which leads to additional regional airport delays. In response, the JFK Delay Reduction Program was developed for moving aircraft to and from the runways more efficiently. Runway 13R-31L taxiway entrance and exit modifications and relocated runway thresholds were included. The scope of the rehabilitation and widening project changed again to include delay reduction program components.

A constructability study was performed in 2007 for two rehabilitation design alternatives: one is 9-inch thick HMA overlay with milling and overlays scheduled every eight years; and the other one is 18-inch PCC with minor concrete repair every eight years. An in-house life-cycle cost analysis was conducted by the PANYNJ using a discount rate of 3.5% and 40-year analysis period. The results indicate that the initial cost for the HMA rehabilitation was 3% cheaper than the PCC reconstruction, but the life-cycle cost for the PCC construction was 35% cheaper than the HMA rehabilitation. In order to consider the effect of noneconomic factors such as sustainability metrics, the energy and environmental impact of materials, equipment, and processes need to be assessed for different pavement design alternatives.

The objective of this case study is to quantify energy and environmental impact of asphalt and concrete runway pavements using LCA. The design alternatives include runway rehabilitation/reconstruction designs considered in the constructability study at the JFK airport and new runway surface layer designs conducted using the FAA pavement design methodology. Life-cycle inventory data were compiled from literature and field surveys to contractors. The data variations in the material-related energy and emission rates were considered for sensitivity analysis. The impact assessment focused on the cumulative energy demand (CED) and greenhouse gas (GHG) emission in the material, construction, and maintenance phases of pavement life-cycle. Both direct energy consumption and GHG emission and their corresponding upstream components related to process fuels were considered in the impact assessment. The study results can be used for decision making among different runway pavement design and rehabilitation alternatives.

Figure 5.1 JFK Airport Runway 13R-31L at New York

5.2 Goal and Scope

This case study follows the basic steps of life cycle assessment: goal definition and scope, inventory analysis, impact assessment and interpretation (ISO 14044, 2006). The goal is to quantify energy consumption and environmental impacts of airport pavement design alternatives. The study scope includes design alternatives for both new pavement design and pavement overlays on existing runway pavements. The pavement structures considered include the surface layer constructed with Portland cement concrete or asphalt concrete over base layers or existing pavement layers. The function unit is defined as one-mile runway with 200-ft width that is designed to carry the aircraft traffic mix in the analysis period at the major hub airport. The system boundary covers the material, construction and maintenance stages of the pavement life cycle. The end-of-life stage was not considered here due to the complexity involved between different pavement types. Concrete runway pavements are usually left in place as base layer for new overlays; while asphalt runway pavements are removed and used as base or sub-base material at other areas of airfield.

The inventory analysis is limited to energy consumption and greenhouse gas emissions (GHG); as a result, the impact assessment determines the cumulative energy demand (CED) and global warming potential (GWP) of the GHG emissions based on their relative contribution. The greenhouse gases considered in this study include Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O). The GWP of a greenhouse gas is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas (IPCC, 2007). The CO_2 was used as reference gas in this study, and the GWP weighted emissions were measured in CO_2 equivalent (CO_2 Eq.) using the GWP equivalency factors.

The unit inventory data for material-related energy consumption and GHG emission were extracted from up-to-dated articles and research papers and the uncertainty of data sources were analyzed. Contractor survey and field observations were conducted to obtain the operation efficiency of construction equipment for runway construction. Direct energy consumptions and GHG Emissions were obtained from fuel combustion and electricity consumption for various material acquisition and process operations in the system boundary. Consideration of energy and emissions associated with the production of process fuels and electricity in the upstream process was included to account for the indirect energy consumption and GHG emission.

5.3 Life Cycle Inventory

5.3.1 Material Acquisition and Production

In order to quantify energy consumption and emission of pavement, the first step is to determine the material components and manufacturing processes for each material or process in the pavement life- cycle. Materials are obtained in raw forms and then manufactured to the final form as required by the construction demand. For the asphalt concrete (AC) pavement and jointed plain concrete pavement (JPCP) considered in this study, raw materials contain asphalt, cement, aggregate, slag cement, polymer additive, and steel (dowel bar in JPCP).

Manufacturing of material includes handling, drying, mixing and preparation of materials for placement, such as production of hot-mix asphalt (HMA) and cement concrete. The manufactured material will then be transported to the construction site for placement. Placement of materials depends on types of construction requirement on the project site and it is accomplished using different types of equipment.

In this study, life inventory data of raw material and manufacturing process were collected from published reports from literature. Although multiple data sources are available for life-cycle inventory data of typical construction materials and processes for pavements, discrepancies may exit due to different geographic locations, technologies, and system boundaries. To address this, baseline analysis was conducted using the inventory data identified as the most appropriate for this analysis. The inventory data used in the baseline analysis were selected from the previous studies conducted in U.S. as compared to a relatively larger set of inventory data reported by European researchers. The extreme ranges of inventory data (minimum and maximum values) reported in the literature were also used in the analysis to investigate the sensitivity of analysis results to the variation of inventory data.

Table 5.1 lists the material-related life-cycle inventory data with references from various data sources including the baseline values based on the studies conducted in U.S., respectively, for energy consumption and GHG emission values.

Table 5.1 Material-Related Life-Cycle Inventory for Asphalt and Concrete Pavements

(LCI references are shown in parenthesis)

Material / Process	Baseline Value		
	LCI Source	Energy Consumption (MJ/t)	Emissions CO_2 eq. (kg/t)
Asphalt Binder	*(Yang,2014)*	5,810	462
Portland Cement	*(PCA,2006)*	4,340	928
Sand or Gravel	*(PCA,2006)*	21	0.073
Crushed Stone	*(PCA,2006)*	32	1.42
Steel	*(GREET Vehicle Cycle Model,2013)*	21,500	1496
Polymer Additive	*(Eurobitume,2012)*	76,742	3715
Slag Cement	*(PCA,2006)*	643.8	7.42
HMA Manufacturing	*(NHCRP 9-47A, 2014)*	266	16.4
PCC Manufacturing	*(PCA,2006)*	18	0.72

Material / Process	Other LCI Data from Literature		
	LCI Sources	Energy Consumption (MJ/t)	Emissions CO_2 eq. (kg/t)
Asphalt Binder	*(VTT,1996); (IVL,2001); (Athena,2006);*	6000; 3634; 5812; 3980	330; 173; 377; 244

	(Eurobitume,2012)		
Portland Cement	*(VTT,1996); (IVL,2001); (Athena,2006)*	5350; 4776; 5232	799; 806; 670
Sand or Gravel	*(VTT,1996); (IVL,2001); (Athena,2006)*	24 ; 6 ; 70	1.74 ; 0.073 ; 6.1
Crushed Stone	*(VTT,1996); (IVL,2001); (Athena,2006)*	52 ; 38 ; 70	2.0 ; 1.42; 6.1
Steel	*(IVL,2001);(Athena,2006)*	21,800; 11,300	2220; 565
Polymer Additive	*(IVL,2000); (CEREA,2010)*	85,730 ; 71710	1100; 1837
HMA Manufacturing	*(IVL,2001);(Athena,2006); (EPA-AP 42,2010)*	485 ; 432 ; N/A	34.8 ; 21.9 ; 15.1
PCC Manufacturing	*(IVL,2001); (Choate-DOE,2003); (Athena,2006)*	40 ; 56; 110	1.67 ; 9.54; 7.70

5.3.2 Transportation and Construction

There are three transport stages in the pavement life-cycle: 1) transportation of raw materials from extraction site to processing facility, such as transport of crude oil to refinery; 2) transportation of processed material to manufacturing plant, such as transport of asphalt from refinery to the hot-mix asphalt plant, 3) transportation of manufactured material from production site to construction site. The first two transport stages were included in the life-cycle inventory of raw material or manufacturing process in most studies. Therefore, only transportation of hot-mix asphalt or cement concrete from the plant to the job site was separately considered. The transportation of milled material from the existing asphalt pavement was negligible because the design allowed for reuse of the removed pavement as subbase materials for new taxiways instead of trucking it off site for recycling or disposal.

In the construction phase, the environmental burdens are due to the combustion-related emissions from construction equipment usage. The NONROAD (nonroad engines, equipment, and vehicles) 2008 model developed by Environment Protection Agency (EPA) was used to calculate CO_2 emission (in g/hour) for off-road equipment by its function, horsepower, and fuel type (EPA, Users' Guide for the Final NONROAD2005 Model,2005). Since NONROAD cannot directly provide energy consumption, the energy consumption was calculated based on the heating value of diesel fuel and the emission factors for CO_2, as shown in Equation 5.1 (EPA, Direct Emissions from Mobile Combustion Sources,2005; EPA, Development of Emission Rates for Heavy-Duty Vehicles in the MOVES2010, 2012). After the energy consumption rate is known, the emission rates for CH_4 and N_2O can be obtained in as similar way using Equation 5.1.

$$r_{energy} = r_{emission} \times \frac{HV}{f(emission)} \tag{5.1}$$

Where, r_{energy} is energy rate in MJ/hour;

$r_{emission}$ is emission rate in g/hour (obtained from NONROAD for CO_2, but solved for CH_4 and N_2O after energy rate is known);

HV is heating value, 138.451 MJ/gallon for diesel fuel; and

$f(emission)$ is fuel-specific emission factor for CO_2, CH_4, or N_2O in g/gallon.

In order to calculate the energy consumption and emissions generated in the construction process, contractor surveys and field observations were conducted to determine the productivity for each type of equipment and operation hours of equipment can be calculated based on the total tonnage or volume of material that is needed to construct one-mile runway with 200-ft width. Table 5.2 summarizes the construction activities with the equipment used, horsepower rating, and operation efficiency.

5.3.3 Consideration of Upstream Components

The overall environmental impact of a process depends on both the combustion (direct) energy and emissions for operating equipment and vehicles, and the upstream energy requirements for producing and delivering the energy source. The upstream (indirect) emissions are generated from processing fuel consumed during various processes from material extraction to construction. Energy is required to produce fuels and electricity used in the downstream processes. Therefore, in addition to the energy use and emission of direct use of fuels and electricity, the energy and emissions associated with the production of these fuels and electricity were considered in the analysis.

Table 5.2 Construction Equipment and Operation Efficiency for Pavement Construction

Construction activity		Equipment	Horsepower (hp) rating	Productivity
HMA	Paving	Vogele Super 2100-2	250	1,500-2,000 tons/12 hours
	Rolling compaction	HAMM HD+140	155	Same as paving (5-10 passes)
PCC	Front Paver (Placer/Spreader)	GOMACO PS-2600	275	275 yards/hour
	Middle Paver (Slip Form Paver)	GOMACO GP-4000	440	275 yards/hour
	Back Finishing Paver (Texture/Cure)	GOMACO TC-600	60	275 yards/hour
	Concrete Saw cutting	Edco SS-26 31D	31	8000 linear feet/10 hours
	Drilling Dowel Bar	EZ Drill 210B-4	20	800 bars/10 hours
	Joint Sealant		10	8000 linear ft./10 hours
General	Milling	Wirtgen 250i	990	1000 cubic yards/12 hours shift
	Grooving	Lincon Electric 10,000 Plus	23	10,000 square yards/ 12 hours
	Articulated Dump Truck	Caterpillar 740	445	40-ton capacity

To incorporate the upstream (indirect) values, the GREET 2013 model developed by Argonne National Laboratory was used. The GREET model is a life-cycle modeling tool to evaluate the impact of fuel use including all fuel production processes from oil exploration to fuel use (from well to wheels) (Wang M.Q.,1999) For process fuels such as coal, natural gas, gasoline, fuel oil, liquefied petroleum gases (LPG), etc., upstream values can be extracted for each specific fuel type. The mix of energy source for production of electricity was obtained for the northeast states of U.S. from the fuel cycle model in GREET and used to calculate the upstream values for electricity. Table 5.3 lists the energy usage profile for production of raw materials and manufacturing processes of PCC and HMA as reported by different literature sources. The process fuel used for transportation and construction can be directly determined from the fuel type used by the specific transport vehicle and construction equipment.

Table 5.3 Energy Usage Profiles for Production of Raw Materials and Manufacturing Processes of PCC and HMA

Process fuels	Asphalt	Cement	Sand	Crushed Stone	Steel	Slag Cement	Polymer	HMA plant	PCC plant
(Source)	*(DOE,2004)*	*(PCA, 2007)*	*(PCA, 2007)*	*(PCA, 2007)*	*(GREET 2, 2013)*	*(Marceau et al.,2003)*	*(Eurobitume , 2012)*	*(NHCRP 9-47A, 2014)*	*(PCA, 2007)*
Coal	0.04%	56.58%	0	1.89%	1.42%	0	9.75%	0	0
Diesel	0	0	0	0	0	0	0	0	0

Gasoline	1.05%	0.04%	3.41%	3.85%	0.25%	0	0	0	0
LPG	0.51%	0.02%	0	0	0	0	0	0	0
Natural Gas	72.54%	0.85%	6.87%	11.63%	33.2%	77.56%	53.9%	80%	39.3%
Distillate Fuel Oil	0.15%	3.45%	39.1%	42.40%	0	0.09%	36.35%	20%	26.2%
Petroleum Coke	18.39%	18.12%	0	0	18.4%	0	0	0	0
Residual Oil	0.47%	0.09%	9.46%	7.11%	2.23%	0	0	0	0
Nuclear Power	0	9.26%	0	0	0	0	0	0	0
Electricity	4.25%	11.58%	41.2%	33.1%	17.8%	22.35%	0	0	34.5%

The calculation of upstream energy consumption and emission for a particular material or process can be shown in Equation 5.2, where the unit upstream energy consumption and GHG emission extracted from the GREET 2013 model are then multiplied with the energy usage profile of process fuels and electricity.

$$UEE = \sum_{i=1}^{n} CE \cdot PE_i \cdot UEE_i \tag{5.2}$$

Where,

UEE = Upstream energy consumption (BTU/ton) or emission (g/ton);

CE = Combustion energy (MMBTU/ton);

PE_i = Percent of the i th type of energy in the energy matrix;

UEE_i = Upstream energy consumption (BTU/MMBTU) or emission (g/MMBTU) for the i th type of energy (calculated from GREET);

i = Type of energy including coal, diesel, gasoline, liquefied petroleum gas, natural gas, distillate oil, petroleum coke, residual oil, and electricity; and

n = Total number of energy type.

5.4 Runway Pavement Design Alternatives

5.4.1 Pavement Rehabilitation Design Alternatives

Since differences in properties of asphalt concrete and cement concrete can have strong influences on pavement structure design and quantities of material usage, it is critical to conduct LCA of different pavement types with the same performance standard. In an early study sponsored by FAA in 2004, field data collected from 30 airports in U.S. concluded that flexible and rigid pavements designed based on FAA standards have structure condition index (SCI) values at or above 80 after 20 years. While the structural performance of flexible and rigid pavements was found comparable, differences in functional performance was noted (Garg et al.2004).

In this study, the two design alternatives for resurfacing runway 13R-31L at JFK airport was based on the analysis of existing pavement condition data and the past experience of PANYNJ, as shown in Table 4. Each design alternative is expected to sustain the desired performance level over the runway's life cycle although they varied significantly due to consideration of pavement life and rehabilitation needs. The PANYNJ's experience with asphalt surfaced runway was no longer lasting over 10 years before rehabilitation was required. Hence, the asphalt pavement was designed to require significant overlay treatments every eight years in the 40-year design life. On the other hand, only concrete repair was required for concrete pavements every eight years.

Table 5.4 Design Alternatives for Resurfacing Runway Pavement

Stage	Year	Rigid Overlay	Flexible Overlay
Initial Construction	1	Milling 6-inch asphalt + overlay 2-inch asphalt	Milling 3-inch asphalt
	1	18-inch Concrete Overlay	9-inch Asphalt Overlay
Maintenance	8	Concrete Repair	Milling 3-inch + overlay 4-inch asphalt
	16	Concrete Repair	Milling 6-inch + overlay 7-inch asphalt
	24	Concrete Repair	Milling 3-inch + overlay 4-inch asphalt
	32	Concrete Repair	Milling 6-inch + overlay 7-inch asphalt

5.4.2 New Pavement Design Alternatives

In addition to overlay design, a series of typical new pavement designs were conducted using the aircraft traffic mix at JFK airport, respectively, for asphalt and concrete pavements. The design procedure outlined in FAA Advisory Circular 150/5320-6E is used for new pavement design using the FAA Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD) software (FAA, Advisory circular 150/5320-6E 2009).

In the FAARFIELD, mechanistic-empirical design correlates critical pavement stresses and strains to empirical performance models. Although the fatigue damage at the bottom of asphalt surface layer can be calculated, the design control criteria is subgrade rutting caused by the vertical compressive strain on top of subgrade. For rigid pavements, failure is caused by the fatigue cracking affected by the ratio of tensile stress to the flexural strength of concrete. The pavement thickness was designed to have the cumulative damage factor (CDF) equal to one at the end of design life. It is noted that in the FAARFIELD, the elastic modulus of asphalt surface layer is set at 200,000 psi and the modulus of PCC layer is fixed at 4,000,000 psi. The flexural strength of PCC can be set in the range of 500 to 800 psi.

The runway pavement surface layers were designed over the crushed stone base layer and the plant mix macadam layer with difference thickness combinations following the design practice used by the PANYNJ. It is noted that the asphalt surface layer is designed with the surface layer (P-401 material based on FAA designation) with 200,000-psi modulus and asphalt stabilized base layer (P-403 material based on FAA designation) with 400,000-psi modulus based on the recommendation from FAA Advisory Circular 150/5320-6E. Table 5.5 shows the design thickness of new runway pavement structure, respectively, for asphalt and concrete surface layer.

Table 5.5 Design Alternatives for New Runway Pavement

Layer	HMA Pavement	PCC Pavement
Surface	9-inch HMA	20-inch PCC
Base	12-inch plant mix macadam	4-inch plant mix macadam
Subbase	14-inch crushed stone (P-209)	6-inch crushed stone (P-209)

5.5 Results and Analysis

5.5.1 Comparison between Different Pavement Materials

The material-related energy consumption and GHG emission were shown in Table 5.6, respectively, for combustion and upstream components of each raw material and manufacturing process (plant operation for producing mixtures). The analysis was conducted using the standard mixture designs that were used at airfield pavements by the PANYNJ and the baseline values in the life-cycle inventory database. The combustion (direct) values are generated in the processes for raw material acquisition and manufacturing process; while the upstream values are related to the type and quantify of process fuel that is consumed in the combustion process. The results show that the upstream components play significantly to the total environmental burdens, although the exact values of upstream components vary depending on the percentage of process fuel and electricity.

Table 5.6 Material-Related Energy Consumption and GHG Emssion for HMA and PCC

Material / Process		Energy consumption (MJ)		GHG emission (kg CO_2 eq.)	
		Combustion	Upstream	Combustion	Upstream
For each ton of HMA					
Raw material extraction and production	Asphalt *(4.93%)*	286.4 *(48%)*	87.7 *(50%)*	23.7 *(62%)*	6.1 *(51%)*
	Aggregate *(94.7%)*	25.3 *(4%)*	26.1 *(15%)*	0.6 *(2%)*	1.1 *(9%)*
	Polymer *(0.37%)*	283.9 *(48%)*	63.1 *(36%)*	13.7 *(36%)*	4.8 *(40%)*
	Total	595.7	176.9	38	12
HMA manufacturing		245.8	58.9	16.4	4.7
For each ton of PCC					
Raw material extraction and production	Portland cement *(6.11%)*	265 *(87%)*	93 *(68%)*	56.7 *(99%)*	8.2 *(81%)*
	Slag cement *(3.47%)*	17 *(6%)*	17 *(12%)*	0.6 *(1%)*	0.7 *(7%)*
	Aggregate *(58.6%)*	22 *(7%)*	26 *(19%)*	0.03 *(0.1%)*	1.1 *(11%)*
	Water	0	0	0	0

	(31.8%)				
	Total	304	136	57	10
PCC manufacturing		18	17	0.7	0.8

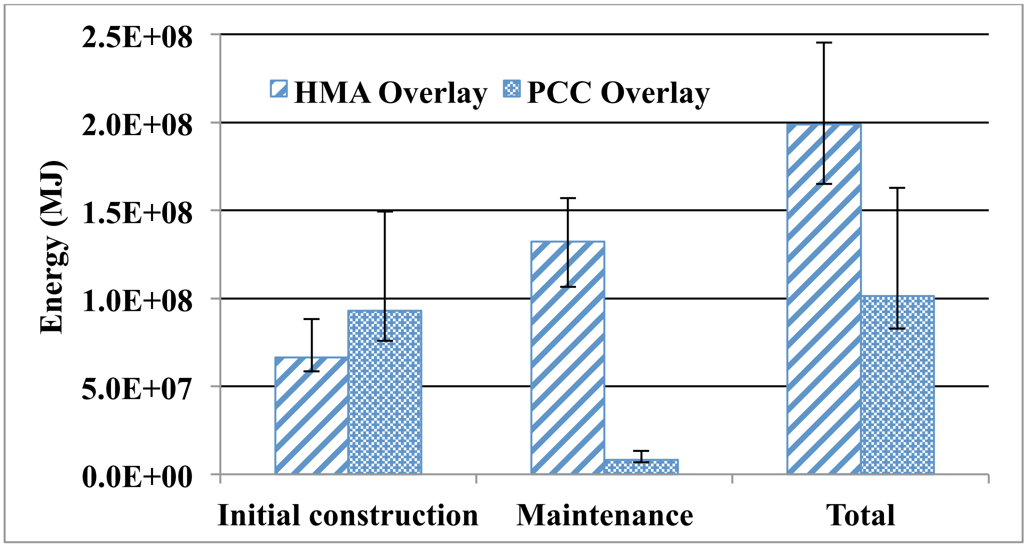
For both hot-mix asphalt and Portland cement concrete, the binding agent (asphalt binder or Portland cement) with small mass percentages has the most significant component in the energy consumption and GHG emission for raw material. The typical process of producing asphalt binder is divided into four stages: crude oil extraction, transport, production in refinery, and storage (Skone,T.J. and K. Gerdes,DOE,2004). The manufacturing process of Portland cement mainly includes quarry and crush, raw meal preparation, pyroprocess, and finishing grind (PCA, 2007). It is noted that Portland cement has roughly the same energy consumption but twice the GHG emission due to the clinker process in cement kilns. On the other hand, aggregates contribute to the total energy consumption and GHG emission in a much less degree as compared to asphalt binder or Portland cement. Aggregates contribute to the total energy consumption in a more significant role as compared to the GHG emission. Crushed aggregate requires mechanical breaking after acquisition or quarrying; while natural aggregates (sand or gravel) are obtained by dredging.

As expected, the manufacturing of HMA consumes much more energy and generates more GHG emission than the production of PCC. Asphalt production includes mixing of asphalt binder, aggregate and other additives at the required temperature, and energy consumption and emission are mainly generated from heating and mixing. The exact amount of heat energy varies depending on the moisture content in the aggregate and the discharge temperature of HMA. On other hand, concrete is produced by mixing cement with fine aggregate (sand), coarse aggregate (crushed stone), and water without heating. This causes much less energy consumption in the concrete plant as compared to the HMA plant. It is noted that energy consumption and GHG emission for steel production are counted separately for concrete pavement. Totally there are 24,000 dowels were used in the joints of concrete slabs, which causes significant amount of environmental burdens that cannot be neglected.

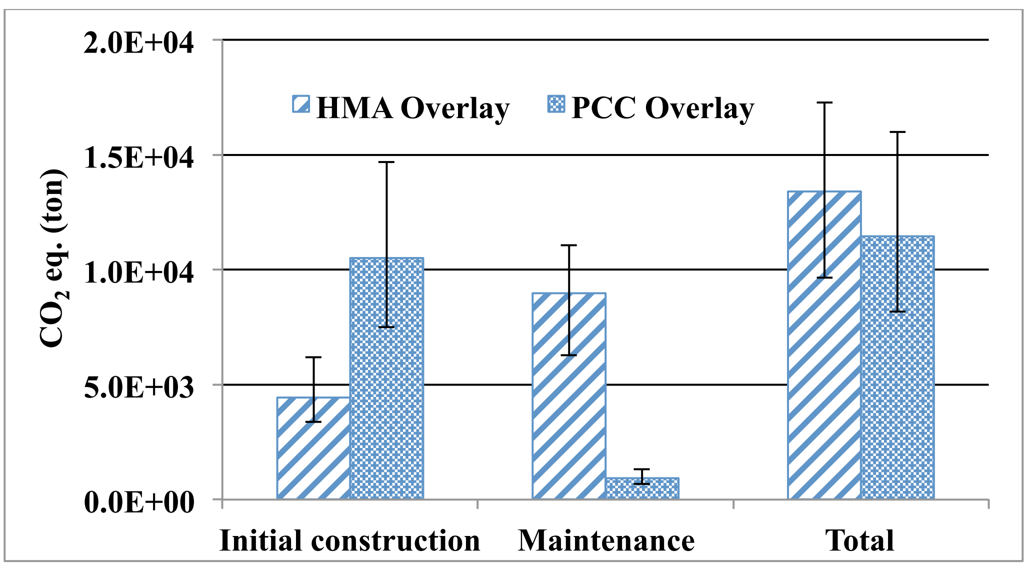
5.5.2 Comparison between Runway Rehabilitation Strategies

Figures 5.1 (a) and (b) compare the environmental impacts of two rehabilitation strategies with HMA and PCC overlays, respectively, for energy consumption and GHG emission. The results using the baseline values in the life-cycle inventory database are show in the column values and the variation of results are displayed in error bars representing the minimum and maximum values. It is noted that this comparison was performed for two rehabilitation strategies in a 40-year analysis period that is different from the pure comparison between HMA and PCC materials. For example, the PCC overlay design includes two-inch asphalt overlay after 6-inch milling of existing asphalt layer.

The results show that the HMA overlay causes greater energy consumption and comparable GHG emission, as compared to the PCC overlay. The similar trend can be observed considering the variations in the inventory data. Maintenance stage constitutes the major component in the life-cycle energy consumption and GHG emission of HMA overlay, although the HMA overlay has less impact during the initial construction stage compared to the PCC overlay.



(a)



(b)

Figure 5.1 Environmental impacts of pavement rehabilitation strategies with HMA and PCC for (a) energy consumption and (b) GHG emission

The percentage distributons of energy consumption and GHG emission at different stages of initial construction were calculated, as shown in Figure 5.2. For both HMA and PCC overlays, the material-related environment impact plays the most significant role in the total energy consumption and GHG emission. The percentages of material-related components (raw material and plant operation) are 89-90% for HMA overlay and 95-99% for PCC overlay. The acquisition and production of raw material consumes 85% of total energy and generates 95% of total GHG emission for PCC overlay; while only 64.6% of total energy and 62.4% of total GHG emission for HMA overlay. On the other hand, the plant operation consumes 25.5% of total energy and generates 26.4% of total GHG emission for HMA overlay.

The on-site transporation component is minor due to the short transport distrance to the HMA plant and the on-site concrete batch plant. The construction equipment causes 8.8% energy consumption for HMA overlay but only 4.2% for PCC overlay. This is because significant amount of milling and paving operation are needed for construction of multi-lifts of HMA; while only one-lift slip-form paving process is needed for PCC construction.

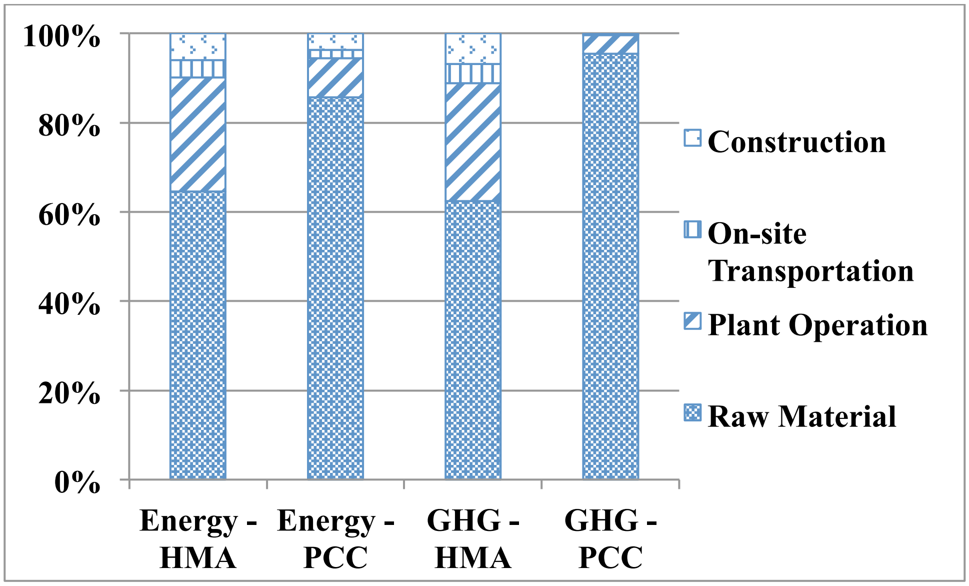


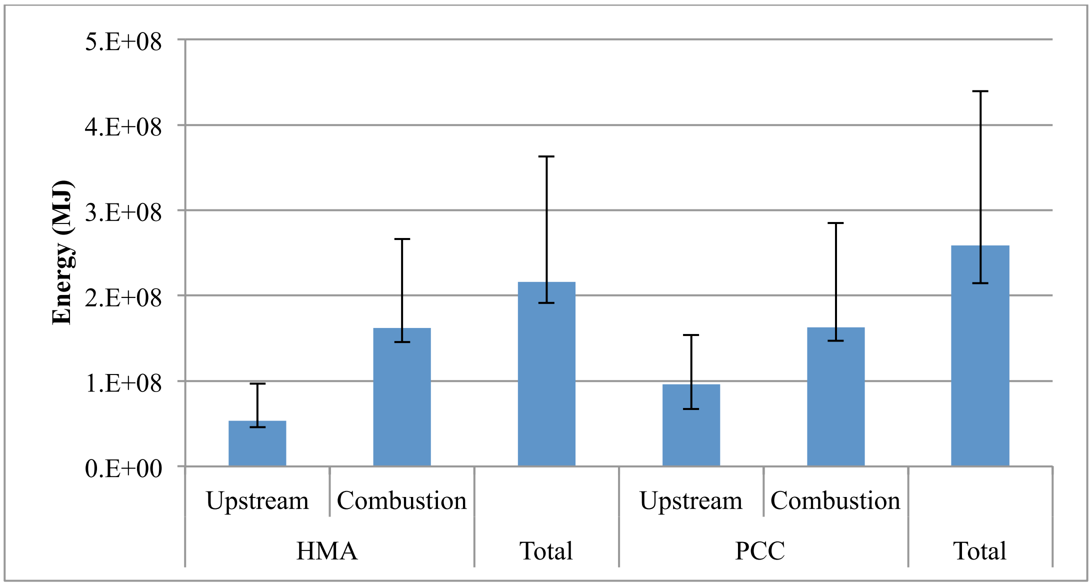
Figure 5.2 Percentage distributon of energy consumption and GHG emission at different stages of initial construction

5.5.3 Comparison between New Runway Pavement Designs

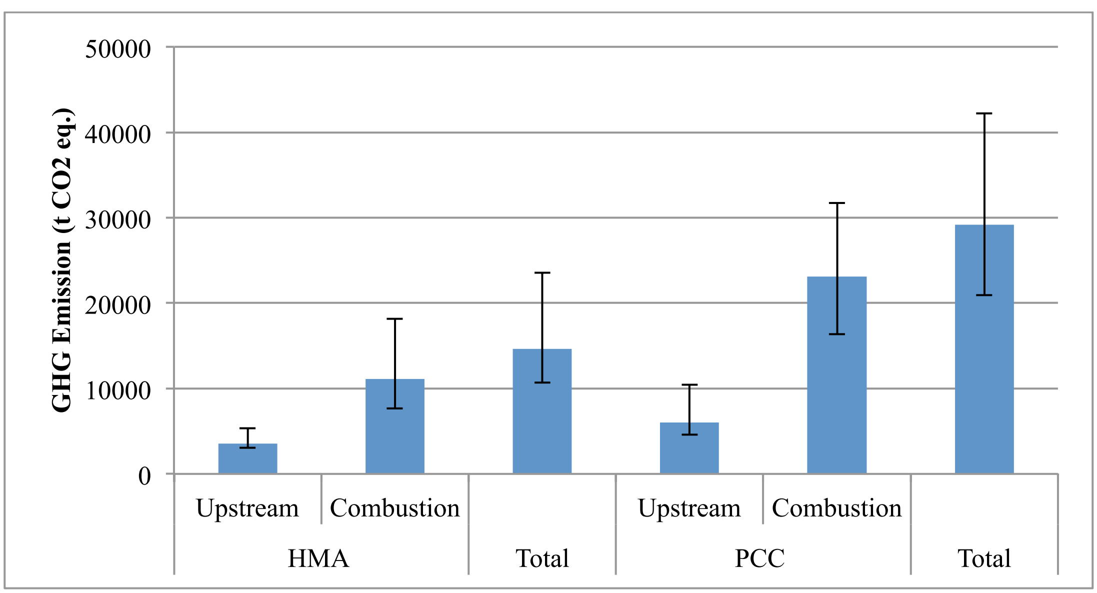
Figures 5.3(a) and (b) compare the environmental impacts of different new runway pavement designs with HMA and PCC, respectively, for energy consumption and GHG emission. Similary, both baseline values and the range of variation were calculated. The energy and emission quantities were calcualted for the whole pavement strucutre including surface, base, and subbase layer. No maintenance phase was considered in this case because these two pavement strucutres were designed to have the same design life without major rehabilitation.

The results indicate that the HMA pavement may consumes slightly smaller but comparable energy as compared to the PCC pavement. On the other hand, the HMA pavement generates less amounts of GHG emission. It is noted that the trends observed here are different from the comparison between runway rehabilitation design alternatives. The percentages of upstream components are 24-25% of total energy or emission quantities for HMA pavement and 21-37% for PCC pavement. This again emphasizes the importance of considering the upstream process in order to accurately quantify the life-cycle energy consumption and environmental impact.

In the new runway pavement design, the HMA surface layer thickness is much smaller than the PCC surface layer thickness; while the thicknesses of base and subbase layer are much thicker in the HMA pavement structure. The design alternatives presented here are based on the practice at the PANYNJ and the design outputs of FAARFIELD. It is expected that different comparison results may be found as the design practice or geographic location changes. There is no unanimous estimation of the pavement life comparison between asphalt and concrete pavements subjected to the same traffic and environmental conditions.



(a)



(b)

Figure 5.3 Environmental impacts of new pavement designs with HMA and PCC for (a) energy consumption and (b) GHG emission

Chapter 6 Findings and Recommendations

6.1 Findings and Conclusion

The preliminary work for the development of a LCA tool with inventory database from pertinent LCI sources was presented in this study. The case studies on airfield pavements for different design alternatives at runway 13R-31L, JFK airport were conducted.

6.1.1 Findings from Literature Review and Life Cycle Inventory Analysis

Based on literature review of current pavement LCA studies, it can be observed that different approaches are used to conduct LCA. Most of the existing studies used process LCA, some studies like Park et al. (2003), Treloar et al. (2004) used hybrid LCA whereas some studies like Horvath and Hendrickson (1998) used EIO-LCA. The primary benefit of using process-based LCA is that the results are more accurate, up-to-date, and can reflect the scope and objective of research more accurately. However, process-based LCA is heavily dependent on the quality and quantity of LCI data collected, making it a resource intensive LCA approach as compared to other LCA approaches.

Even if the same process-based LCA methodology is used, the results varied among different studies. For example, Stripple (2001) and Athena Institute (2006) compared flexible and rigid pavements for the environmental impacts of energy consumption and CO_2 emissions, but their results were contradictory. Stripple (2001) concluded that in comparison to flexible pavements, the energy consumption and CO_2 emission for rigid pavement were 17% and 34 % higher. On the other hand, Athena Institute (2006) concluded that compared to rigid pavement, the energy consumption and CO_2 emission for flexible pavements were 41% and 11 % higher.

These inconsistencies in results recommend that there are many factors that can affect the results of LCA like the system boundaries, inventory data quality, validity, demographics, assumptions etc. For this reason, inventory from different sources should be used to report the variation in LCA results.

6.1.2 Findings from Case Studies

This case study assessed the cumulative energy demand (CED) and greenhouse gas (GHG) emission of different airport pavement design alternatives using a LCA approach. The results indicate that the expected pavement service life and maintenance treatments significantly affect the comparison between HMA and PCC pavements. The consideration of energy and emissions associated with the production of process fuels and electricity in the upstream process cannot be neglected in the LCA. The implementation of LCA approach enables decision makers to quantify energy consumption and GHG emissions among alternative pavement designs.

The environmental impact among different pavement design alternatives significantly depend upon pavement type, design assumptions, and maintenance strategies. Although there are no general conclusions on pavement type selection, the comparison of energy consumption and GHG emission due to upstream, construction and maintenance stages brings awareness to the airport engineer on the differences between HMA and PCC pavements. The project-level analysis needs to be conducted for selecting the most appropriate design alternatives in the airport planning process. Airport agencies and contractors should work together to select the preferred pavement designs considering performance, economic cost, and sustainability.

6.2 Future Research Recommendations

Inventory database development is one of the most critical and time consuming component of LCA. This study shows the variation in the inventory database for raw material extraction and plant production phases collected from pertinent LCI studies. Data quality and representativeness are the key factors for conducting a comprehensive LCA. Therefore, it is highly recommended to collect data from regional sources like manufacturers, producers and suppliers.

The future development of pavement LCA tool model can proceed in several directions. Firstly, the tool can be applied in practice for more case studies representative of the current practice for pavement construction and maintenance. Secondly, the application of LCA tool in different geographical locations can be more accurate by incorporating the inventory data collected at the specific regions. Thirdly, the environmental impact assessment for acidification, eutrophication; criteria air pollutants, photochemical smog, etc. can be conducted.

The current case studies focused on the difference between asphalt and concrete pavement design for new runway pavements and overlays on existing pavements. Further analysis should consider the environmental impact of other sustainable pavement practice in the airport, such as recycled asphalt mixture or warm-mix asphalt, permeable pavements at runway or taxiway shoulders, and heated pavements at apron. The extra environmental burdens caused by airline delays due to construction activities in the airfield is analogy to the use phase of highway pavements and should be considered in future work.

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